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Utilisation of Cryotherapy in Sport: Understanding the Multifaceted Response

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i. Author's Declaration

This thesis is submitted as partial fulfilment of the requirements of the University of Central Lancashire for the degree of Doctor of Philosophy by Published Works. No portion of this work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institution of learning. This original work is my own.

Jill. E. Alexander

Date: 12th July 2021

For my dad,

Scott William Robert Alexander

ii. Acknowledgements

What were my reasons for pursuing study at doctorate level? My dad, tragically killed at the age of 35, I didn't get to say goodbye that day. Scott instilled my love for sport and participation from an early age. The smartest person I knew, an incredible artist, ostentatious skier, unreal gymnast and professional footballer. His passions for flying in his microlite are treasured memories. A lover of adventures and all things sport. The best Christmas present I ever got were those football nets in the garden, although I think they were a purchase more for him than me, we enjoyed them that summer, nonetheless. He never had the opportunity to complete a PhD, he would have smashed it though. I wonder what topic he would have written about.... His passion, trials and tribulations of playing in the Scottish football leagues perhaps? or how to butcher the best pork rib (tales from our family farm and butchery in Scotland). Both would have been a fascinating read no doubt! So, when I turned 35, I decided to complete 35 challenges or take up new opportunities that year that my dad never had the chance to do in his lifetime. COVID-19 put a spanner in the works with going sea fishing or tackling a sky dive, however completing this Ph.D. was one of those challenges.

I hope I have made you proud dad.

The body of scientific study presented in this thesis is a representation of several years of applied research and development of a research interest in cryotherapy application in sport. I would like to thank all my co-authors involved in the multiple collaborations over the years, within the division, across universities and internationally that have dedicated time to each publication and provided support throughout. I will always be grateful to you. I would like to particularly thank Professor James Selfe DSc, (Manchester Metropolitan University), whom without his encouragement, expertise and guidance over the years this work would simply not exist. Thank you to Professor Jim Richards Ph.D. (University of Central Lancashire) for your direction, support in the early publications and belief in the thesis. To Dr Sarah Jane Hobbs taking me on as your Ph.D. student, thrown on you at the 11th hour when I transferred to UCLan, your support and time will always be appreciated, thank you. To Dr David Rhodes Ph.D. (University of Central Lancashire) I am so grateful to you for never giving up on me. Thank you for bringing me back from dark places, making me laugh, friendship, honesty and advice, celebrating the best, and being there during the worst. I also 'appreciate' the very candid critical insights of all the anonymous reviewers contributing to each publication, although not the months of agony and cyber dust that accumulated on unopened "under review" manuscript submissions in some cases…painful is an understatement.

Aside from the hours, days, months and years of sacrifices dedicated to completing this work, this journey was not easy. To those that mistook my kindness for weakness, although sometimes I felt like giving up, I am thankful you showed your true self, sad that loyalty and friendship meant nothing to you, as it did to me, however I am stronger now because of it. I came to realise, when a toxic person no longer controls you, they try to control how others see you. At the time, this misinformation to others broke me, hurt and was unfair, however I tirelessly worked at staying above it, trusting that other people will eventually see the truth, just as I did. Ultimately, this provided the determination to finish this body of work, my work, believe in myself, pick up those broken pieces, a shell of a person, my lost confidence and smile again. So, this is my opportunity for closure.

Finally, I thank myself, for never giving up! Working every hour to finance myself through the years of education, not relying on anyone. Thankful to my family, my husband and those true friends that you can count on one hand, you know who you are.

I told him I was lost in this world,
and he smiled.
Because he was too,
we were all lost somehow,
But we didn't care,
we had, in the chaos and hurt,
found each other.
Atticus.

Here's to the next chapter…. it's called '*flying'*.

iii. Abstract

Cryotherapy is commonly used in sport for injury, rehabilitation, and recovery in readiness to perform. The principal aim of this thesis was to examine the effects of cryotherapy on several responses that underpin the optimisation of its application in sport. A substantial evidence base investigates the effects of various modes of cryotherapy across different populations and protocols, yet no body of literature examines multiple responses across several domains (*biomechanical, biochemical, physiological, psychological)* with an emphasis on contemporary in-field applied practices of cryotherapy in sport. This approach defines the originality of the thesis. Fifteen peer reviewed publications represent the body of work, structured by five themes:

Theme 1: KINEMATIC RESPONSES TO CRYOTHERAPY
Theme 2: MUSCLE STRENGTH RESPONSES TO CRYOTHERAPY
Theme 3: THERMOGRAPHY AND SKIN SURFACE RESPONSES TO CRYOTHERAPY
Theme 4: CONTEMPORARY CRYOTHERAPY APPLICATIONS AND RESPONSES
Theme 5: MULTIFACETED RESPONSES TO CRYOTHERAPY AS A RECOVERY STRATEGY IN ELITE SPORT

The studies representing several underpinning concepts from which key research questions evolved, adopted several methodologies and styles, presented in a conceptual arrangement within the five themes as opposed to chronological order. The purpose being to demonstrate synergy between concepts that might be considered important for the development of optimal cryotherapeutic applications in sport. This is an expression of the author's interest in and evolution of research over several years working in sport rather than a pre-determined plan of studies which allowed adaptability to contemporary issues in practice as they emerged. Populations ranged from amateur to elite professional athletes, with data collection protocols developed from laboratory-based to high-performance sports environments within mid-competitive seasons.

Key findings note the ability to reduce skin surface temperature for optimising intended physiological response differs between dose, modality type, compression adjunct and physical positional characteristics in team sport. Further, consensus on optimal protocols for cryo-compression is lacking, despite compression being known to increase the magnitude of cooling. Sports practitioners

should appreciate the potentially detrimental biomechanical responses to local cooling at the lower limb when considering the multidirectional demands of sport. Consequently, several variables can influence the optimisation of cryotherapeutic protocols seen in biomechanical and perceptual responses over rewarming periods. Further, where cold-water immersion may be useful to ameliorate potential deficits in eccentric hamstring strength, differences in neuromuscular performance suggest periodisation and individualisation of cryotherapy protocols in these environments is important to negate responses that may be inhibiting readiness to perform. The progression of advantageous cooling protocols in sport are inherent to the understanding of the response and relationship between key variables that underpin the effected output and response in the working context of the cryotherapeutic application. Considerations for applied practitioners to optimise cryotherapy protocols are illustrated (Table 10. pg. 227) and an infographic (Figure 23. pg. 231) to provide recommendations for future applied research demonstrates the originality of the work.

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iv. Abbreviations

AAR	Active Angle Reproduction
AMS	Anatomic Marker System
AvT	Average Torque
CWI	Cold Water Immersion
CNS	Central Nervous System
CMJ	Counter Movement Jump
CI	Crushed Ice
CC	CryoCuff®
C_p	Heat Capacity
EMG	Electromyography
EMD	Electromechanical Delay
EBP	Evidenced-Based Practice
FWCI	Field-Weighted Citation Impact
GR	Game Ready®
GTO	Golgi Tendon Organ
HI	HyperIce®
HR	Heart Rate
ICE	Ice, Compression and Elevation (Bleakley *et al,* 2012)
IM	Inertial Measurement
IRT	Infrared Thermography
JPS	Joint Position Sense
KT	Knowledge Transfer
KTP	Knowledge Transfer Partnership
KPI	Key Performance Indicators
MIVC	Maximal Isometric Voluntary Contraction
MS	Muscle Soreness
NCV	Nerve Conduction Velocity
NIRS	Near-Infrared Spectroscopy
NMF	Neuromuscular Function
PBC	Partial Body Cryotherapy
PCM	Phase Change Material

Abbreviations Cont.

PKPM	Photographic Knee Pain Map (Elson *et al*, 2011)
PRICE	Protect, Rest, Ice, Compression, Elevation (Bleakley *et al,* 2011)
PkT	Peak Torque
POLICE	Protect, Optimal Loading, Ice, Compression, Elevation (Bleakley *et al,* 2012)
PEACE & LOVE	Protection, Elevation, Avoid Anti-Inflammatories, Compression, Education & Load, Optimism, Vascularisation, Exercise (Dubois & Esculier, 2019)
RICE	Rest, Ice, Compression & Elevation (Bleakley *et al,* 2012)
RICES	Rest, Ice, Compression, Elevation & Stabilisation (Long and Jutte, 2020)
RSA	Repeated Sprint Ability
ROM	Range of Motion
SKB	Small Knee Bend
SSS	Skin Surface Sensitivity
SA	Swellaway
SNIP	Source Normalised Impact per Publication
SQ	Squid® System Cooling Device
$\mathbf{T}_{ia}$	Intra-articular Temperature (°C)
TC	Thermal Comfort (questionnaire)
TS	Thermal Sensation (questionnaire)
TI	Thermal Imaging
$\mathbf{T}_{sk}$	Skin Surface Temperature (°C)
$\mathbf{T}_{im}$	Intra-muscular Temperature (°C)
VFH	Von Frey Hair
$\mathbf{VO_2}$	Maximal Oxygen Uptake
WBC	Whole Body Cryotherapy
WI	Wetted Ice
$\mathbf{\Delta H}_{fus}$	Enthalpy of Fusion

v. Definition of Terms

Analgesia: Reduction in sensation, or pain that can be caused by a pharmacological agent, including cryotherapy (Sinatra *et al*, 2010).

Cryotherapy: The therapeutic application of any modality that removes heat from the body, resulting in decreased tissue temperature (Knight *et al,* 1995; Nadler *et al,* 2004; Block, 2010).

Conduction: The transfer of energy from substances with more energetic particles to less energetic particles because of particle interaction (Çengel and Boles, 2015).

Dynamic Stability: A component of proprioception, to prevent abnormal movement patterns as a response to maintain ideal body position (Cordeiro *et al,* 2014).

Heat Transfer: unidirectional temperature from high to low regions. Those that contain higher kinetic energy (hot) transfer the energy to regions with lower kinetic energy (cold) (Cengel and Boles, 2015).

***h*-index:** An author-level metric that measures your research output and its citation impact, based on most cited work and number of citations received

Infrared Thermography: The science of data analysis from non-contact thermal imaging devices (Vellard and Arfaoui, 2016).

Joint Position Sense: A common measurement of proprioceptive acuity. An individual's ability to perceive a target joint angle or limb position and to replicate the same position after return of the limb to a starting position, to reproduce that predetermined angle (Rozzi *et al*, 2000; Ribeiro *et al,* 2007; Costello *et al*, 2010).

Kinesthesia: A constituent of proprioception; it is a combined sense of movement from a variety of anatomical structures (Williams and Krishnan, 2007; Lephart *et al*, 1992).

Modality: An application or device that delivers a physical agent for therapeutic use, applied to the body (Knight and Draper, 2013).

Partial-Body Cryotherapy: Whereby the human body except for the head/neck is exposed to cold conditions below -100°C in a mobile cryo-cabin (Bouzigon *et al,* 2016).

Pneumatic: Movement of gas/air through pressure, adapted for use to inflate with compressed air or a device with air-filled cavities to induce compression (Knight, 1989; Knight and Draper, 2008).

Phase Change: A change from one state to another without a change in chemical composition (Çengel and Boles, 2015).

Phase Change Material: Substances that release or absorb amounts of latent heat when the go through a change in their physical state (i.e., from solid to liquid) (Guarino and Ambrosio, 2018).

Proprioception: Multiple complex sensorimotor or neuromuscular parameters for control (Richards and Selfe, 2012, Chapter 8). Components of proprioception include Detection from joints (Joint Position Sense), Sensation of force, contraction, body segment orientation or whole-body orientation (Williams and Krishnan, 2007, Chapter 9). Proprioception requires cumulative neural input from mechanoreceptors to the central nervous system (Lee *et al*, 2003; Sherrington 1906).

Proprioceptive Acuity: An individual's ability to sense joint position, movement, and force to distinguish limb movements (Gandevia *et al,* 2002; Muaidi *et al*, 2008).

Raynaud's Phenomenon: A painful circulatory disorder caused by a reaction to cold application (Lewis, 2014).

Recovery: Multifaceted restorative process relative to time (Halson, 2014; Kellmann *et al,* 2018).

Thermal equilibrium: When two substances in physical contact with each other reach the same temperature and no heat flow occurs between them, maintaining constant temperature. The equality of temperature is required for thermal equilibrium (Çengel and Boles, 2015).

Whole-Body Cryotherapy: The subject is entirely exposed to short cold treatment via cryochambers usually divided into two or three compartments of varying temperatures (-10°C, -60°C, -110-140°) (Bleakley *et al,* 2014).

vi. Laws Relative to Heating and Cooling Principles

Grotthuss-Draper Law – Amount of energy absorbed by tissues and depth of penetration are inversely related. As the depth of treatment increases, the amount of energy absorbed by the tissues reduces as it is being absorbed by tissues in close vicinity to the source of energy (Kolasinski, 2016).

Fourier's Law – The governance of heat transfer by conduction. Per unit area, the transfer in any given direction is proportional to the temperature gradient (Fourier, 1807; Çengel and Boles, 2015).

Stefan-Boltzmann Law – The total radiant heat power that is emitted from any surface is proportional to the fourth power of its absolute temperature (Stefan, 1879; Boltzman, 1884; Çengel and Boles, 2015).

Kirchhoff's Law – (Of radiation) the emissivity and the absorptivity of a surface area are equal at the same temperature and wavelength (Kirchhoff, 1860).

Zeroth Law of Thermodynamics - There exists a property called temperature T. When the temperature of two systems is equal, the two systems are at thermal equilibrium (Fowler and Guggenheim, 1939; Kolasinski, 2016).

First Law of Thermodynamics - There exists a property called the internal energy U, which is the sum of all kinetic and potential energies as well as all chemical and physical interaction energies. Work and heat change U equivalently (Kolasinski, 2016).

Van't Hoff's Law – For every 10°C reduction/rise in tissue temperature, chemical reaction rate will decrease between two to threefold (van't Hoff, 1884). This principal term is considered an important rationale behind the application of cryotherapy (ice) during the immediate stage of acute injury management to reduce cellular metabolism, consequently limiting further tissue damage and reducing the risk of secondary injury.

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0.1 Ethical Approval

Ethical approval for investigations carried out for the fifteen publications was provided and approved by the applicable ethical committee and panel at the University of Central Lancashire. Where applicable, all associated clubs provided written consent for dissemination of anonymous data through publication.

0.2 Context and Structure of the Thesis

The topic of cryotherapy has been widely investigated for its use in sport for the management of acute injury and recovery methods. Despite this, the current field of research that encompasses the role of cryotherapy for recovery or injury management suggests that further rigorous examination of cooling modalities should continue in sports medicine and performance environments. Well-known acronyms of RICE (rest, ice, compression and elevation), PRICE (protection, rest, ice, compression and elevation) (Bleakley *et al,* 2011) and more recently POLICE (protection, optimal loading, ice, compression and elevation) have evolved the topic of local cooling and its use (Bleakley *et al,* 2012) in sports medicine. It is advocated as essential for these paradigms of treatment to be contemporary, in line with the present evidence base (Bleakley, Glasgow and MacAuley, 2012). Dubois and Esculier, (2019) offer an alternative perspective on the absence of cryotherapy in acute injury management under the acronym 'PEACE' and 'LOVE' (Protection, Elevation, Avoid Anti-Inflammatories, Compression, Education and Load, Optimise, Vascularisation, Exercise). The application of therapeutic modalities is a fundamental element in the management of injury, rehabilitation, recovery and readiness to perform in sport, however, highly dependent upon a practitioner's application protocol. Often this is expectantly determined by the evidence base or anecdotally informed.

At an elite level, the opportunity to evaluate injury or recovery management strategies is a common objective to improve overall performance leading sports medicine practitioners to explore and challenge current evidence. Although heavily applied within sport for injury and recovery, local cooling modalities differ significantly in the physiological responses they can achieve (Merrick *et al*, 2003; Kennet *et al,* 2007; Alexander *et al,* 2020a). That said, the evidence available to support or refute the use of various cryotherapeutic modalities is developmental and still lacks consensus in key influential areas. Which is, in part, the basis for making informed judgements on optimal protocol applications of cryotherapy in sport. Inadequate research methodologies with variable or inconsistent outcome measures reduce the effectiveness of current research in cryotherapy for any conclusive evidence to be established. Therefore, it is imperative that data collected in such studies are accurate, reliable and objective to inform practice. In deliberation of the available evidence, and although literature reports the effectiveness of injury management through cryotherapy applications, to establish the beneficial effects of cryotherapy further, conclusive investigation is warranted. Information gained from robust studies is used to guide decision-making in terms of optimal injury management or rehabilitation to recovery protocols that aim to optimise performance.

Justification for contemporary applications of cooling cannot be solely based on the physiological responses known to occur through traditional application methods. Over recent years the development of more complex modalities that incorporate simultaneous cryotherapy and compression, or whole-body cryotherapy (WBC) for example are becoming widespread in elite or high-performance environments (Banfi *et al,* 2010) and of interest in the current literature (Partridge *et al,* 2019; Malone *et al,* 2021). These developments bring the opportunity to explore protocols through investigation of the cryotherapy responses and influential variables to maximise application. With comprehensive approaches to develop optimal evidenced-based protocols in elite sport anchored around the science, this encourages the applied researcher to investigate multiple objective markers, including physiological, biomechanical and performance outputs in response to cooling. Knowledge translation from research studies that is useful in an applied context is paramount to have a meaningful impact, yet not a new concept (Barton and Merolli, 2019). It is perhaps only recently that this approach has been employed in cryotherapy literature relevant to the applied and elite sport setting in terms of replicable methodologies. This strategy was used to develop the body of work presented in this thesis.

This body of work is the first to examine in detail multiple components behind multifaceted responses of cryotherapy in sport, encompassing five themes applicable to current practice. Within each theme the publications generated include multiple parameters of measures reflective of key performance markers in sport frequently cited. The intended outcomes for this body of work were to advance knowledge around key responses of cryotherapy in sport, contribute to the development of optimal protocols for application, and ultimately directly impact real-world practices. Data for the studies were collected across laboratory and practical elite sport settings and analysed using a variety of approaches for interpretation of intervention response. The publications presented in the thesis that make up the body of work are listed in critical review and theme order (Table 1). Each theme is synchronised by a corresponding colour which is translated throughout the thesis.

Aim of the Research

The principal aim of this thesis was to examine the effects of cryotherapy on several responses that underpin the optimisation of its application in sport from an applied, multiple study design and methodological approach. The intention of the approaches was to optimise the use of cryotherapy in sporting contexts with investigations reflecting contemporary practices and multi-measures of performance reflecting *biomechanical*, *biochemical, physiological* and *psychological* responses.

Objectives

- To determine the effects of local cryotherapy applications on multiple mechanistic responses in the lower limb affecting immediate return to functional activity in sport.
- To examine effects of cryotherapy applications over rewarming periods and multiple parameters of objective and subjective measures.
- To critically examine contemporary cryotherapy applications in elite sport and their effects on readiness to perform.
- To develop innovative research designs that investigate applied protocols of local and whole-body cryotherapy modalities in elite sport for recovery and performance.
- To systematically determine underpinning strategies to optimise the application of cryotherapy modalities and protocols in sport.

Table 1. List of publications by theme.

Theme	Publication Number	Title and Year of Publication	Journal, Volume, Issue, Page Numbers	Authors	Appendix
Theme 1: **KINEMATIC RESPONSES TO CRYOTHERAPY**	1	An exploratory study into the effects of a 20-minute crushed ice application on knee joint position sense during a small knee bend. (2016)	Physical Therapy in Sport, 18(1): 21-26.	Alexander, J., Selfe, J., Oliver, B., Mee, D., Carter, A., Scott, M., Richards, J., and May, K.	APPENDIX 1a.
	2	Delayed effects of a 20-minute crushed ice application on knee joint position sense assessed by a functional task during a re-warming period. (2018)	Gait and Posture, 62: 173-178.	Alexander, J., Richards, J., Attah, O., Cheema, S., Snook, J., Wisdell, C., May, K and Selfe, J.	APPENDIX 1b.
Theme 2: **MUSCLE STRENGTH RESPONSES TO CRYOTHERAPY**	3	The effect of knee joint cooling on isokinetic torque production of the knee extensors; Considerations for application. (2018)	International Journal of Sports Physical Therapy, 13(6): 6-8.	Rhodes, D, and Alexander, J.	APPENDIX 2a.
	4	Temporal patterns of knee-extensor isokinetic torque strength in male and female athletes following comparison of anterior thigh and knee cooling, over a rewarming period. (2019)	Journal of Sports Rehabilitation, 18(29): 723-729.	Alexander J, and Rhodes, D.	APPENDIX 2b.
	5	Exploratory evaluation of muscle strength and skin surface temperature responses to contemporary cooling modalities in sport. (2021)	Isokinetics and Exercise Science, In Press.	Alexander, J., Selfe, J., Greenhalgh, O., and Rhodes, D.	APPENDIX 2c.

Theme 3: **THERMOGRAPHY AND SKIN SURFACE RESPONSES TO CRYOTHERAPY**	6	Mapping knee skin surface sensitivity and temperature following cryotherapy. (2019)	PRM+ Journal of Quantitative Research in Rehabilitative Medicine, 2(1): 1-5.	Alexander, J., Selfe, J., Rhodes, D., Fowler, E., May, K., and Richards, J.	APPENDIX 3a.
	7	Comparison of cryotherapy modality application over the anterior thigh across rugby union positions: A crossover randomised controlled trial. (2020)	International Journal of Sports Physical Therapy, 15(2): 210-220.	Alexander, J., Selfe, J., Birdsall, D., and Rhodes, D.	APPENDIX 3b.
	8	Editorial Commentary - Thermography for defining efficiency of cryotherapy modalities in sport. (2020)	Temperature, 8(2):105-107.	Alexander, J, and Rhodes, D.	APPENDIX 3c
Theme 4: **CONTEMPORARY CRYOTHERAPY APPLICATIONS AND RESPONSES**	9	Short Communication - Cryotherapy in Sport: A warm reception for the translation of evidence into applied practice. (2021)	Research in Sports Medicine, 10: 1-4.	Alexander, J., Allen, R., and Rhodes, D.	APPENDIX 4a
	10	Cryotherapy and compression in sports injury management: A scoping review. (2021)	International Journal of Therapy and Rehabilitation. In Press.	Alexander, J., Greenhalgh, O., Selfe, J., and Rhodes, D.	APPENDIX 4b
	11	Physiological parameters in response to levels of pressure during contemporary cryo-compressive applications: Implications for protocol development. (2020)	Journal of Athletic Enhancement. 9(1): 1-6.	Alexander, J., Greenhalgh, O., and Rhodes, D.	APPENDIX 4c

Theme 5: MULTIFACETED RESPONSES TO CRYOTHERAPY AS A RECOVERY STRATEGY IN ELITE SPORT	12	Recovery profiles of eccentric hamstring strength in response to cooling and compression. (2021)	Journal of Bodywork and Movement Therapies. 27: 9-15.	Alexander, J., Jeffrey, J., and Rhodes, D.	APPENDIX 5a
	13	Effects of contemporary cryo-compression on post-training performance in elite academy footballers. (2021)	Biology of Sport, 39(1): 11-17.	Alexander, J., Keegan, J., Reedy, A., Rhodes, D.	APPENDIX 5b
	14	Utilisation of performance markers to establish the effectiveness of cold-water immersion as a recovery modality in elite football. (2021)	Biology of Sport, 39(1): 19-29.	Alexander, J., Carling, C., and Rhodes, D.	APPENDIX 5c
	15	The effect of three different (-135°C) whole body cryotherapy exposure durations on elite rugby league players. (2014)	PLoS ONE, 9(1): 1-9.	Selfe, J., Alexander, J., Costello, JT., May, K., Garratt, N., Atkins, S., Dillon, S., Hurst, H., Davison M., Przybyla, D., Coley, A., Bitcon, M., Littler, G., and Richards, J.	APPENDIX 5d

Thesis Structure

The structure of the thesis consists of four chapters. Preceding chapter 1, the researcher journey is presented followed by an introduction to the scope of the work and original contribution to knowledge. Chapter 1 reviews the available literature to provide context to the body of work and underpins the justification of the publications. Furthermore, the narrative of the critical review within chapter 1 identifies gaps in the evidence base, research questions and accordingly the five themes and associated publications are presented in Table 1, (pg. 26-28). Chapter 2 describes the research perspectives that influenced the methodological and study designs. Critical analysis of each publication per theme formulates Chapter 3, evaluating the scope of each study and the implications of findings to both practice and scholarship. Finally, Chapter 4 concludes with a synopsis of the entire thesis pertaining to the applied impact to practice resulting from the body of work, the limitations of the studies and future research considerations. Full copies of each publication are presented in the appendices.

0.3 The Researcher Journey

My development as a researcher originated from my experiences working in sport in a medical capacity. Graduating in 2008, with first-class honours in BSc (hons) Sports Therapy, subsequent employment commenced in rugby union and over 15 years worked in amateur, semi-professional and elite, international sport. It was clear to me whilst working in sport that the practice of cryotherapy application was common with little evidence for its use, nor did the evidence available provide sufficient real-world cryotherapeutic or recovery protocols for practitioners in these environments. From my observation of different approaches, applications, practitioner and athlete preferences, I could see the need to address some of the issues, inevitably driving the progression of this body of work. Examples included:

- My observation of different approaches by practitioners when applying common applications of cooling modalities during half-time, stoppages in play or short periods of player bench rotation in rugby and the inability to locate applied evidence to fully understand the physiological, biomechanical or psychological effects when returning the athlete to the field of play immediately following local cryotherapy application.
- Noting the minimal evidence or understanding around rewarming periods or recommended protocols required post-cooling applications in sport for safe return to competition or functional sport demands.
- Lack of clarity available in the literature applicable to real-world scenarios surrounding dose or mode responses of cryotherapy for recovery strategies in sport that consider periodisation of cooling and multiple parameters of investigation or individual response and performance, including perceptual responses.
- Equivocal understanding of whole-body cryotherapy practices on physiological measures, mainly dose-response, despite anecdotal application of its use as a developing recovery strategy in elite sport often promoted through social media as a benefit for performance.

- My observation of limited literature that identified the benefits or approaches to optimise protocol applications of contemporary cryotherapy / cryo-compressive devices for injury or recovery in sport with inconsistent application approaches seen in practice.

An interest in cryotherapy evolved from the development of my undergraduate dissertation which investigated the effects of ankle cooling on dynamic stability. In 2008 following completion of my undergraduate studies, I applied for and was successful in gaining a 12-week postgraduate research internship. This provided me with the opportunity to investigate the parameters of lower limb cooling on postural sway, presenting the findings at a research internship conference held at the University of Central Lancashire. Although this project established my interests around cryotherapy it presented more questions than answers. Observation of cryotherapeutic practices in sport developed as I gained practical experiences working in industry and in 2013, the opportunity to advance my interests in cryotherapy and elite rugby developed through a tri-partite funded Knowledge Transfer (KT) project, at the University of Central Lancashire in conjunction with Wigan Warriors RLFC First Senior Squad and BOC Linde. This 14-week randomised controlled trial study investigated dose-response of whole-body cryotherapy in elite rugby league players. Subsequently a highly cited publication in PLOS ONE (publication 15) demonstrates the findings of this work and was the first study to establish an optimal exposure time of WBC in an elite rugby league population. This project inspired my interests in how cryotherapy protocols could be optimised in sport for injury, rehabilitation, recovery and performance. Moreover, it highlighted several gaps in the evidence to determine this from a practitioner perspective. Latter to this publication my role at the university developed through various Research Assistant, Associate and Lecturing posts alongside continuing to work in sport as a Sports Therapist. Consequently, this study heavily influenced my research-informed teaching at the time. With responsibility for the delivery of several research methods modules, supervision of undergraduate and postgraduate dissertation projects across two programmes, and practical teaching, I could see first-hand how the research publications supported the delivery of applied research into the classroom. Something I reflected on through my delivery of practical and research-based modules on the BSc (hons) Sports Therapy and MSc Sports Medicine programmes.

Effective education through contemporary evidenced-based practice (EBP) aims to exploit the synergy between theory and practice (Collins and Collins, 2019). A personal observation was the notable gap between the translation of research into practice evident in sports medicine and performance environments where cryotherapy use is employed. The integration of practitioner and academic approaches (McDonald and Mooney, 2011) reduces the gap between theory derived from research and real-world practice in the field (Tunison, 2016; Collins and Collins, 2019). Hence one intention throughout all the publications in this thesis was to develop the study methodologies to represent parameters and protocols pertinent to elite sport settings. The intention to reduce the scepticism amongst practitioners (Tunison, 2016) and encourage buy-in to the purposes behind the work. Well intentioned research often results in poor credibility of academic study if a lack of synergy between important practical topics and what is published by academics ensues (Tunison, 2016). Consequently, the Practitioner-Academic style supported the pragmatic development of EBP I intended in the publications presented in this thesis. The aim of the thesis however was primarily developed from my experiences gained from working within medical and performance teams in sport, and curiosity around the limiting EBP to support the justification of common practices such as cryotherapy for acute injury management (on-pitch and pitch-side) and recovery strategies, despite implementing such methods frequently. Although this may suggest that a fundamental approach to research throughout the collection of works, the studies represent an applied research approach with the intention to impact practice. Collectively I felt the need to explore contemporary cryotherapy approaches further, noting where the evidential gaps appeared, such as optimal cryotherapy protocols. This process guided the questions and associated themes around responses to cryotherapy and subsequently presented through the outputs and applied nature of the studies in this thesis.

My interests, research output and public engagement in the scope of cryotherapy led to my involvement in the early developments of the Swellaway® portable cooling device. My research role at the time involved providing technical reports through the development of intervention studies to test the device. Subsequently that work led to the research team achieving competitive funding from Innovate UK for a KTP project (£195,857.47) over a three-year period (2018-2021). This tripartite

KTP project with UCLan and Manchester Metropolitan University is the first of its kind reflecting a multi-university KTP partnership developed as part of an ongoing relationship with the cooling technology company, Swellaway®. The 3-year KTP due for completion in 2021 built upon previous commercial contract research projects and technical reports testing the efficacy of the Swellaway® device and its use in elite sport. Currently the device has launched to market as ProMotion EV1 (Swellaway, LTD) with the backing of investor Wayne Rooney and current England International Footballer Harry Maguire (https://promotion.fitness/). My involvement in the KTP in a supervisory capacity has provided the opportunity to develop collaboration, contributing to the project development and guiding the research output alongside personal growth in design, marketing, CE and FDA approval and understanding the processes behind a KTP funded research project.

Alongside my KTP supervisory role in 2018, following my progression into Senior Lecturer, I incorporated the course lead position for the BSc (Hons) Sports Therapy programme at the University of Central Lancashire. My teaching commitments developed across multiple programmes including the MSc Football, Science and Rehabilitation course. This provided the opportunity to develop modern delivery of research methods and thesis supervisory roles. I continually embedded research-informed teaching across multiple programmes and aimed to influence the teaching delivery of staff and development of course programmes reflecting industry demand and research agendas collectively. At this time, I was invited to contribute to a book chapter, published by Elsevier, in the context of thermoregulatory responses to cooling, local cooling applications and effects, and WBC in sports medicine practice (Selfe, *et al,* 2020). In addition, I was asked to write a short feature publication for the Football, Medicine and Performance Association (FMPA) on the topic of whole-body cryotherapy in elite sport. I had not produced these types of literature before and thus provided the opportunity to further develop my writing styles.

Earlier team-based research projects developed my learning and provided experiences to initiate personal interests and enabled me to explore my own ideas for further research projects. Henceforth, issues surrounding the effects of local cooling on functional parameters in sport and rewarming initial studies investigated the effects of local cooling on kinematics and muscle strength parameters. My development in this area is evidenced through the submission of my first conference presentation and further publications (Appendix 6). Studies within Theme 1 were accepted at the Sports Kongress Conference in Copenhagen in 2017 (Appendix 6). Further studies around the effects of local cooling on muscle response were developed consequently from these projects. Agreement on the effects of cooling on muscle strength at the time was evidently lacking. Subsequent publications 3, 4 and 5 incorporated the effects of knee and muscle cooling on muscle strength parameters and the implications for application (Appendix 2). My interests in contemporary vs traditional methods of cooling grew from this point due to the technological advancements in cooling devices exposed through the KTP and work with elite sport environments. Prospective studies in the thesis therefore incorporated several modern methods of cooling resembling typical applications in sport.

Coinciding with skin temperature parameters, the investigation of skin surface sensitivity (SSS) became of interest to me and consequently I developed a research study to investigate this. To my knowledge at the time, no research had investigated the potential changes in SSS following local cooling in the lower limb, specifically the knee. Therefore, the idea of incorporating the photographic knee pain map (PKPM) (Elson *et al,* 2011) was of interest with the idea of producing a superficial visual mapping dissection of the anterior knee following local cooling. At this time, lab research had identified that superficial sensory input through athletic tape applied to the skin was modifiable therefore I was interested to determine whether a pattern in cooling could be established using the same tool that may rationalise the findings from earlier studies around the changes in kinematic response to cooling at the knee. It was considered that results from this study may have provided insights into components of neurophysiology in respect to superficial sensory inputs via the skin that may be affected from local cooling. Study 6, published in PRM+ in 2019, demonstrated a new concept in understanding cooling response in relation to SSS, and the potential effects this may have in sport. This approach also developed my understanding around physiological responses, one of the four categories underpinning the thesis themes further. The extent of which, including each publication are critiqued in Chapter 3.

I frequently observed the common use of cryotherapeutic / cryo-compressive modalities for recovery management strategies following fatiguing exercise. Interestingly in high-performance settings, inconsistent protocols, a one size fits all approach and various levels of accessibility to technological advancements in contemporary cryotherapy modalities often determined the application. This, despite a growing body of evidence often failed to translate into the applied environment. To ensure the progression of studies in the thesis reflected contemporary issues, the applications of cryo-compressive devices were acknowledged, and subsequent publications explored variations aside from crushed ice or compared them to traditional cooling methods. What was of interest to me was the use of technologies that incorporate cooling and compression (cryo-compression). Such applications applied electronically or manually and their effects on the magnitude of cooling efficacy were only briefly acknowledged in the literature at the time. Other effects of such devices on physiological and biomechanical responses were limited, and ideal protocols seemed non-existent. My interest grew around cryo-compressive devices from witnessing their application in professional sport and anecdotal positive athlete and practitioner feedback without any evidenced-based protocols available. The efficiency of cryo-compressive modalities in sporting contexts was an element of the thesis I wished to develop from this. To address the dearth of understanding of cryo-compressive devices and present a current prospective overview on the topic I designed a scoping review (publication 10). This work demonstrates the inadequacy of consensus and poor methodological approaches available to determine any quantification of optimal protocols for cryo-compressive modalities. In recognition of this, it felt necessary to develop further investigations which quantified the effects of current cryo-compressive devices utilised in sport and the physiological effects observed over significant periods of rewarming. This interest led to determine the effects of the cryo-compressive Squid® and Game Ready® devices which explored muscle oxygenation and T_{sk} following exposure (publication 10). This study was published open access, funded by the University of Central Lancashire. From the results of this work, I wanted to further my interests and develop my knowledge on the effects of cooling on muscle strength as this was an area not considered in my previous study design. To develop personal knowledge around this strand of the thesis I considered broadening my scope in successive studies that quantified eccentric strength instead of concentric measures alone.

Simultaneous to the development of applied outcomes measures, contemporary cryo-compressive devices were utilised in the study designs. I felt the opportunity to investigate different cryo-compressive modalities that reflected modern strategies of cooling for recovery provided an opportunity to simultaneously reduce the lack of evidence in this area and impact my own practices through testing of current protocols in the field. Personally, I felt that the inclusion of contemporary equipment used in industry which quantified performance was important in the methodological designs of the latter studies (publications 12-14) and helped underpin research informed teaching as part of my Senior Lecturer role and has since been accepted for presentation at the Isokinetics Football Medicine conference in Lyon in 2022. Furthermore, to engage undergraduate and postgraduate students to become research active required the demonstration between the evidence base and the ability of application of current findings into practice through contemporary equipment. As a result, this approach in study design, data collection, output and impact, linked *industry – delivery – practice – evidence* together in the classroom.

At this stage a noticeable gap, pertinent to dose-response relative to cooling application was emerging as a natural consideration in the thesis. Evidently an absence of knowledge around dose-response and my interests around periodisation of contemporary cooling in sport for optimal recovery met recommendations for future research identified in the literature (Haq *et al,* 2018; Murray and Cardinale, 2015). The emphasis on streamlining recovery processes and maximising athlete readiness to train / compete was something I witnessed when working with France XV U20's squad for game preparation and post-competitive fixtures recovery strategies. Although the effects of cryotherapy for recovery had been explored on the periphery in the thesis through the study: '*Recovery Profiles of Eccentric Hamstring Strength in Response to Cooling and Compression'* (Alexander *et al,* 2020d) (Appendix 5a), the methodology lacked ecological validity in respect of typical temporal patterns of fatigue experienced within elite sport settings. In my current SL role alongside programme lead, my post-graduate supervisory responsibilities include MProf / DProf in Elite Performance students from high-performance backgrounds which consequently generate topical debate around issues around recovery strategies in sport. To optimise the impact of the studies in the thesis on practice, applications of cryotherapy in sport with a greater understanding of the influence of fatigue within mid-competitive seasons was important to explore. Consequently, I developed two study protocols that would capture this (publications 13 and 14). A critique of both studies is presented in Chapter 3. The publication, '*Utilisation of performance markers to establish the effectiveness of cold-water immersion as a recovery modality in elite football',* (Alexander *et al,* 2021) I felt was pivotal in my development as a researcher as it incorporated multiple aspects of study design and reflection of applied practice that I wanted to combine in my research. A key recommendation was the approach of statistical analysis for individual athlete response. In terms of personal development this developed my appreciation of statistical analysis and dissemination of results that can impact practice from a different perspective.

One consideration, transient throughout the Ph.D. was to ensure contemporary methods of cooling in sport and the methods in which functional output was quantified and reported were employed. Several considerations were acknowledged in the publications in respect to the way fatigue is currently monitored in elite sport. This aligned to my aim of producing publications specifically targeted and accessible to the applied sports medicine and performance practitioner. As such the impacts of study results had both scientific and practical influences discussed further in Chapter 4. Practitioners were informed about the work through club / industry presentations, social media and post-graduate teaching. Overall impact and citations of studies are reported in chapter 4. The journey however, started with small-scale exploratory laboratory projects that presented more questions than answers understandably leading to further complexities surrounding the multifaceted responses to cryotherapy to optimise applications. A continuous theme which ran through all publications and my approaches to understanding the efficiency of cooling applications, was the use of thermology to quantify of skin surface temperature (T_{sk}). My first experience of this technology was through my undergraduate dissertation and to develop its use within the teaching, successive CPD and research projects with undergraduates ensued with physiological measures of T_{sk} at the heart of the projects. Progression of this interest has led to its use within the KTP project and others in the Allied Health Research Unit with further technology purchased for use within the faculty for teaching and research. Consequently, I felt passionate about developing a short commentary to present a critical reflection of the use of thermography that challenged preferences of cooling applications in sport (publication 8). This along with another editorial piece (publication 9) developed my range of writing within the thesis and experiences of different styles of publication along with constructive debate with internal and external colleagues.

My experiences within sport, an experienced practitioner and as a senior lecturer in higher education and the gaps critically identified in the knowledge base, inspired my journey through this body of work and influenced the publication strategy for the studies in this thesis. That being to target journals aimed at practitioners or practicing academics in the remit of sports medicine and performance. In addition to disseminate the findings through international sport medicine / science / performance conferences, CPD or club presentations. The publications in this thesis demonstrate the natural journey of investigation over a period bringing together personal experience working in sport as a graduate Sports Therapist, my role as a senior lecturer, programme lead and personal research interests and developments with the intention of bridging the gap between academic and real-world submission of research. During this research journey ironically, I have become more conversant with the perspective of there being a '*journey'* other than simply reflecting on what I have done, and rather to understand and embrace '*reflexivity'* in the context of reflecting on what I have learnt through the process including reasoning, consideration and deliberation. My awareness of maintaining neutrality in the research process from inception through field work, data interpretation and the impact of findings has developed. Consequently, I am more aware of my role within the research process and have a better understanding of possible influence of perceptions or beliefs. The journey of a Ph.D. by research is different in terms of skill development, where writing for publication in a traditional Ph.D. format often comes after a finished thesis, where in this case fundamental skills for publication of studies were developed much earlier in the learning process for the dissemination of work. The greatest challenges where patience was developed was through the unknown length of review processes and being open to the consideration of differing perspectives regarding study design, data analysis or interpretation of the impact of findings during the peer-review process which differed significantly between journals and reviewers. Having now completed the Ph.D. I can see a change in how I approach, think and analyse. Taking forward the debate around the approach of my research, between fundamental vs applied when the underpinning aim of future studies is to impact applied practice in high performance sport environments is a key learning experience through the complexity of the Ph.D. process. The Ph.D. (by publication) process was not linear and often left a frustrating challenge of uncertainty and differing feedback in the supervisory and peer-review processes. That said, these situations developed into positive experiences as I developed confidence around my own knowledge and direction of the work. Differing opinions and perspectives although conflicting at times helped to identify multiple aspects from each to strengthen the body of work. In addition, journal reviewers' feedback is a fundamental part of doctoral development which became a mechanism for improvement to each publication and the body of work and consequently impacting the synopsis chapter, knowing that my work had been critiqued by experts in the field. Lastly although uncomfortable initially, I developed the appreciation of the conflicting debates around what constitutes a Ph.D. by publication, and instead considered it as an opportunity to produce something unique in structure and purpose and as an outlet to produce a contemporary body of work that articulates my knowledge in this topic and the impact of my work in applied practice.

Although research and citation data can be interesting, the impact of my work from a practical perspective may be quantified more importantly from the successful translation into modern EBP in the applied performance setting. Both approaches are critiqued in Chapter 4. In summary, I am actively developing my personal research record although not a full-time researcher. My current position is senior lecturer and programme lead for the BSc (hons) Sports Therapy course with over 200 students and imminently joining the Institute of Coaching and Performance (ICaP) team as the MProf in Elite Performance programme lead. I have several ongoing funded projects generating income for the university, produced over 40 peer-reviewed publications, and developed internal and external international research collaborations in elite sport. In addition I am the research and funding lead for the Football Performance Hub (UCLan), editor-in-chief for a sport performance journal (Journal of Elite Sport Performance), part of the research team behind the portable cooling device ProMOTION EV1 (Swellaway LTD.) and have led the submission of funding bids to UEFA, FIFA and lead an active consultancy research role within the Premier League.

0.4 Scope of the Research

The scope of the publications and original contributions to knowledge from each of the publications (1-15) are presented in this section. Figure 1 (pg. 41) and Table 2 (pg. 42-52) present and rationalise the styles of methodological approaches throughout the publications within this body of work. The five themes presented in the thesis (Table 1, pg. 26-28) encompass four key categories of response (*biomechanical, physiological, biochemical, psychological*) and multiple variables (Figure 1, pg. 41), that are derived from the research questions identified in Table 2 (pg. 42-52) and by gaps noted in the critique of evidence (Chapter 1). Research questions presented in Table 2 coincide with each theme representing the investigations on the effects of cryotherapy in relation to two main areas: injury (including rehabilitation) and recovery strategies in sport. The publications presented in this thesis aimed to investigate those four key categories of response identified in Figure 1, to answer the research questions presented in Table 2 (pg. 42-52). Contemplation of the issues highlighted in section 0.3 '*The Researcher Journey'*, established the scope of this research from a practical perspective. This body of work therefore evaluates critically the contemporary approaches of cryotherapy in sport to extend the knowledge around optimal applications of which, *biomechanical*, *biochemical, physiological* and *psychological* responses are considered influential to determining optimal cryotherapy protocols and the resultant effects on performance and function.

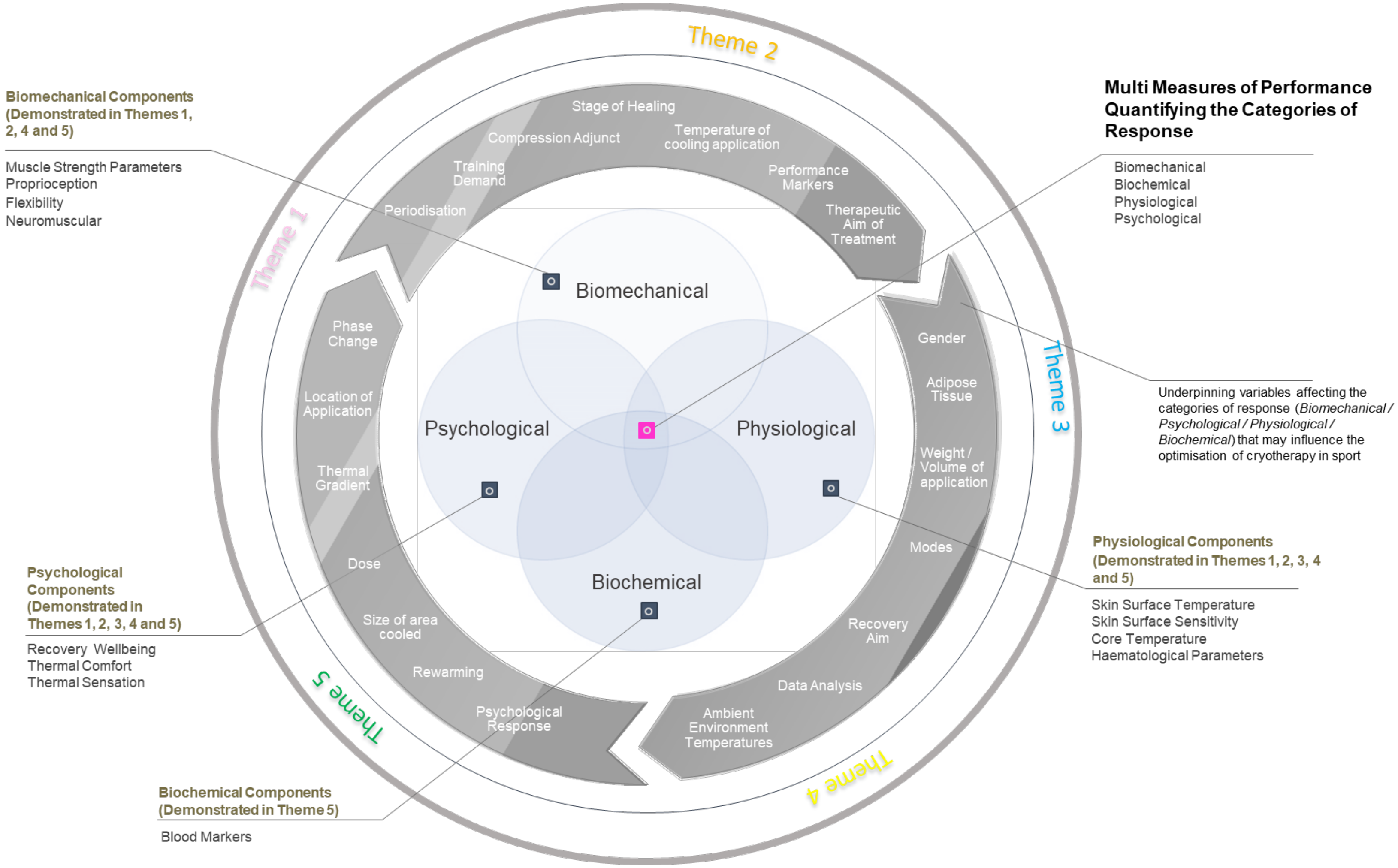


Figure 1. This figure demonstrates four categories of response that cryotherapy is often targeted to affect within a sport context *(biomechanical, biochemical, psychological and physiological).* Circulating the four responses are several influencing variables identified that may affect optimal application of cryotherapy and the outcomes on such parameters. Components identified within each response category relate to subjective and objective considerations that are utilised across the publications presented in this thesis, falling under five themes presented in Table 1 and 2. Themes encompass multiple variables and the categories of response to cryotherapy considered here.

Table 2. Research questions developed from the identification of issues highlighted in *Preface* '*0.3 The Researcher Journey*' and responses of cryotherapy (Figure 1), represented in five themes.

Evidence Gap	Research Questions	Associated Publication Reference and Chapter	Responses of Cryotherapy Considered	Original Contribution to Knowledge and Practical Impact
THEME 1: KINEMATIC RESPONSES TO CRYOTHERAPY (Publications 1 and 2)				
• Limited consensus on the effect of local joint cooling on kinematic response (Costello, *et al,* 2010). • Inconsistent measures of proprioceptive output. • Minimal acknowledgement as to the effect of changes in stability on returning to functional activity (Bleakley *et al,* 2012).	What are the effects of local cryotherapy applications on dynamic stability at the knee? Do changes in kinematic response to cooling affect safe return to functional activity in sport? What are the latent effects of local cryotherapy applications on dynamic stability at the knee over a rewarming period?	**Publication 1:** Alexander, J., *et al* (2016). An exploratory study into the effects of a 20-minute crushed ice application on knee joint position sense during a small knee bend. *Physical Therapy in Sport*, 18(1); 21-26. **Publication 2:** Alexander, J., *et al* (2018). Delayed effects of a 20-min crushed ice application on knee joint position sense assessed by a functional task during a re-warming period. *Gait and Posture,* 62;173-178.	Physiological Biomechanical	**Publication 1 (Alexander *et al*, 2016):** ***Aim:*** To investigate the immediate effects of a 20-minute crushed ice application, applied over the anterior aspect of the knee, on JPS during a functional movement task. Objectives observed knee joint kinematics during a functional weight bearing task through three-dimensional motion analysis (Qualisys Medical AB, Gotham, Sweden) and T_{sk} measures using thermography (Flir Systems, Danderyd, Sweden) in a group of male athletes. ***Novelty:*** First experimental study that assessed knee joint motion in all three planes of movement during a functional weight-bearing task, using 3D motion analysis following a local cryotherapy application to the knee. ***Key Original Finding:*** Increased valgus shift of the knee in the coronal plane during the eccentric phase of a SKB. ***Practical Impact:*** Reductions in eccentric control at the knee with a valgus shift may subject the athlete to risk of injury specifically for the ACL or medial knee complex structures. **Publication 2 (Alexander *et al,* 2018):** ***Aim:*** To investigate the effects of a 20-minute crushed ice application, applied over the anterior aspect of the knee, on T_{sk} and JPS during a functional movement task. Objective measures were quantified immediately post removal of the crushed ice and 20-minutes later. T_{sk} quantified using thermography (Flir Systems, Danderyd, Sweden) and knee joint kinematics (JPS) during a functional weight bearing task (single limb knee bend) through three-dimensional (3D) motion analysis (Qualisys Medical AB,

				Gotham, Sweden) in a group of male athletes after a 20-minute exposure of crushed ice over the knee joint. ***Novelty:*** Assessed knee joint motion in all three planes of movement during a functional weight-bearing task over a rewarming period, using 3D motion analysis following local cryotherapy application to the knee ***Key Original Finding:*** Findings supported that of publication 1 (above) and reported adverse effects in dynamic function at 20-minutes post removal of cooling with increased rotational range in the transverse plane by 25%. ***Practical Impact:*** Reduced eccentric control and increases in rotational range may have potential to increase the risk of non-contact knee injury following local cooling for up to 20 minutes after removal, highlighting the effect on neuromuscular responses within deep knee structures.
THEME 2: MUSCLE STRENGTH RESPONSES TO CRYOTHERAPY (Publications 3 - 5)				
• Inconsistent consensus on the effects of cooling on muscle strength that may affect dynamic stability through direct or distal cryotherapy applications (Bleakley *et al,* 2012). • Unknown as to whether responses to cooling effects isokinetic strength when comparing direct or distal cryotherapy applications.	Does cooling application at the joint distal to the quadriceps (knee) affect concentric isokinetic strength of concentric isokinetic torque production of the quadriceps? Do differences occur in temporal isokinetic strength production patterns following anterior thigh compared to direct knee joint cooling, over a rewarming period? Do differences occur between current	**Publication 3:** Rhodes, D and Alexander, J. (2018). The effect of knee joint cooling on isokinetic torque production of the knee extensors; considerations for application. *International Journal of Sports Physical Therapy,* 13(6); 6-8.	Physiological Biomechanical Psychological	**Publication 3 (Rhodes and Alexander, 2018):** ***Aim:*** To investigate the effects of local cooling over the anterior knee joint on concentric quadriceps strength, over a rewarming period in a group of male athletes. T_{sk} measures were quantified using thermography (Flir Systems, Danderyd, Sweden) and concentric quadriceps muscle strength quantified through an isokinetic dynamometer (IKD) (Cybex, division of Lumx Inc., Ronkonkoma, NY, USA) for peak (PkT) and average torque (AvT). Measures were taken at specific timepoints following previous methods (Alexander *et al,* 2018) being, pre intervention, immediately post intervention, and 20-minutes post intervention. ***Novelty:*** Innovative study which explored the effect of knee joint cooling on adjacent muscle strength immediately and up to 20 minutes post cooling removal. T_{sk} measures were quantified using thermography (Flir Systems, Danderyd, Sweden) and concentric quadriceps muscle strength quantified through an isokinetic dynamometer (IKD) (Cybex, division of Lumx Inc., Ronkonkoma, NY, USA) for peak (PkT) and average torque (AvT).

• Unknown as to whether differences in temporal patterns occur in muscle strength parameters over rewarming periods of muscle strength.	technological cooling devices when investigating the effect on isotonic strength of the knee extensors over re-warming periods?			***Key Original Finding:*** Isokinetic peak torque strength of the quadriceps diminished after knee joint local cooling and strength reductions were noted at 20 minutes post cooling removal, with a 16% reduction in PkT and AvT respectively ***Practical Impact:*** The effects of local knee joint cooling may not be isolated only to the effects on dynamic JPS, associated reductions in strength output in surrounding musculature have implications to overall dynamic stability, consequently heightening injury risk when returning to dynamic functional activity post cryotherapy exposure.
		Publication 4: Alexander J, and Rhodes, D. (2019). Temporal patterns of knee extensor isokinetic torque strength in male and female athletes following comparison of anterior thigh and knee cooling, over a rewarming period. *Journal of Sports Rehabilitation,* 18: 1-7.		**Publication 4 (Alexander and Rhodes, 2019):** ***Aim:*** The investigation of the physiological and biomechanical effects of knee versus anterior thigh cooling, immediately post application and over a rewarming period in male and female athletes were determined. Isokinetic dynamometry quantified concentric quadriceps strength (AvT and PkT) over two testing speeds (60°/s; 150°/s) and infrared thermal imaging to measure T_{sk} were utilised over a rewarming period of up to 30 minutes post intervention in healthy male and female athletes competing in land-based sports. ***Novelty:*** Measure of functional isokinetic effects over joint and muscle structures / separate regions within the same study and inclusion of both male and female athletes. Isokinetic dynamometry quantified concentric quadriceps strength (AvT and PkT) over two testing speeds (60°/s; 150°/s) and infrared thermal imaging to measure T_{sk} were utilised over a rewarming period of up to 30 minutes post cryotherapy intervention. ***Key Original Finding:*** Significant performance deficits in concentric knee extensor strength (PkT and AvT) in both genders regardless of cooling (knee joint / direct muscle) and not returning to baseline measures at 30-minutes. ***Practical Impact:*** Immediate and lasting performance deficits in muscle strength, regardless of cooling location (knee joint vs quadriceps muscle) may expose an athlete to heightened risk of

				injury at the lower limb and considerations for establishing safe parameters to return to dynamic functional activity are required following cooling.
		Publication 5: Alexander, J., *et al,* (2021a). Exploratory evaluation of muscle strength and skin temperature responses to contemporary cryotherapy modalities in sport. *Isokinetics and Exercise Science.* In Press.		**Publication 5 (Alexander *et al,* 2021a):** ***Aim:*** To compare the effect of cooling through the applications of wetted ice, Swellaway® and Game Ready® on muscle strength parameters and T_{sk}. ***Novelty:*** Comparison of three contemporary modalities of cooling, considering targeted vs circumferential applications. First study to explore the effects of the Swellaway device using Peltier technology to achieve local cooling. ***Key Original Finding:*** Acute reductions in strength parameters post cooling. Significant differences occur in the amount of strength loss when comparing between modalities when applied at the knee for the same dosage (15-min) and over rewarming periods. ***Practical Impact:*** Precaution for athletes immediately returning to sport following cryotherapy is required and influenced by the type of cooling modality chosen on muscle strength responses. Alternate targeted treatment modalities to minimise deferred deleterious effects on muscle strength may be considered.
THEME 3: THERMOGRAPHY AND SKIN SURFACE RESPONSES TO CRYOTHERAPY (Publications 6 - 8)				
• No literature that quantifies the effects of local cooling on skin surface sensitivity. • No available published data on dose-response of cooling on the effect on skin	What is the impact of local cryotherapy application on skin surface sensitivity at the knee? What are the visual differences across multiple cryotherapeutic modalities used in sport via the quantification of	**Publication 6:** Alexander, J., *et al,* (2019). Mapping of skin surface sensitivity and skin surface temperature at the knee over a re-warming period, following cryotherapy. *PRM+ Journal of Quantitative Research in Rehabilitative Medicine*. 2(1): 1-5.	Physiological Psychological	**Publication 6 (Alexander *et al,* 2019):** ***Aim:*** To investigate the effects of crushed ice applied over the anterior knee joint on SSS and T_{sk} in male and female athletes. SSS was measured using monofilaments (Aesthesio®, Precise Tactile Sensory Evaluator. DanMic Global, LLC, USA) and infrared thermal imaging (FLIR Systems ThermoVision™ A40M, Sweden) quantified T_{sk} over the patella and tibialis anterior over a 20-minute rewarming period post cryotherapy exposure. Data was collected immediately post and at precisely 5-minute intervals throughout the rewarming period. To define regions over the

surface temperature in rugby union populations looking at positional differences. • No comprehensive catalogue of evidence to visually highlight potential differences in cooling ability of commonly applied cryotherapy modalities in sport.	skin surface temperature in sport? What are skin surface responses to cooling across multiple common cryotherapeutic modalities in sport? Do different physiological responses occur in skin surface temperatures across multiple cryotherapeutic modalities utilised in sport? How does the use of thermology for challenge the preferences and define efficiencies of cryotherapy applications in sport?	**Publication 7:** Alexander, J., *et al,* (2020a). Comparison of cryotherapy modality application over the anterior thigh across rugby union positions: A crossover randomized controlled trial. *International Journal of Sports Physical Therapy.* 15(2): 210-220.		anterior knee and map SSS response, the use of a photographic knee pain map (PKPM) was applied (Elson *et al,* 2011). ***Novelty:*** First study to investigation mapping of skin surface sensitivity (SSS) over the knee following local cooling application of crushed ice utilising a Photographic Knee Pain Map (PKPM) over a 20-minute rewarming period. SSS was measured using monofilaments (Aesthesio®, Precise Tactile Sensory Evaluator. DanMic Global, LLC, USA). ***Key Original Finding:*** Significant reductions in SSS over medial aspects of the anterior knee were reported, and at 20-minutes post removal of the cooling application, SSS did not return to baseline measures. ***Practical Impact:*** Neuromuscular and sensorimotor feedback at the knee joint and should be considered as important mechanisms involved in receptor feedback for accurate JPS, which, when reduced due to local cooling may expose greater risk of non-contact injury in the lower limb. **Publication 7 (Alexander *et al,* 2020a):** ***Aim:*** To investigate the effects of three different cooling modalities (Wetted Ice, Crushed Ice, and Cry Cuff®), applied for 20-minutes, on T_{sk} over the anterior thigh and perceptual responses of thermal comfort and sensation in a population of male semi-professional male rugby union players. Players were grouped by their normal playing position, i.e., forward, or back, consequently presenting with different characteristics (Duthie *et al,* 2003; Cahill *et al,* 2013) and levels of adipose tissue. ***Novelty:*** First study to compare multiple cooling modalities considering positional specific influences in rugby players on the effectiveness on physiological and perceptual measures. ***Key Original Finding:*** Wetted ice produced the greatest decreases in T_{sk} and variability was noted across positional factions (forwards and backs) in terms of skin temperature reductions and perceptual preferences between modalities.

		Publication 8: Alexander, J and Rhodes D (2020). Editorial Commentary - Thermography for defining efficiency of cryotherapy modalities in sport. *Temperature.* 8(2):105-107.		***Practical Impact:*** Results highlight the importance of individualisation of cooling applications in sport, especially those with high variability in physical characteristics that relate directly to levels of adipose tissue, impacting practitioner approach in their choice of cryotherapy modality. **Publication 8 (Alexander and Rhodes 2020):** ***Aim:*** To produce a critical perspective commentary on the use of thermology for defining efficiency of cryotherapy modalities in sport. ***Novelty:*** Contemporary commentary publication critiquing the use of thermology to determine efficiency of cryotherapy modalities in sport reflecting on several articles published in the thesis. ***Key Original Finding:*** Findings support the use of thermal imaging to maximise the understanding and development of cooling protocols in sport through quantification of skin surface temperature. ***Practical Impact:*** Approaches for the use of thermology are dependent on the aim of the research. That said thermal imaging is beneficial in challenging preferences of contemporary cooling applications in sport. Multiple objective measures alongside thermal imaging provide the best approach for sports-related cryotherapy investigations.
THEME 4: CONTEMPORARY CRYOTHERAPY APPLICATIONS AND RESPONSES (Publications 9 - 11)				
• Contradictory literature surrounding current perspectives on modern day use of cryotherapy for acute injury management.	What is the current stance on the application of cryotherapy for acute injury management, taking into consideration the evolving publication of current acronyms such as POLICE / PEACE and LOVE and their	**Publication 9:** Alexander, J., *et al,* (2021b). Cryotherapy in Sport: A Warm Reception for the Translation of Evidence into Applied Practice. *Research in Sports Medicine.* 10: 1-4.	Physiological Psychological	**Publication 9 (Alexander *et al,* 2021b):** ***Aim:*** The aim was to produce a critical review in short communication format on the current approaches and perspectives of cryotherapy use for acute injury management. The objective was to present a topical debate around current knowledge in this area and to present new discussion for future research considerations.

• No understanding as to a consensus on cryo-compressive modality protocols in sport.	implementation in practice, where is the research going next? What are the current perspectives on contemporary cryo-compressive applications in sport for injury and recovery management? Do physiological differences occur in response to varied cryotherapy and compression dosages in sporting populations?			***Novelty:*** Innovative editorial critically evaluating modern approaches in the application of cryotherapy for injury management. ***Key Original Finding:*** Opposing conclusions in relation to the efficacy of cryotherapy on inflammatory response are noted. Several acronyms presented in the literature intended to provide guidance on cryotherapy for acute sport injury management only aid to the confusion in practice. ***Practical Impact:*** The editorial stimulates the approach of new research that suggests rigorous design of contemporary studies that reflect real-world practices to provide clarity and credible evidenced-based literature which influences and impacts modern applied practice of cryotherapy in sport.
		Publication 10: Alexander, J., *et al,* (2021c). Cryotherapy and Compression in Sports Injury Management: A Scoping Review. *International Journal of Therapy and Rehabilitation.* In Press.		**Publication 10 (Alexander *et al,* 2021c):** ***Aim:*** To provide a comprehensive review of the current position in the literature on contemporary cryo-compression applications for musculoskeletal sports injury management. ***Novelty:*** First scoping review to explore current agreement of cryo-compression and its application for sport injury management and rehabilitation. ***Key Original Finding:*** Little empirical evidence is available to provide clear guidance for sports medicine or performance practitioners to apply optimally applications of cryo-compression. ***Practical Impact:*** Findings highlight to applied practitioners the scarcity of agreement for optimal cryo-compressive application. Consequently, this directed subsequent investigations in the thesis which utilise contemporary cryo-compressive devices applied in nature.

		Publication 11: Alexander, J., *et al,* (2020b). Physiological Parameters in Response to Levels of Pressure during Contemporary Cryo-Compressive Applications: Implications for Protocol Development. *Journal of Athletic Enhancement.* 9(1): 1-6.		**Publication 11 (Alexander *et al,* 2020b):** ***Aim:*** To investigate the physiological effects and subjective responses of different cryo-compression dosages offered by two cryo-compressive devices. The objectives were to determine if differences occurred in muscle oxygenation (SmO_2) using MOXY sensors, and T_{sk} through thermography in male and female athletes. ***Novelty:*** Investigation of contemporary cryo-compressive devices and multiple protocols and the effect of compression adjuncts on simultaneous physiological and perceptual measures. ***Key Original Finding:*** Significant differences in muscle oxygenation were reported relevant to level of compression. Greater magnitudes of skin surface temperature reductions were achieved through compression adjunct. ***Practical Impact:*** Dose-response relationships between cryotherapy and compression adjuncts exist and affect magnitude of skin cooling, muscle oxygenation and perceptual preferences. Applied practitioners should consider therapeutic aim of treatment to determine optimal cryo-compressive applications in sport.
THEME 5: MULTIFACETED RESPONSES TO CRYOTHERAPY AS A RECOVERY STRATEGY IN ELITE SPORT (Publications 12 - 15)				
• Inconsistent conclusions as to whether different modes of cryotherapy applied for recovery are beneficial within competitive seasons. • Lack of evaluation around the effects of CWI on functional biomechanical	Are cryo-compressive modalities advantageous to the athlete in terms of recovery of eccentric strength profiles following fatiguing exercise? How do therapeutic cooling devices affect recovery profiles in elite sport populations?	**Publication 12:** Alexander, J., *et al,* (2021d). Recovery Profiles of Eccentric Hamstring Strength in Response to Cooling and Compression. *Journal of Bodywork and Movement Therapies*. In Press.	Physiological Biomechanical Psychological Biochemical	**Publication 12 (Alexander *et al,* 2021d):** ***Aim:*** To investigate the effectiveness of cryo-compression in the form of a pneumatic circumferential device on hamstring eccentric strength following a bout of fatiguing exercise. Objectives were to determine whether the Game Ready® cryo-compression device affected recovery response of hamstring eccentric strength when fatigued in male football players compared to passive recovery in the form of rest for the same period of 15-minutes. ***Novelty:*** Reflecting current practices in sport this investigation examined the effects of a contemporary pneumatic cryo-compressive device as a recovery tool following a bout of fatiguing sport specific protocol, not explored previously.

markers in elite sport populations. • Lack of substantial evidence as to dose-response of contemporary cryotherapeutic modalities in elite populations. • Optimal dose-response unknown for WBC exposures in elite sport.	How does consideration of periodisation around training demand impact application of cold-water immersion exposures compared to passive recovery in elite football? Is there an optimal exposure duration for whole-body cryotherapy and what are the effects on physiological markers in elite sport populations?	**Publication 13:** Alexander, J., *et al,* (2021e). Effects of contemporary cryo-compression on post-training performance in elite academy footballers. *Biol Sport.* 39(1): 11-17.		***Key Original Finding:*** No significant changes in hamstring eccentric strength, quantified using the Nordbord, occurred after exposure to cryo-compression or rest immediately following a sport specific fatiguing protocol was reported. ***Practical Impact:*** Sports Medicine and performance practitioners should consider that skin surface temperature fell outside therapeutic range for physiological changes to be induced through cooling and should be mindful of dose-response. To induce fatigue, protocols should include high velocity; sprinting and high-speed multi-directional protocols to induce higher levels of fatigue to determine effectiveness of recovery strategies. **Publication 13 (Alexander *et al,* 2021e):** ***Aim:*** To investigate the immediate effects of the Game Ready® device on biomechanical and physiological performance in elite academy age footballers compared to passive recovery (PAS). Application of cooling or PAS was performed mid-competitive season following a fatiguing training session. ***Novelty:*** First study available which focusses on the utilisation of the Game Ready® device in youth elite footballers measured through relevant performance markers. ***Key Original Finding:*** Reductions in CMJ performance (jump height) in the group exposed to cryotherapy immediately-post exposure following a fatiguing training session were reported, the same however was not demonstrated in the passive recovery group. ***Practical Impact:*** Reductions in performance may negate the justification of this recovery strategy if neuromuscular responses are required in immediate short term. Cryo-compression as a recovery strategy is dependent on recovery demand and should be adapted individually to optimise readiness to train/play.

		Publication 14: Alexander, J., *et al,* (2021f). Utilisation of performance markers to establish the effectiveness of cold-water immersion as a recovery modality in elite football. *Biol Sport.* 39(1): 19-29.		**Publication 14 (Alexander *et al,* 2021f):** ***Aim:*** To investigate the effects of CWI recovery strategies, following a fatiguing training session within mid-competitive season, through the observation of multiple performance markers in a population of professional, senior elite male footballers. Multiple measures of recovery status through a triad of physiological, psychological and biomechanical performance measures included eccentric hamstring strength (PkT, PkF), isometric adductor strength, hamstring flexibility, T_{sk}, perceptual wellbeing including individual scores for fatigue, sleep, muscle soreness, stress level and mood. Data was collected at multiple timepoints from matchday+3 as baseline, immediately-post training, and immediately-post intervention (CWI / PR) and repeated at matchday+4 for time-course recovery. ***Novelty:*** First study to investigate the effects of CWI compared to PR on readiness to train multi-measures encompassing biomechanical, physiological and psychological, within an elite population of male footballers following a football specific fatiguing training session during mid-competitive season, representing readiness to train / play and individual player response. ***Key Original Finding:*** CWI group reduced further detrimental declines in EHS following a football specific training session, displaying higher strength output compared to PR, up to 24hrs post-intervention. CWI improved perceptual recovery responses. ***Practical Impact:*** CWI may be useful to ameliorate potential deficits in eccentric hamstring strength that optimise readiness to train/play in elite football settings. The use of multi-measures and individual analysis of recovery responses provides sports medicine and performance practitioners with direction on the application of modified approaches to recovery strategies, within mid-competitive season training cycles. Findings have implications on decision-making utilising CWI as a recovery strategy, individualisation of approach and ideal periodisation of this modality compared to PR in an elite football setting.

		Publication 15: Selfe, J., *et al*, (2014). The Effect of Three Different (-135°C) Whole Body Cryotherapy Exposure Durations on Elite Rugby League Players. *PLoS ONE,* 9(1); 1-9.		**Publication 15 (Selfe *et al,* 2014):** ***Aim:*** To investigate whether the length of WBC exposure affected changes in physiological, biochemical and psychological markers of recovery in an elite rugby league population. The study was a crossover-randomised design with WBC exposures taking place mid-competitive season, each randomised exposure followed a league fixture. Objectives were to determine differences in dose-response through the quantification of several recovery markers in a group of elite male rugby league players. Objective markers included $T_{sk,}$ SmO_2, core body temperature, venous blood samples, and perceptual thermal comfort and sensation scores taken as baseline at immediately post WBC exposure. ***Novelty:*** This publication was the first of its kind to compare exposure durations (1, 2, and 3 minutes) of WBC in elite athletes utilising several simultaneous physiological markers. ***Key Original Finding:*** Findings suggests that the optimum safe WBC exposure is 2 minutes at -135°C, with variances in dose affecting physiological responses. ***Practical Impact:*** Sports medicine or performance practitioners working in elite sporting environments whereby WBC is common practice, are advised to follow the optimal WBC protocol of 2 minutes exposure when temperature settings of -135°C are applied.

0.5 Original Contribution to Knowledge

Collectively this body of work has examined contemporary practices and issues regarding cryotherapy and its application for sport injury, rehabilitation, recovery and readiness to perform. Original contribution has been made through the investigation and findings of the optimisation and quantification methods of responses to cryotherapy in sporting contexts, for practice, education and research. Optimising protocols of cryotherapy in sport through the understanding of mechanistic responses and influences of moderating variables were the goals of the work. The impact to help guide practitioners in the field on necessary adaptations to protocols are dependent on several factors found in the results of the studies. The programme of work has generated several interesting findings, notably illustrating the appraisal and critique of current cryotherapeutic practices applied by practitioners working in amateur to high-performance sporting environments. Consequently, with findings supporting the '*one size does not fit all'* approach of cryotherapeutic applications in sport, a table of considerations for practitioners based on the findings of the fifteen publications was designed (Table 10, pg. 227). In addition, an infographic that aims to illustrate the considerations for applied research protocols for cryotherapy was also developed (Figure 23, pg. 231). Both are an original attempt to provide guidance to applied practitioners within the field for enhancing cooling applications advantageous to the athlete or the investigation of such modalities in an applied context. The author has implemented many of the findings from the studies into practice. Furthermore, dissemination of Table 10 (pg. 227) and the infographic (Figure 23, pg. 231) as an opinion piece and its presentation within high-performance environments has commenced to gain feedback from applied practitioners and researchers. Importantly the findings from the studies provide original knowledge reducing the gaps in the current evidence base for the application of cryotherapy for injury, rehabilitation, recovery and performance in sport.

Chapter 1

~ Critical Evaluation of the Literature ~

CHAPTER 1 - CRITICAL EVALUATION OF THE EVIDENCE

1.0 Introduction

The therapeutic application of any modality that removes heat from the body, resulting in decreased tissue temperature defines the term cryotherapy (Knight *et al,* 1995; Nadler *et al,* 2004; Block, 2010). Cryotherapy in its various forms is recognised as a useful commodity based on physiological responses induced via its application, however literature is still contentious with minimal agreement in optimal protocols or evidence for its use. Earlier discussions by Lehmann (1990) suggest how desirable therapeutic effects in sporting or clinical settings, through the application of cryotherapy modalities, is a result of understanding the effectiveness of such applications. A plethora of studies that examine cryotherapy use for musculoskeletal sports injury (Hubbard *et al,* 2004; Bleakley *et al,* 2006; Herrera *et al,* 2010; Hawkins and Hawkins, 2016; Galiuto, 2016) or as a recovery strategy are available (Crowther *et al,* 2017; Allan and Mawhinney, 2017; Broatch *et al,* 2018; Cross *et al,* 2019; Ihsan *et al,* 2020; Peake 2020). Yet, evidence fails to provide a definitive conclusion on the efficacy of cryotherapy modalities to potentially optimise their applications in sport (Galiuto, 2016; Kalli and Fousekis, 2019), due to several factors simply not yet understood in normative or uninjured populations.

Well-established in both clinical and sporting practice, cryotherapy is usually an early consideration in the management of acute sports injury (Bleakley *et al,* 2012), with the goal to reduce inflammation, pain and return the athlete to sport (Smith, 2005; Topp *et al,* 2013). Hawkins and Hawkins (2016) questioned from this perspective the types of cryotherapy modalities applied in practice by Sports Physical Therapists (SPT), reporting wide variability not always in accordance with the available evidence base. Evidence for the use of cryotherapy as a recovery strategy in sport is as buoyant, yet conflicting. Perhaps due to large variations in study design, limited applied research, and lack of randomised trials that reflect applied practices, an inability to draw a consensus from the evidence base still exists. Based on current scientific evidence across numerous aspects of cryotherapy application in a sporting context, several gaps in the literature exist that reflect optimal cryotherapy protocols and modality choices. A consensus deficiency, due to varying application suggestions appear consistently emphasised throughout the literature (Hubbard and Denegar, 2004; Bleakley *et al,* 2004;

Hawkins and Hawkins, 2016) despite cryotherapy being a frequently used intervention for musculoskeletal sports injury (Järvinen *et al,* 2005; Sarver *et al,* 2017) and recovery strategies (Kalli and Fousekis, 2019). This includes the complexities of variables outlined in Figure 1 (pg. 41) that may influence the efficacy and consequently the decision-making of applied practitioners working in sport (Peiffer *et al,* 2009; Janwantanakul, 2009; Yanagisawa and Fukubayashi, 2010; Crystal *et al,* 2013; White and Wells, 2013; Galiuto 2016; Haq *et al,* 2018).

The following chapter critiques the current literature pertaining to cryotherapy applications and responses for sports injury and recovery strategies to provide context and justification for the fifteen publications presented in this thesis. Acknowledgement of thermodynamics, physics and thermoregulatory mechanisms underpinning human responses to cooling are examined initially due to their influence on efficacy of cryotherapy modalities utilised in sport. The evidence base for current applications of cryotherapy in sport follows with a focus on several of the variables highlighted in Figure 1 (pg. 41), thought to influence applied practices and underpin the five themes of the thesis (Table 1, pg. 26-28). Decision making processes within sports medicine or performance departments are often made by considering information collated to determine the *physiological*, *biomechanical*, *biochemical*, and *psychological* responses. The current thesis aims to align academia to practice, consequently the structure of this chapter is presented to reflect the five themes providing clarity on how cryotherapy may affect the four categories of response and applied practices simultaneously. The effects of cryotherapy on multiple performance measures and quantification techniques are explored. With the intention to guide methodological strategies in which to investigate the effect of cryotherapy over multiple categories of responses that affecting optimal cryotherapy protocols in sport (Figure 1, pg. 41), an understanding around the influence cryotherapy has on the immediate, delayed and time-course recovery response for performance are also presented. Lastly, clarity regarding the application of contemporary cryotherapy applications for recovery in elite sports performance environments are critiqued.

CRITICAL EVALUATION OF THE EVIDENCE

1.1 THE APPLICATION OF CRYOTHERAPY

1.1.0 Thermodynamics of Cooling (Physics)

Molecular kinetic energy relates directly to thermal energy, accordingly a rise in temperature increases molecular kinetic energy (Çengel and Boles, 2015). This is manifested by an increase in vibration and motion linearly. In short, less linear molecular motion and vibration occurs as temperature decreases (Cameron, 1999). When two substances become in physical contact with each other reaching and maintaining the same constant temperature with no heat flow between them, this is known as thermal equilibrium (Sieron *et al,* 2010; Çengel and Boles, 2015). When thermal energy is exchanged between two systems at differing temperatures this is recognised as heat transfer and as heat transfer is always unidirectional, warmer tissues lose heat to colder structures (Çengel and Boles, 2015). Unidirectional heat transfer therefore always occurs, from high to low (Lide, 1994 p. 5.1-5.17), and summarised as regions that contain higher (hot) kinetic energy sequentially transfer this energy to regions with lower (cold) kinetic energy. Applicable to human cooling, five methods of heat transfer exist: convection (Kelman, 1980), conduction, evaporation, radiation, and conversion (Cameron, 1999). In context, deeper tissues therefore are reduced in temperature by heat lost to the superficial tissues. An understanding of thermodynamics is significant when considering the properties and efficiency of cryotherapeutic modalities. The translation of thermodynamic principles practically to develop advantageous applications of cooling in sport settings is the focus of many studies and discussed later in the chapter; with interests around modalities that undergo phase change to optimise the effects of cryotherapy (Merrick *et al,* 2003; Dykstra *et al,* 2009; Kwiecien *et al,* 2020).

The physical process of spontaneous heat transfer is important to consider in the choice of cryotherapy modalities available. Hence, cryotherapy modalities do not transfer cold, they work by absorbing heat from the immediate environment, such as the skin (Kennet *et al,* 2007) from deeper tissues through conduction to the skin surface (Enwemeka *et al,* 2002; Merrick *et al,* 2003). Due to cold tissues having low kinetic energy and therefore because cold is not transferable, heat from the warmer deeper tissues is lost to the cold modality when in direct contact via the skin (Merrick *et al,* 2003).

Multiple variables are known to interact and subsequently determine how much cooling takes place by way of human physiological responses (section 1.1.1) through cryotherapy exposures, these include specific heat capacity of the modality; latent heat of fusion; contact area and thermal gradient (Merrick *et al,* 1993; 2003). Knowledge surrounding the physics of cooling is important to support the practical reasoning of cryotherapy applications in concepts such as dose-response, location and choice of application, alluded to in recent literature (Glasgow *et al,* 2014; Alexander and Rhodes, 2019). The magnitude of soft tissue temperature change caused by physiological responses to cryotherapy is subject to the interaction of four factors according to Von Nieda and Michlovitz (1996). These include consideration of Fourier's Law (1807), length of cooling exposure (dose), heat capacity of the cooled area relating to thermal conductivity and the thermodynamic properties of the cooling modality (Von Nieda and Michlovitz, 1996). It is important consequently, to note that the effectiveness of cryotherapy modalities is reliant on the capability to absorb heat, *'heat capacity'* (C_p) and this can vary dependent on the effectiveness of a term known as *'phase change*' (Knight and Draper, 2008). The thermodynamic principle of thermal conduction is the transfer of heat from hot to cold areas (Lide, 1994; Merrick *et al,* 2003). The transfer of heat through thermal conduction encompasses the understanding of the relationship between conduction rate of material and temperature gradient in consideration of energy flow direction formulated by Fourier originally in 1822. Therefore, it is thought that cooling effects differ between cryotherapy modalities used in sport due to their variance in thermodynamic properties (Merrick *et al*, 2003; Kennet *et al,* 2007; Alexander *et al,* 2019). Practically this has key influences over application in the field. The consideration of phase change as introduced earlier is imperative to the development of optimal cooling protocols for sports injury and recovery strategies that employ cryotherapeutic modalities. Phase change is described as a change from one state (solid or liquid or gas) to another without a change in chemical composition (Çengel and Boles, 2015). Merrick *et al,* (2003) expresses this in terms of the ability of cryotherapy modalities to undergo phase change correlating to the magnitudes of tissue temperature reductions following application. Literature by

Kennet *et al,* (2007) advocates that energy required for phase change is not a consideration in Fourier's Law. When investigating cooling efficiency of four commonly used cryotherapeutic agents at the ankle joint the authors also disagree that agents with lower pre-application temperatures provide opportunity for better heat energy transfer, resulting in lower T_{sk} (Kennet *et al,* 2007). The ability of modalities to go through efficient phase change therefore is more important than a modalities pre-application temperature to optimise cooling efficacy. The term phase change also known as *'phase transition'* can be presented as the transitions of single components (that being solid, liquid and gas) shifting because of temperature or pressure. Table 3 demonstrates examples of phase change transitions relevant for understanding the concepts of thermodynamics in respect to cryotherapy modalities often used in sport and applied superficially to the skin.

Table 3. Example of phase change / phase transitions for solids, liquid and gas components.

	To			
From		Solid	Liquid	Gas
	Solid		Melting	Sublimation
	Liquid	Freezing		Vaporization
	Gas	Deposition	Condensation	

Important to note is the enthalpy of fusion (**ΔH_{fus}**) which relates to the properties of material (Lide, 1994). **ΔH_{fus}** is the required amount of heat needed for phase change in the material to occur, i.e., from a solid to a liquid (Merrick *et al,* 2003). Both heat capacity and enthalpy of fusion affect the ability of cold modalities to absorb heat (Merrick *et al,* 2003). Several studies might underestimate this relationship when considering thermodynamic properties of cryotherapy modalities, subsequently affecting their hypotheses in predicting cooling function and applicability in a practical setting. Although Fourier's Law (1807) considers that modalities with lower pre-application temperatures may be able to offer better opportunities for heat energy transfer this is unsupported by the concepts of thermodynamics and research on cryotherapeutic modalities commonly applied in sport (Kennet *et al,* 2007). It is understood that regardless of the starting temperature of a modality it is the efficiency of phase change ability in the material that ensures optimal capability of absorbing heat. Therefore, some agreement that colder is not always better is evident (Chesterton *et al,* 2002; Kennet *et al,* 2007; Hardaker *et al,* 2007). In relation to the thermodynamic properties of ice, it is known that the physical state of melting occurs and by understanding this, it is assumed that ice-based cryotherapy modalities in comparison to gel-based modalities can therefore absorb more heat. This is of note in a practical setting where optimal cooling treatments for injury, rehabilitation or recovery are imperative for an athlete to return to functional activity.

Another notion affecting the efficacy of cryotherapy modalities in relation to phase change is *'specific heat'*. The greater the amount of specific heat a substance has the more heat energy can be withdrawn (Knight and Draper, 2008). Latent heat of fusion combines the understanding of specific heat with the process of phase change. To convert a substance from a solid to a liquid state (to undergo phase change), latent heat of fusion represents the amount of energy required to do so (Knight and Draper, 2008). In terms of ice through local application in practice, a significant amount of energy is required therefore to convert this from a solid to a liquid, hence more extraction of heat from soft tissues is desirable. This being one advantage of ice for cooling. In contrast this mode of cooling cannot sustain a cooling capacity for prolonged periods (Kwiecien *et al,* 2020) which is important in a post-exercise scenario for recovery strategies in terms of athlete preparation for readiness to train / play. Breslin *et al,* (2015) results clearly demonstrate this, suggesting that an ice bag compared to gel-pack had a significantly greater cooling rate and thus more effective at reducing $T_{sk.}$ Previously Merrick *et al,* (2003) reported this and suggested that modalities with greater ability to absorb heat will therefore produce cooler temperatures in the tissues where the cooling modality is applied. That said, local application of ice for recovery purposes is poorly attributed to effective structural damage repair following exercise (Kwiecien *et al,* 2020). The magnitude and rate of temperature changes in soft tissue through cryotherapy applications however change depending on several factors identified across literature which include, rate of conduction, tissue type and depth (Knight and Draper, 2008). In terms of recovery, guidelines around application, frequency, duration and temperature of traditional methods of cooling in sport are still limited because of methodological differences in studies, controversy around efficiency and practicality of modalities (Kwiecien *et al,* 2020). Aside from positive subjective responses a significant gap in understanding optimal cooling protocols for recovery is evident in terms of physiological responses. Studies often present atypical applications of cooling to those considered common practice in real-world sport environments (Ihsan *et al,* 2020). Human response to cooling modalities, such as the relationships between T_{sk} reductions and other musculoskeletal structures will be discussed further in section 1.1.1.

Mode of cooling represents the different available types of cryotherapeutic modalities. Examples commonly applied in sports injury or as a recovery strategy are summarised in Table 4. Earlier literature suggests that modes of cooling differ significantly in the ability of phase change and magnitude of skin temperature reductions as a result (Belitsky *et al,* 1987; Chesterton *et al,* 2002; Janwantanakul, 2004; 2009; Kanlayanaphotporn and Janwantanakul, 2005; Leite and Ribeiro, 2010). Further, Hamid *et al,* (2013) reports that ambient temperature and relative humidity can affect efficacy of cryotherapeutic agents and found cubed-ice better than wetted-ice on cutaneous temperature reductions in a Malaysian climate. In addition, suggestions that chemical gel packs are unsafe when applied directly to the skin without a barrier have demonstrated the potential for causing frostbite (Starkey, 2013). Furthermore, Costello and colleagues (2010) suggestion that different cooling techniques influence magnitude of joint cooling signify that the choice of cooling modality is critical in governing the effects it has on joint position sense (JPS), for example. Yet, methods of cooling applications that include a compression adjunct often do not consider the effects of such in the literature. Studies reporting comparison of multiple cold therapy modalities are numerous (Myrer *et al,* 1998; Merrick *et al,* 2003; Kennet *et al,* 2007; Kanlayanaphotporn and Janwantanakul 2005; Janwantanakul 2009; Herrera *et al*, 2010; Vieira *et al,* 2013), however the plethora of cryotherapeutic modes available along with consideration of other variables presented in Table 3 (pg. 59), make methodological decisions difficult when designing current studies in this remit. An efficient cryotherapy mode is suggested to reduce and maintain temperature reductions over a period but cool the superficial area quickly without inducing tissue damage (Breslin *et al,* 2015). An optimum modality and protocol based on this assumption not yet established thoroughly in the evidence base, limits the identification of optimal cooling protocol development within sport environments. Consequently, this adds to the limited translation of evidence into applied practice due to the inability to reach agreement due to conflicting methodologies and modalities investigated that replicate contemporary cryotherapy applications in sport. Evidently obtaining a thorough consensus of cryotherapeutic protocols when considering multiple variables is difficult however research that considers multi-variables to determine individual responses may be beneficial.

Many studies that explore between common modes of cryotherapy investigate specifically the effectiveness of cooling on T_{sk} in healthy populations and commonly apply a 15 (Khanmohammadi *et al,* 2011; Fullam *et al,* 2015) or 20-minute dose (Merrick *et al,* 2003; Kanlayanaphotporn and Janwantanakul 2005; Kennet *et al,* 2007; Hawkins *et al,* 2012). The consensus as to which mode of cooling is 'best' for local applications for injury management tends to demonstrate agreement for crushed or wetted ice (Kennet *et al,* 2007; Dykstra *et al,* 2009), determined by their ability to reduce T_{sk} to within optimum therapeutic ranges for physiological effects to ensue. Although these findings are useful, there is an apparent gap in applied evidence that considers multiple variables and multifaceted responses to cryotherapy in the same study design or the investigation of contemporary modalities. This is important to understand as variables are unlikely to be affected in isolation and modalities with different phase change ability may be influential to the development of optimal protocols. In the inquiry to determine optimal protocols for sports injury or recovery strategies, the development of methodological approaches that investigate multiple variables across several modalities require suitable objective measures to do so. Consequently, this emphasis underpins many of the publications in this thesis.

Table 4. Modes of cryotherapy commonly applied in sport.

Modes of Cryotherapy				
Whole-Body Cryotherapy	Ice (wetted, cubed, crushed)	Peas	Cold-Water Immersion	Peltier Cell Cooling Technology
Partial Body Cryotherapy	Pneumatic Cryo-compression Devices	Cooling Sprays	Gel Pack	Ice / Cooling Vest

Modality choice which influences decision-making highlighted earlier by Hawkins and Hawkins (2016) indicates the variability in cryotherapy treatment approaches for sports injury management by Sports Physical Therapists (SPT). With insufficient literature supplying the body of EBP, this leads to confusion in what may be the best modality and / or protocol to apply. To induce beneficial physiological effects a reduction in T_{sk} of at least 5–15°C is outlined in traditional PRICE guidelines (ACPSM) (Bleakley *et al,* 2011), with T_{sk} below 12°C required to induce analgesia (Bleakley and Hopkins, 2010). Adverse effects are however reported following local cryotherapy applications, notably resulting in nerve (Moella *et al,* 1997) or skin burn/damage (Keskin *et al,* 2005; Selfe *et al,* 2007), although determining risk factors is difficult as older evidence of adverse reactions are based on case studies (Bleakley *et al,* 2011). Typically, adverse reactions were evident from prolonged or continuous applications of cold or compression, cold allergy or location of cooling over superficial nerves for example (Keskin *et al,* 2005; Moella *et al,* 1997). For a cold modality to be effective and safe, a rapid reduction in T_{sk} and the ability to maintain these reduced temperatures over a pertinent period, without causing damage to tissue is essential (Breslin *et al,* 2015). Evidently there are multifactorial variables to consider when aiming to decipher what may be the optimum cryotherapy application for sports injury or recovery, with human responses to cooling being at the forefront of investigations.

1.1.1 Thermodynamics of Cooling (Human Response)

Human thermoregulation relies on homeostatic mechanisms for the protection against overheating (Sawka and Wegner, 1988) with lower capacity of adaptation to cold exposure compared to heat exposure for prolonged periods (Young, 1988). Human body temperature regulation takes place following a hierarchical order, according to Fu (2016) that being; thermal reception by temperature sensitive neurons; the integration of thermal data through neural pathways, followed by thermoregulatory response through separate branches of the nervous system. Thermal receptors located in the skin monitor temperature of the external environment, and those receptors that monitor internal core temperature are found in the hypothalamus (Kelman, 1980; Campbell, 2008). Appropriate thermoregulatory responses are delivered via the hypothalamus where processing and integration of thermal sensory data occurs (Green, 1981; Campbell, 2008). Through shivering and an increase in metabolism as body temperature decreases, the posterior hypothalamus stimulates heat production (Green, 1981). Alternatively, heat loss is controlled via the anterior hypothalamus, through vasodilation in skin and through sweating as body temperature increases (Green, 1981).

Thermoregulatory responses are determined by the temperature of the hypothalamus regulated via peripheral and central receptors inputs (Campbell, 2008) (Figure 2, pg. 65). Temperature receptors situated centrally and peripherally direct outputs from core structures, including hypothalamus, abdominal viscera, great veins and spinal cord and outer shell (skin) of the body (Campbell, 2008). A sensory modality of the skin, cutaneous thermosensation mediated by afferent nerve fibres transmit thermal information (Lumpkin *et al,* 2007). Cold and heat receptors present in skin transmit responses to the hypothalamus via the spinal cord and selectively respond to either warm or cold temperatures. Both cutaneous cold and warm receptors exhibit a steady-state discharge and slow conducting, with dynamic responses to changes in temperature (Hensal, 1981). Output from sensory hot and cold response is via the sympathetic nervous system, through motor nerves are reflected in the changes in subcutaneous tissue, sweat glands and blood vessels situated in the skin (Kurz, 2008). Thermosensitive mechanoreceptors and nociceptors that respond to noxious low and high temperatures (<20°C and >45°C) can be distinguished from those cold-specific and warm-specific receptors (Hensel, 1981).

Local cooling via the application of cryotherapeutic modalities therefore stimulates thermoregulatory responses via cold-specific afferent mechanisms (Krause, 2003). T_{sk} can fluctuate widely, unlike core temperature, and human skin temperature is comparatively lower than core temperature (Green, 1981; Campbell, 2008). A decrease in T_{sk} gradients in humans is noted generally from the central trunk to distal peripheral limbs (Green, 1981). At the knee however, the patella acts as a heat shield therefore an exception to this occurs, whereby T_{sk} at the patella remains cooler than the distal lower limb (Ammer, 2012). Evidently this has implications on practical cryotherapy applications for optimal intra-articular cooling of deeper joint structures at the knee. Knowledge of such responses may help to decipher and develop protocols of cooling applicable to sport. These thermoregulatory mechanisms also underpin the rationale for further studies in this area that acknowledge skin surface, core, and intra-muscular temperature responses, of which conflicting evidence as to the effect of cooling still exists.

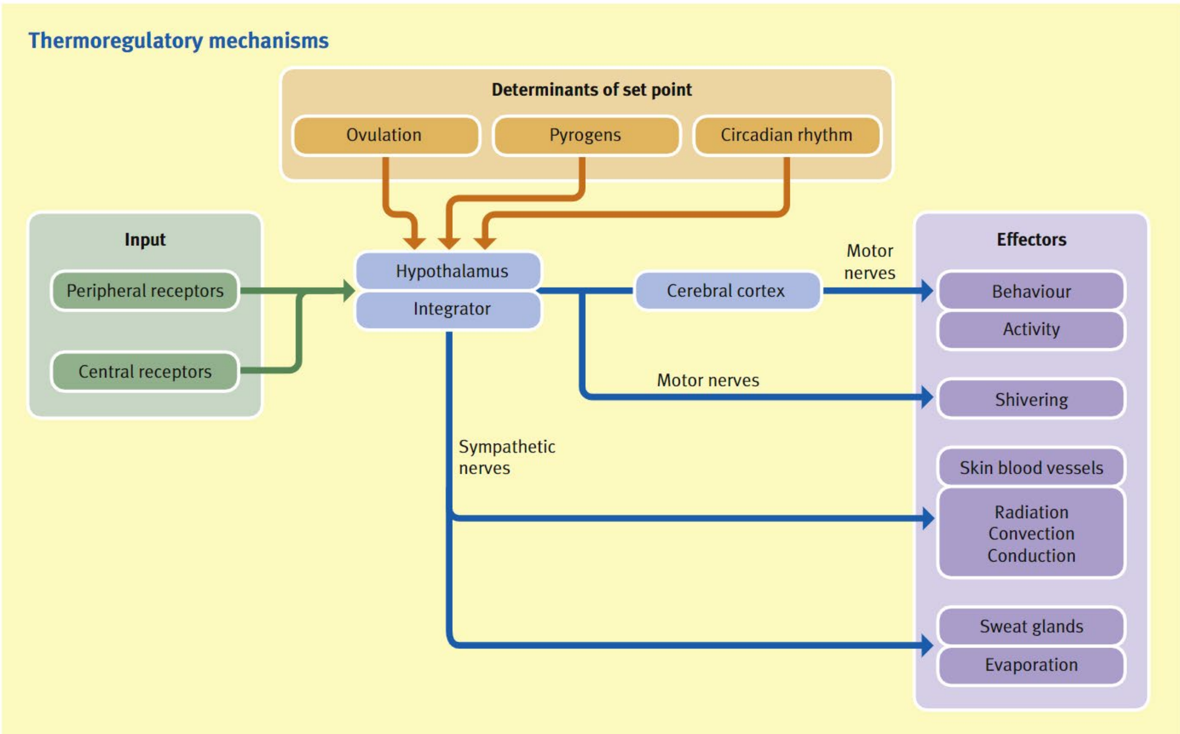


Figure 2. Thermoregulatory Mechanisms (Campbell, 2008).

As many physiological changes are temperature-dependent but integral to the therapeutic benefits of local cryotherapy (White and Wells, 2013), the cooling ability of many cryotherapeutic modalities are therefore important to decipher. Assumptions that greater and faster cooling result in better outcomes in minimising effects of acute trauma, highlighted by Merrick *et al.* (2002) ultimately provide rationale for the investigation of cooling magnitudes across various cryotherapy modalities. The study considered several concepts of thermodynamics and concluded that differences in intramuscular temperatures (T_{im}) occurred in relation to the thermodynamic properties of modalities (Merrick *et al,* 2003). The authors proposed that those modalities which do not undergo enough phase change fail to reduce skin surface tissue temperatures enough to initiate sub-adipose tissue temperature reductions (Merrick *et al,* 2003). Alternatively, Vieira *et al,* (2013) suggested that cold modalities with different thermodynamic properties have similar effects on the activation and performance of muscles when comparing icepacks and cold-water immersion (CWI). Evidently this leads to confusion as to the most effective modality to meet therapeutic aims of treatment or recovery strategies in sport.

Another consideration to appreciate is the influence of adipose tissue levels on human response to cooling. To produce similar intramuscular temperatures through cooling, adaptation to the duration of cryotherapy protocol is recommended based on level of adipose thickness (Otte *et al,* 2002). Otte and colleagues (2002) suggest a 25-minute treatment is adequate for skinfold measurements of ≤20mm, but by contrast a 40-minute application is required to produce similar results for skinfolds between 21-30 mm. Furthermore, skinfolds of 30-40 mm require a 60-minute cooling duration. This study however did not take into consideration the phase change ability of the modality tested or compared the modality to other common cryotherapeutic applications. Nor did the population group represent an athletic population through which positional factions common in team sports may influence levels of adipose tissue and subsequently cryotherapeutic dose requirements (Alexander *et al,* 2020b). The ability to achieve target intramuscular temperature therefore may differ when compared to other modalities considering the same classification of adipose tissue levels. Optimising cryotherapeutic protocols with these aspects in mind is addressed in the thesis through several studies where comparison of the thermodynamic properties behind modalities owes to the findings. By considering phase change capabilities of contemporary modalities provides some clarity in the pursuit to aid decision-making for optimising cryotherapy applications in practical settings.

Deeper tissues and structures reduce in temperature following cryotherapy applications via conduction as heat is extracted to the superficial dermal layers initially cooled by the modality (Enwemeka *et al,* 2002; Breslin *et al,* 2015). In the absence of hemarthrosis, Martin *et al.* (2002) reports how cryotherapy decreases intra-articular temperature. A high correlation between T_{sk} and intra-articular temperature (T_{ia}) was recently reported by Breslin *et al.* (2015), however evidence prior to this failed to report any strong correlations between that of T_{ia} and T_{sk} following cold applications (Martin *et al,* 2002; Warren *et al,* 2004). Differences nonetheless between cryotherapeutic modalities and their ability to cool T_{sk}, intra-articular spaces or intra-muscular tissues effectively are acknowledged (Warren *et al,* 2004). Early literature is suggestive that conductivity of cooling is more efficient and quicker through either water immersion or when wet material is placed between a cryotherapeutic modality and the skin (Lavelle and Snyder, 1985). With the efficacy of conduction underpinning possible mechanisms behind efficient intra-articular cooling for example, heat transference is another consideration mentioned in research. Recent studies agree with Lavelle and Snyder (1985), and methodologies subsequently have investigated a plethora of material barriers such as wet towel, bandages, Kinesio® Tape, and adhesive dressings to determine which is most favourable in the efficiency of cooling applications in medicine (Ibrahim *et al,* 2005; Okcu and Yercan, 2006; Liete and Ribeiro, 2010). Janwantanakul (2004) reported contradictory results suggesting that the application of an ice bag directly to the skin was more effective than an ice bag placed over a damp towel barrier, achieving a greater effect of cooling on physiological response. Most recently, the combination of cryotherapy with a Kinesio® Tape application is supported with no adjustments to cryotherapy duration required (Lyman *et al,* 2018). Although these findings fail to compare this to the efficiency of placing a wetted towel interface as recommended by Janwantanakul (2004) to enhance cryotherapy applications particularly that of wetted or crushed ice. Alternatively, Ibrahim *et al.* (2005) suggest material such as wool and crepe dressings following knee surgery prevent effective cryotherapy, compared to thinner adhesive dressings. Table 5 (pg. 72) provides an overview of variables that are considered to influence the optimal design of cooling protocols for musculoskeletal injury management or recovery strategies in sport, yet within the considerations of application and material, there are several methods utilised across different cryotherapy modalities. Consequently, this influences the effectiveness or optimisation of response, whether this is for acute injury management or accelerating recovery following exercise, and despite this many applications and material differences between modalities are left unexplored in the scientific evidence base despite their anecdotal use and preference in sport. Consequently, this gap in knowledge underpins several approaches of the publications in this body of work where different application protocols and cooling modalities of different materials utilised in practice are investigated in this thesis.

Continuing the evaluation of phase change, Clifford *et al,* (2018) examined the capability of innovative lower limb garments with temperature-controlled phase change material (PCM) as an advantageous method of recovery for elite footballers following muscle-damaging exercise. Previously Kwiecien *et al,* (2017) reported the benefits of such a modality, aiding recovery when worn by untrained athletes with a PCM targeted temperature of 15°C. Recovery in terms of muscle soreness (MS) and maximal isometric voluntary contraction (MIVC) of the quadriceps were enhanced following application of the garment and positive changes were reported at 36- and 60-hours post-match (Clifford *et al,* 2018). In the consideration of the thermodynamics evidently the efficacy of phase change in this modality may provide lasting influences on psychological and biomechanical responses of cryotherapy. Although it may be argued that MIVC is not the optimal measure of performance from fatiguing exercise. Considerations of this are discussed further in THEME 5 (section 1.7).

The efficiency of cryotherapy modalities places an important factor on the decision-making around optimal cryotherapy applications. Although research has acknowledged this through several studies noting the impact of phase-change for example, the translation of this knowledge into practice appears somewhat behind. Ultimately this highlights again the fragmentary ravine which undeniably separates academic cryotherapy research from the demands of practically applied evidence to develop and optimise cryotherapy application for athletes. This may be pertinent in the elite sport setting where the refinement of current recovery protocols through cooling may be impactful on performance and measurable outcomes, yet the evidence is not currently reflective of this. Through well designed research, which considers the end-user, the effects of physical barriers on the efficiency of conduction of cold and response in consideration of thermodynamic principles would be further understood. Future comparison of contemporary cryotherapy modalities and quantification of the impact of variables as presented in Table 5 (pg. 71) would benefit the understanding around human response to cooling and help determine optimal protocols for sports injury or recovery management.

1.1.2 Cryotherapy Application Guidelines for Sports Injury

Protocols for the application of cooling for sports injury management have traditionally followed the original Ice, Compression and Elevation (ICE), and Rest, Ice, Compression and Elevation (RICE) guidelines (Bleakley *et al,* 2012), evolving to; Protection, Rest, Ice, Compression and Elevation (PRICE) (ACPSM, Bleakley *et al,* 2011), despite an influx of research interest since 2011 investigating elements of the 'PRICE' acronym, utilised within treatment paradigms (Bleakley *et al,* 2012). These guidelines reviewed the pathophysiological rationale and clinical effectiveness for PRICE components and provided clinical relevance for each part of the acronym. A recent development of the acronym 'POLICE' represents the concept and importance of optimal loading in respect of mechanotransduction through appropriate mechanotherapy techniques, which complements and updates the original PRICE guidelines (Bleakley *et al,* 2012). The abbreviation of POLICE, corresponding to Protection, Optimal Loading, Ice, Compression and Elevation demonstrates an updated view on rehabilitation protocols: in addition, it emphasises a lack of comprehension surrounding optimal cryotherapy protocols to support management of musculoskeletal sports injury. The authors stress the intention to generate new areas of research from the proposal of POLICE (Bleakley *et al,* 2012). Specifically, the notion of identifying not only the role of 'ice' and other cooling modalities through rigorous enquiry but leading to determining the most optimum cryotherapy application protocols too. This underpins many of the publications in this thesis, as these are the key guidelines followed in practice by sports medicine practitioners.

Recently Dubois and Esculier (2019) presented the acronym of, 'PEACE' and 'LOVE' encompassing management of both acute and subacute to chronic stages of healing of soft tissue injury, with their underpinning message to avoid cryotherapy in the acute stage. Their argument to avoid cooling despite its widespread application in sport is based on the disruption of the inflammation process of angiogenesis and revascularisation thought to be caused by cryotherapy, ultimately leading to a negative effect on repair of tissue and redundant synthesis of collagen (Singh *et al,* 2017). Publication 9 in the thesis presents a debate around this topic, and in consideration that the application of cryotherapy on-pitch and pitch side for acute injury is still heavily evident in current practice, often the return of an athlete to the field of play post cooling application is seen. Arguably applications in these scenarios are acute, suggestive that the effect is related to overriding pain sensation through touch and sensation, yet limited studies investigated the responses that may be affected in such applications to quantify safe parameters for this practice. In contrast to the recent opinions of Dubois and Esculier (2019), a substantial body of evidence supports the application of cooling during these healing phases of injury, with recent discussions by Long and Jutte (2020) refuting this argument. These challenges to current guidelines only strengthen the rationale for the publications in this body of work. Applications of cryotherapy should be implemented as optimally as possible in each scenario to provide advantageous benefits for the athlete whether it be for sports injury treatment, rehabilitation or as a recovery strategy. There are many influencing variables however which affect the efficiency of cryotherapeutic protocols in sport in these circumstances, critiqued in the following section (1.1.3).

1.1.3 Variables Influencing Cryotherapy Applications

As practitioners in sport, it is important to consider the four categories of response (*biomechanical*, *biochemical, psychological* and *physiological)* presented in Figure 1 (pg. 41), as the quantification of these often determine readiness to train / play or return to play of an athlete. It is proposed therefore, based on the current literature, that underpinning those categories are several variables thought to influence the development of 'optimal cryotherapy protocols' that may be advantageous to athletes in a sporting context for injury or recovery. Introduced in Figure 1 (pg. 41) table 5 illustrates further external factors to consider in protocol development. Through examination of these variables and their influence on the efficiency of cryotherapeutic applications for injury or recovery we may be able to determine optimally, when how and why to use such intervention. Consequently, these categories of response are acknowledged and overlap across the five themes of the thesis structure.

Table 5. Variables that influence the optimal design of cooling protocols for musculoskeletal injury management or recovery strategies in sport.

Influencing Variables on Cryotherapy Efficiency	
• Compression Adjunct and Protocol • Dose • Initial Temperature of Modality • Thermal Gradient • Phase Change Ability of Modality • Time of Application • Therapeutic Aim • Ambient Environment Temperatures • Pre-Cooling Temperatures • Recovery Aim • Mode • Tissue Healing Phase • Psychophysiological Influences • Material	• Adipose Tissue Levels • Gender • Psychological Response • Location of Application • Size of surface area cooled • Weight / Volume of Application • Experimental Methodology • Training Demands • Pre-cooling Temperature (human structures) • Analysis of Response • Rewarming Response • Application Technique • Periodisation of Application • Repeat Exposures
External Factors Influencing Optimal Cryotherapy Application	
• Fixture Congestion • Training Demand • Individual Athlete Preferences • Practitioner Beliefs, Knowledge and Experience	• Schedules Changes • Access to Equipment • Budgetary Allocations • Club Ethos / Philosophy

Many of the variables presented in Figure 1 (pg. 41) and Table 5 (pg. 72) are discussed in terms of the thermodynamics of cooling (Section 1.1.0) such as mode of cooling. Other variables that can be manipulated by the practitioner through application rely on the evidence base to support decision making around the best protocol to apply; these include, dose (refer to THEME 5 for WBC dose-response: Section 1.7), location (refer to THEME 3: Section 1.5), size of surface area cooled, weight/volume of application, periodisation (refer to THEME 5: Section 1.7) and compression adjunct (refer to THEME 4: Section 1.6). Several of these variables are considered in individual studies throughout the body of work and many were chosen because of the ability to quantify their influence on the response to the cooling application in consideration of the four categories of response (*biomechanical, biochemical, physiological, psychological*) (Figure 1, pg. 41) or that most optimally answered the specific research question and may provide the greatest impact to practical applications in the field. Others were chosen through the applied approach of the study design, reflecting protocols and multi measures of performance through familiar practices within the applied setting from which the study was captured. Consequently, this approach reflected the pragmatic and applied desire of the research through the thesis.

The term dose or dosage is representative of a measured quantity or frequency of any therapeutic agent. Despite PRICE guidelines, suggesting general recommendations for cryotherapy practice (Bleakley *et al,* 2012) there is no clear consensus on a dose response relationship evident in the literature. This is because no optimum protocol for the application of cryotherapy exists (Merrick *et al,* 2003; White and Wells, 2013; Hawkins and Hawkins, 2016) contrary to current practice (Bleakley *et al,* 2014). Otte *et al,* (2002) reported a relationship between adipose tissue thickness and adjustments to applications times of local cryotherapy and an abundance of studies compare different types of cryotherapy modalities in local (Chesterton *et al,* 2002; Kanlayanaphotporn and Janwantanakul, 2005; Breslin *et al,* 2015) and whole-body cooling forms (Selfe *et al,* 2014), however many do not compare variations in dose. Research agrees that repeated application of ice and gel packs are perceived to yield a more therapeutic effect (Bleakley *et al, 2*007; Breslin *et al,* 2015). Through repeated applications, heat energy is constantly withdrawn in the attempt to reduce inflammation (Breslin *et al,* 2015). The efficacy of cooling via gel packs however has received scrutiny within the evidence base in comparison to other modes of modality (Kanlayanaphotporn and Janwantanakul 2005). Subsequently with differences in methodologies, it is hard to derive a consensus of recommendation for optimal dose. This accounts for both application length of dosage and number of dose exposures. Recommendations for local cooling applications in sport traditionally follow PRICE guidelines; minimum of 10-minutes, but no longer than 20-30-minute dose applied at 2-hour intervals but can be less and is typically dependent on pain (Bleakley *et al,* 2011). By contrast, literature surrounding WBC as a recovery modality in sport is suggestive that a dose-response relationship exists in relation to the frequency of WBC treatment applications (Haq *et al,* 2018). Some studies have investigated WBC dosage in respect to length of exposure comparisons (Selfe *et al*, 2014) and multiple exposures within a given period to replicate camp-based competitive schedules (Russel *et al,* 2017). WBC and dose-response are presented further in THEME 5 (Section 1.7).

The location of cooling application is typically dependent on the site of injury or the aim of the recovery strategy. Therefore, investigations which compare physiological and biomechanical outputs of different cooling locations, i.e., over a joint versus direct muscle, and the effects on proximal muscle strength are relevant to several scenarios that reflect cooling applications in sport. Although, consensus is lacking because earlier studies report a mixture of increases (Sanya and Bello, 1999; Kinugasa *et al,* 2005; Hopkins *et al,* 2001; Hopkins, 2006) decreases (Ruiz *et al*, 1993; Mattacola and Perrin, 2003; Hatzel and Kaminski, 2000; Loro *et al*, 2019) or no changes (Draper *et al,* 1990; Lessard *et al,* 1997) in muscle activity or force after muscle vs / or joint cooling (Hopkins and Stencil, 2002). Findings presented in publication 4 (Alexander *et al,* 2019) have demonstrated reductions in concentric PT and AvT knee extensor strength, which did not fully recover to baseline at 30-minutes post-wetted ice application, regardless of cooling location over the knee joint or anterior thigh in males and females. The debate around the impact of these findings ultimately depends on the intended aim of treatment and requires further investigations.

In terms of recovery strategies in sport, applications of cooling may be influenced by other variables, such as those outlined in table 5 (pg. 71). The translation of evidenced based protocols that consider such factors in applied practice are anecdotally minimal however, and this may be due to the lack of studies available that consider or quantify relevant measures or the influencing variables that may affect individual athlete response to cryotherapy applications. Although, the combinations of variables and external influences (Table 5, pg. 72) in elite sport settings make designing optimal cryotherapeutic protocols difficult. The aim of many studies is to investigate the influences of such variables and develop adaptations to protocols based on the findings. Yet often studies fail to quantify multi-measures of performance which represents the environment in which cryotherapeutic applications are applied. Despite the influx of research interest in cryotherapy topics in the context of sport, agreement around optimal protocols is still under contention due to many variables not yet considered. Key areas of cryotherapeutic principles and variables such as those presented in table 5 (pg. 72), still lack agreement and examination. In summary, a breakdown of such variables follows and are critiqued pertinent to and within each theme of this thesis (Themes 1-5).

CRITICAL EVALUATION OF THE EVIDENCE

1.2 RESPONSES TO CRYOTHERAPY PERTINENT TO EACH THEME

The following section as part of Chapter 1 aims to provide a critical review on the effects of cryotherapy on the human body within a sporting context. Key areas of sports injury management and recovery strategies and the quantification of such responses are evaluated in relation to the five themes of the thesis (Table 1, pg. 26-28). As such, the critique of evidence that follows is structured and presented as five themes with evaluation alluding to the four categories of responses described in Figure 1 (pg. 41) (*biomechanical, biochemical, physiological, psychological*), and the variables influencing cryotherapy application in practice. Table 6 attempts to collectively illustrate the associations between those four categories of responses in addition to anatomical structures, measures, quantified outputs, and evidence of related literature for each theme in which the publications pertain to. This chapter provides practical rationale for the fifteen studies presented in the thesis. Importantly it highlights the significant gaps in the existing literature and current practice within each theme providing justification for each publication at the time of writing.

Table 6. Categories of response, structures, quantified outputs to cryotherapy with examples of evidence, responses to the gap in the scientific literature through publications 1-15 and the associated themes in which the publications sit.

Response	Anatomical Structure Affected	Output Measured	Equipment / Technology	Examples evidenced within current literature	Evidenced in Thesis Publications	Associated Themes
Physiological (Associated Themes Include: 1-5)	Skin	Skin Surface Temperature (T_{sk}) (°C)	Thermography / Thermal Imaging	Costello *et al,* (2012a); Moreira *et al* (2017)	Selfe, Alexander *et al,* (2014) Alexander *et al* (2016; 2018; 2019 2020a; 2020b; 2021a; 2021c; 2021d; 2021e) Rhodes and Alexander, (2018) Alexander and Rhodes, (2019; 2020).	THEME 3
	Intra-muscular	Muscle Temperature (T_{im}) (°C)	Thermocouple (directly into muscle)	Ostrowski *et al,* (2018; 2019); Gillette and Merrick (2018).	n/a	n/a
	Intra-articular	Intra-Articular Joint Temperature (T_{ia}) (°C)	Temperature Probe	Warren *et al,* (2004); Furmanek *et al,* (2014); Stevens *et al,* (2019);	n/a	n/a
	Thermoregulatory Mechanisms	Core Temperature	Core Temperature Pills Thermometers (Rectal/Auditory/Tympanic)	Palmieri *et al,* (2006);	Selfe, Alexander *et al,* (2014).	THEME 5
	Haemodynamic	Blood Pressure (mm Hg)	Sphygmomanometer	Dębiec-Bąk *et al,* 2016	n/a	n/a
	Nerve Conduction	Nerve Conduction Velocity (NCV)	Surface Electrodes	Algafly *et al,* (2007); Herrera *et al,* (2010)	n/a	n/a
	Skin Surface Receptors	Skin Surface Sensitivity (SSS) Superficial Feedback Mechanisms	Esthesiometers	Gregório *et al*, (2014)	Alexander *et al,* (2019).	THEME 3
	Haematological Parameters	Muscle Oxygenation (SmO_2)	Moxy	Hohenauer *et al,* (2019);	Alexander *et al,* (2020b);	THEME 4

		Tissue oxygenation saturation – Total Oxygenation Index (TOI) Haemoglobin Content - Oxyhaemoglobin (O2Hb) Deoxyhaemoglobin (HHb)	Near-Infrared Spectroscophy (NIRS)	Yeung *et al,* (2016); Selfe *et al,* (2014); Ihsan *et al,* (2013).	Selfe, Alexander *et al,* (2014).	THEME 5
Biomechanical (Associated Themes Include: 1, 2 and 5)	Muscle	Muscle Strength (Isometric / Concentric / Eccentric) (AvT / PkT)	Isokinetic Dynamometer NordBord Handheld Dynamometer Sphygmomanometer	Torres *et al,* (2017); Kalli and Fousekis (2019)	Rhodes and Alexander (2018); Alexander and Rhodes, (2019); Alexander *et al,* (2021a; 2021c; 2021d; 2021e).	THEME 2
	Joint	JPS Kinematics Dynamic Stability (Proprioception)	3D Movement Analysis	Furmanek *et al,* (2018);	Alexander *et al* (2016; 2018).	THEME 1
	Neuromuscular Functional	Counter Movement Jump (CMJ) Vertical Jump Performance Repeated Sprint Ability	Application Based Devices 3D Motion Analysis Force Plate GPS Speed Gates	Wassinger *et al,* (2007); Fischer *et al,* (2009); Russell *et al,* (2017)	Alexander *et al,* (2021d; 2021e)	THEME 5
Biochemical (Associated Themes Include: 5)	Muscle damage	Levels of creatine Kinease (CK) Muscle damage Inflammation (Il-6)	Blood Markers	White *et al,* (2014); Hohenauer *et al,* (2015); Peake *et al,* (2017); Allan *et al,* (2019).	Selfe, Alexander *et al,* (2014).	THEME 5
Psychological (Associated Themes Include: 3,4 and 5)	Subjective Response to Cold Applications	Perceptual indices of local cooling applications	Thermal Comfort (Scale) Thermal Sensation (Scale)	Cholewka *et al,* (2012); Costello *et al,* (2012b).	Selfe, Alexander *et al,* (2014). Alexander *et al,* (2020a; 2020b).	THEME 3 THEME 4 THEME 5
	Wellbeing Recovery	Perceptual indices of recovery from fatiguing exercise	Recovery, Wellbeing and Soreness Questionnaires	Russell *et al,* (2017); Peake *et al,* (2017); Hohenauer *et al,* (2018); Hohenauer *et al* (2019).	Alexander *et al,* (2021).	THEME 5

CRITICAL EVALUATION OF THE EVIDENCE

1.3 THEME 1: KINEMATIC RESPONSES TO CRYOTHERAPY

Several functions and anatomical structures are considered to constitute '*biomechanical'* response. For clarity, in this body of work, biomechanical responses to cooling are split into kinematic and muscle strength parameters, coinciding with THEME 1 (kinematic responses), and THEME 2 (muscle strength responses). For THEME 1 the following topics are critically analysed; components of proprioception (joint position sense (JPS), dynamic stability, nerve conduction velocity (NCV)), intra-articular temperature (T_{ia}) and their response to cryotherapy aligning with the two publications in this thesis under THEME 1 (Alexander *et al,* 2016; 2018). A further breakdown of the quantification of proprioceptive components, such as three-dimensional (3D) motion analysis for JPS, in relation to the effects of cryotherapy on such parameters are explored.

1.3.1 Proprioceptive Responses to Cryotherapy

Defined frequently as cumulative neural input from mechanoreceptors to the central nervous system (CNS) (Lee *et al,* 2003), the term '*proprioception'* was established originally from the work by Sherrington in the 1900's (Sherrington, 1906). Mechanoreceptors detect stimulus changes in pain, touch, movement and pressure (Costello *et al,* 2010) and are found in several structures such as ligaments, muscles, skin, tendons and joint capsules (Lephart *et al,* 2002; Wassinger *et al,* 2007). These processes contribute to the optimal function required for performance in sport (Costello *et al,* 2010), yet there is no universally accepted operational definition of proprioception (Lephart *et al,* 2000). Often a misused term being incorrectly or synonymously interchanged with kinesthesia, JPS or balance, rather *'proprioception'* encompasses a multitude of components, JPS being one (Riemann *et al,* 2002; Surenkok *et al,* 2008; Costello *et al,* 2010), dynamic stability another (Cordeiro *et al,* 2014). Ultimately describing afferent information (Riemann and Lephart, 2002a). Evidence therefore is confusing due to varying terminology or methodological approaches that aim to quantify proprioceptive parameters.

Proprioception is commonly described in the sports medicine literature as the ability to sense orientation of the body within the immediate environment, known also as kinesthesia (Taylor, 2009; Torres *et al,* 2012). Although within applied practice it is the effected output of proprioception that is quantified not the physiological processes (Ribeiro *et al,* 2008; Changela *et al,* 2012). JPS is recognised as the recreation of a joint angle via sensation awareness (Grob *et al,* 2002; Peiffer *et al,* 2009; Daneshjoo, *et al,* 2012) through cumulative neural input to the CNS via mechanoreceptors (Lee *et al,* 2003). As such, this functional movement is recognised as the quantification of dynamic stability of which proprioception, fundamentally important for sensorimotor control, is conveyed (Riemann and Lephart, 2002b).

An extensive body of literature investigates the term JPS in relation to the effect of local cryotherapy, as a measure of proprioception (LaRiviere and Osternig, 1994; Ozmun *et al,* 1996; Uchio *et al,* 2003; Dover *et al,* 2004; Wassinger *et al,* 2007; Surenkok *et al,* 2008; Costello *et al,* 2010; Oliveira *et al,* 2010; Costello *et al,* 2011; Ribeiro *et al*, 2013; Watanabe *et al,* 2013; Furmanek *et al,* 2014; 2018, Alexander *et al,* 2016; 2018). Numerous studies acknowledge the term '*proprioception'* and report proprioceptive deficits following local cooling applications through measurement of joint movement sense, dynamic stability or JPS (Hopper *et al,* 1997; Uchio *et al,* 2003; Surenkok *et al,* 2008). Contradictory literature however reports no changes in proprioceptive feedback following local cooling (Ozmun *et al,* 1996; Dover *et al,* 2004; Aboeleneen *et al,* 2018). The debate as to the extent of which cryotherapy affects dynamic stability after immediate application or over rewarming periods is therefore ongoing. An earlier review by Costello et al, (2010) identified the equivocal evidence available to conclude the effects of cryotherapy on proprioception or the components thereof. Consequently, weak consensus affects the translation of evidence into practice and a call for further research replicating typical protocols of cryotherapy application in sport is evident. In a practical sense this is significant to the development of "real-world" impact and essential for optimising the development of advantageous protocols for sport injury, rehabilitation or recovery management.

Publications within THEME 1 (Alexander *et al,* 2016; 2018) address the deficit of research by investigating the effects of cooling on knee JPS, immediately following local cooling (Alexander *et al,* 2016) and over a rewarming period (Alexander *et al,* 2018). Quantification of JPS through 3D motion analysis during a functional movement of a small knee bend (SKB) as demonstrated in those publications provides an understanding of the effects of cooling on dynamic stabilisation responses. As a valid and reliable method of quantifying JPS, 3D motion analysis is an established method of kinematic quantification (Richards, 2018). Findings in publication 1 reported immediate significant changes in the ability to reproduce knee joint flexion and lack of varus control which consequently increased valgus shift in the coronal plane during the eccentric loading phase of the SKB (Alexander *et al,* 2016). Reductions in JPS, and consequently changes in dynamic stability response following cooling, as noted in several studies (Uchio *et al,* 2003; Surenkok *et al,* 2008; Ribeiro *et al,* 2013; Watanabe *et al,* 2013) is a key aetiological contributory risk factor to non-contact lower limb injury (Read *et al,* 2016). The decrease in ability to control joint stability following cryotherapy, amounting to a 18.2% valgus shift in this example, suggest the potential for excessive strain being placed on stabilising knee structures, thus heightening the potential risk of sustaining an injury. The delayed affects following the removal of cooling at the knee joint on JPS were reported in publication 2

(Alexander *et al,* 2018) observed over a rewarming period, with findings reporting a change in rotational range 20 minutes after the removal of cooling. Although the magnitude of difference was small, it represented a 25% increase in rotation in the transverse plane at 20-minutes after exposure, and therefore presents implications for athletes returning to dynamic functional activities with a potential increased risk of injury (Alexander *et al,* 2018). These findings are from one study; although the consensus presented in the most recent systematic review (Bleakley *et al,* 2012), on whether athletes should return to activity after cryotherapy concludes that caution during functional tasks following removal of cryotherapy modalities should be taken. Suggestions in the review consider potential increases in injury would be due to deleterious changes in JPS (Surenkok *et al,* 2008; Costello *et al,* 2010; Alexander *et al*, 2018), proprioceptive components (Wassinger *et al,* 2007; Oliveira *et al,* 2010) or dynamic stability feedback mechanisms (Douglas *et al,* 2013; Yi-Wen and Hong-Wen, 2017), including muscle strength components influencing joint stability and stiffness. Yet collectively research findings suggest inadequate parameters for optimum performance or a heightened risk of injury / re-injury following local cooling exist. Many inconsistencies in application techniques not representative of those applied in sport, such as dose of application were evident from the review by Bleakley *et al,* (2012). Since, investigations into the applications of contemporary cooling methods reflective of those in applied practice are available (Douglas *et al,* 2013; Fullam *et al,* 2019), however further investigations are required with accurately developed prescriptions to fully understand the effects of joint cooling on functional performance. Consequently, a comprehensive model that presents the associations between cryotherapy and proprioceptive components might be developed.

1.3.2 Quantification of Proprioceptive Responses

Quantification of JPS is useful to provide information on the affected output following cryotherapy, and reasons behind these results and those found in previous literature may be presumed to be linked to sensorimotor mechanisms. Publications within THEME 1 (Alexander *et al,* 2016; 2018) utilise the method of quantification though JPS effectively to demonstrate the immediate and latent effects of local knee joint cooling. Collectively studies propose that cooling has key effects on sensorimotor mechanisms that play a role in control of dynamic stability, which include afferent signal input from mechanoreceptors in muscles and joint structures (Cordeiro *et al,* 2014). Considering the processes of proprioceptive input in peripheral joints, reflective of those receptors most prominent is of continuous interest (Proske *et al,* 2000; 2012; Proske, 2005). It is considered that muscle spindles are a key and dominant provider of afferent feedback of proprioceptive information and applicable to the knee joint (Proske and Gandevia, 2012). Yet, it is unlikely that independent muscle afferent information is enough to provide optimal proprioceptive feedback in isolation. It is understood that in the knee joint several types of mechanoreceptors contribute to its homeostasis (Johansson *et al,* 1991) with complex articulations and multi-directional movement the accumulation of such afferent inputs (da Fonseca *et al,* 2004) important for optimal movement, position and ultimately performance in sport (Table 7). The effects of cryotherapy on such structures are important to understand from a practical perspective, as electromechanical delay (EMD) in neuromuscular (NM) response has the potential for heightened risk of injury in athletes. NM responses are discussed further in THEME 2 (Section 1.4), however, practically important as sufficient and rapid muscle tension through muscular activation and force generation output for dynamic stability at the knee is required to withstand external loads occurring through sporting tasks (McClean *et al,* 2010; De Ste Croix *et al,* 2015). How cryotherapy may affect this, and other receptors outlined in Table 7 remain to be fully elucidated when considering the practical and functional implications. Muscle contractions that stabilise the body through deviations in loading through joints, a neurological / NM response known as dynamic stability (Williams *et al,* 2001; Cordeiro *et al,* 2014), is discussed further in THEME 2 (Section 1.4).

Table 7. Summary of receptor types relevant to the knee joint, adapted from Purves *et al,* (2001), Jha *et al,* (2017) and Richards and Selfe, (2012).

Receptor	Location	Stimulus	Function based on Classification
Pacinian Corpuscle (II)	Joint Capsule, Menisci, Skin, Ligament, Bursa, Periarticular connective tissue	Pressure / Compression	Low threshold rapid adapting receptor with low threshold for evaluation of acceleration rate during movement (Chaitow and DeLany, 2008; Lephart et al. 1998).
Muscle Spindle (Ia; II)	Muscle fibre	Stretch	Length of the muscle evaluation, responsible for muscle tone (Chaitow and DeLany, 2008; Lephart et al.1998). Input for muscle velocity in terms of changes and contraction (Chaitow and DeLany, 2008; Lephart et al. 1998). Providing the basis of stretch reflex through stimulus of agonist muscle, (Lephart et al. 1998).
Merkel's Discs (Aβ)	Skin	Pressure (Incessant)	Low-threshold (high-sensitivity), senses gentle touch/weak mechanical stimulus, essential for complex sensory tasks or tactile discrimination (Purves *et al,* 2001).
Rafinni Ending / Ruffini Corpuscles (II)	Joint Capsule, Menisci, Skin, Ligament	Strain and / or Stretch	Low-threshold (high-sensitivity), concerned with static positions, joint angle perception and direction of movement, progressive recruitment, not easily fatigued (Chaitow and DeLany, 2008; Lephart et al. 1998).
Golgi Tendon Organ (Ib)	Musculotendinous Junction	Tension and / or Strain	Silent during static joint position (Lephart *et al,* 1998). Slow adapting discharges continuously over long periods (Chaitow and DeLany, 2008). Associated with joint position irrespective of muscle activity (Chaitow and DeLany, 2008).
Free Nerve Ending (C, Aδ)	Joint Capsule, Menisci, Skin, Ligament	Nociceptive	Activated with the mechanical deformation and inflammatory mediators (Lephart et al, 1998).
Meissner's Corpuscles (Aβ)	Skin	Touch (Deformation)	Low-threshold (high-sensitivity) to weak mechanical stimulation of the skin (Purves *et al,* 2001).

Other specific responses through which cryotherapy may alter knee joint control alluding to the sensorimotor system for example may include changes or adaptations in nerve conduction velocity (NCV) (THEME 3, Section 1.5), neuromuscular control mechanisms, sensory feedback in superficial skin receptors, and muscle strength (THEME 2, Section 1.4). The effect of cryotherapy on skin surface sensitivity (SSS) is considered to have greater relevance than previously thought reflecting proprioceptive feedback for JPS and is further discussed in THEME 3 (Section 1.5). The relationship between neuromuscular and neurosensory systems is multifaceted and encompassed by the sensorimotor system which incorporates vestibular, visual and peripheral mechanoreceptor sensory information (Lephart *et al,* 2000) globally incorporating tactile, pain, temperature and postural response components, many of which are investigated in the publications in this thesis.

1.3.3 Intra-articular Temperature (T_{ia}) *in Response to Cryotherapy*

Although changes in intra-articular temperatures (T_{ia}) are not quantified in the publications presented in this thesis, the complex and combined relationships between NCV, skin surface temperature (T_{sk}) and the known relationship between intramuscular temperature (T_{im}) in response to cryotherapy require consideration to explain potential mechanisms behind altered JPS and dynamic stability responses. Collectively temperature changes through decreases in T_{im}, T_{ia}, T_{sk} or NCV further supports the evaluation of cryotherapeutic efficacy across modalities (Herrera *et al,* 2010) and their application in sporting contexts.

Several studies report decreases in T_{ia} following cryotherapeutic application to peripheral joints (Oosterveld *et al,* 1992; Martin *et al,* 2001; Stevens *et al,* 2019). Although, often as a treatment following surgery from sports injuries such as ACL reconstruction, beneficial effects through decreases in T_{ia} from cryotherapy applications are acknowledged (Martin *et al,* 2001; Song *et al,* 2016). These include analgesic response (Warren *et al,* 2004) providing reductions in pain scores (Barber *et al,* 1998) and pain medication post ACL surgery (Jutte *et al,* 2001). Other research demonstrates reductions in joint swelling (Webb *et al,* 1998). The advantages of cryotherapy immediately post-surgery to manage acute symptoms and initiate joint movement are recognised (Whitlaw *et al,* 1995; Mumitt *et al,* 2015; Kijkunasathian *et al,* 2017). Alternatively, suggestions of the importance of applications through rehabilitation to improve range of motion (ROM), muscle disinhibitory and consequently functional return to sport are documented (Schrőder and Pässer, 1994; Kuenze *et al,* 2017). This is well received in context, yet in contrast to athletes returning to functional activity post-cooling the desired effects of T_{ia} are somewhat different and should be considered for effective cryotherapeutic applications to be implemented in practice.

Decreases in inhibition following joint injury, thought to occur due to decreases in NCV, exist through a slowing rate of discharge in joint mechanoreceptors (Hopkins *et al,* 2002). Arthrogenic muscle inhibition (AMI) specifically protects the joint from further damage following injury (Hopkins *et al,* 2000) however; despite integrity of the muscle, AMI can affect the timescales of the rehabilitation process, especially in post-operative conditions. Although neuromuscular control through various rehabilitative techniques is successful, AMI caused by joint effusion can reduce strength and proprioceptive gains during joint rehabilitation (Barrack *et al,* 1994). It is reported that disinhibition occurs following the application of cold to an effused knee joint, thus, facilitation of motoneuron pools of the quadriceps ensues (Hopkins *et al,* 2002). This is thought to be caused by the responses in cutaneous receptors (mechanoreceptors and thermoreceptors) instigating excitement of the quadriceps motoneuron pool. Considering these findings, it is worth highlighting the potential link to decreases in NCV being a pre-cursor for injury following local cryotherapy applications if applying the same principles and considered as an important response behind several results reported in the publications within this thesis.

Earlier observations over rewarming periods further indicate a continual decrease in T_{ia} after cooling has been removed (Oosterveld *et al,* 1992; Hopkins *et al,* 2002; Stevens *et al,* 2019). Research suggests these physiological responses are useful to promote functional knee recovery thus accelerating the rehabilitation process of postoperative patients (Song *et al,* 2016). It should be considered however, that although it is reported that an increase in the availability of motoneurons within the quadriceps motoneuron pool follows cooling exposures, representing a change in excitability, the measurement does not equate to increases in functional strength (Hopkins *et al,* 2002). The benefit is the opportunity to facilitate joint mobilisation, is through proprioception engagement and reduction of muscle wasting within the rehabilitation process (Young, 1993). By contrast, publications within this thesis demonstrated through a comparison of cooling over the knee joint vs. the quadriceps muscle noted reductions in muscle concentric strength in uninjured athletes (Rhodes and Alexander, 2018; Alexander and Rhodes, 2019). Further discussion around the effects of cryotherapy on muscle strength and function parameters are presented in relation to THEME 2, (Section 1.4).

CRITICAL EVALUATION OF THE EVIDENCE

1.4 THEME 2: MUSCLE STRENGTH RESPONSES TO CRYOTHERAPY

With relevance to THEME 2, this section critically evaluates the biomechanical (muscle strength parameters and quantification methods) and physiological (T_{im}) responses to cryotherapy in sporting context, from the available evidence.

1.4.1 Muscle Strength Responses to Cryotherapy

To maintain dynamic stability in load baring joints such as the knee, muscle strength is required to effectively withstand subjected load by maintaining neuromuscular pathways (Williams *et al,* 2001). Reduced NCV in sensory and motor nerves are reported in response to cryotherapy (Chesterton *et al,* 2002; Algafly and George, 2007) yet with controversy over muscle strength affects. The delayed and immediate physiological effects on biomechanical (muscle strength) and subsequent performance markers reported across literature which allude to muscle strength parameters, demonstrate contrasting results on the effect of cooling on the force generating capacity of muscles however (Rubley *et al,* 2003). Immediate isokinetic strength reductions are reported following cooling when applied directly to the muscle belly region (Ferretti *et al,* 1992; Mattacola and Perrin, 1993; Hatzel and Kaminski, 2000; Patterson *et al,* 2008; Rhodes and Alexander, 2019; or distal joint structure (knee) (Alexander *et al,* 2018; 2019). Whereas others report no change in muscle strength across various types of contraction (Cornwall *et al,* 1996) or question whether cooling induces muscle fatigue (Halder and Gao, 2014). Publication 4 in the thesis notes no differences in concentric muscle strength when comparing joint cooling vs direct muscle cooling over the knee or quadriceps. Cold application directly over muscle sites such as the hamstrings influence co-contraction response related to performance deficits, previously reported by Fischer *et al,* (2009). Recommendations suggest active warm-up to ensure appropriate muscle warming following ice-bag application (Richendollar *et al,* 2006). It is, however, difficult to provide a consensus on strength or performance changes following cooling, due to methodological, cohort, modality and outcome measure differences.

Ultimately, any decreases in functional strength negatively effects the ability to provide optimal stabilisation at the knee through the lack of load it may endure, and consequently control it can maintain (Abulhasan and Grey, 2017), refer to THEME 1 (Section 1.3). Further adverse effects on performance measures are noted because of functional muscular deficits post-cooling and include reductions in reaction time, power and speed (Bergh and Ekblom, 1979; Ferretti *et al,* 1992; Mattacola and Perrin, 1993; Schniepp *et al,* 2002; Richendollar *et al,* 2006; Patterson *et al,* 2008). Although controversy over the functional impact of cryotherapy techniques in muscular performance is ongoing, the consensus is that caution is recommended in the literature prior to return to sport following local cooling (Douglas *et al,* 2013; Furmanek *et al,* 2014; Alexander *et al,* 2018; Alexander and Rhodes, 2019). Alternatively, some literature disagrees presenting improvements in muscular performance following local cooling (Thornley *et al,* 2003). Most recently, Tassignon *et al.* (2018) observed changes in EMG amplitude and functional hop performance with cooling protocols of 10°C, but not at 18°C. Inferring that local temperature manipulation may not always be detrimental to performance. The need for further investigation on the effects of cooling on muscle mechanical contractile properties and responses is therefore evident through much controversy and confusion remaining and addressed in publications throughout THEME 2.

1.4.2 Quantification of Muscle Strength Responses

Muscle strength can be quantified through several measures, including dynamometry, clinical assessment and isokinetic testing (Dvir and Steffen, 2020), with isokinetic dynamometry (IKD) regarded as gold standard and functional (Bohannon, 1990; Hirano *et al,* 2020). Maximal concentric (CON), eccentric (ECC) and isometric (ISO) muscle strength can be assessed through full available range of motion and constant velocities (Carvalho *et al,* 2013) via IKD technologies for example. For the lower limb isokinetic approaches are often used to quantify the functional output, although functionality may be considered limited due to a single muscle measure (Svennson *et al,* 2005). Good test-retest reliability however is published around the eccentric knee flexor torque metric (Impellizzeri *et al,* 2007; Maffiuletti *et al*, 2007; Greig, 2008; Cesar *et al,* 2013; Ribeiro et al., 2015) with high reproducibility of measures of the Cybex IKD (r = 88) and the Biodex IKD (r = 0.92) (Ribeiro *et al,* 2015). Other isokinetic dynamometer such as the Kin Com, Con-Trex and Merac have been examined for reliability in other populations (Capranica *et al,* 1998*;* Ordway *et al,* 2006; Sole *et al,* 2007; Maffiuletti *et al,* 2007; de Carvalho Froufe Andrade *et al,* 2013), with variable results across equipment comparison. High reliability and validity are reported for the IKD over varying speeds which range from 30°·s-1 to 180°·s-1 (Svensson *et al,* 2005; Impellizzeri *et a.,* 2007; Maffiuletti *et al*, 2007; Greig, 2008; Cesar *et al*, 2013; Ribeiro *et al*, 2015). Lower speeds may be useful in pre-habilitation or rehabilitation scenarios and profiling of eccentric hamstring strength at higher speeds (300°·s-1) are reported useful to replicate demands placed through change of direction or acceleration and deceleration phases, with good reliability and validity (Drouin *et al,* 2004; Greig, 2008). An important consideration to determine whether athletes can facilitate loads required for return to play following injury or as an injury risk reduction consideration. Although, several influencing factors affect measurement of reproducibility across measuring devices including testing protocols, characteristics of subject populations (Carvalho *et al,* 2013).

The design of prospective studies investigating lower limb strength differences within sports populations in terms of screening, rehabilitation programmes for the assessment of risk factors for injury are common applications for IKD assessment (Impellizzeri *et al,* 2008; Carvalho *et al,* 2013).

Comparatively, the measurement of muscle strength parameters and function following cryotherapy interventions have previously utilised both handheld (Halder *et al,* 2014; Loro *et al,* 2019) and IKD equipment (Torres *et al,* 2014; Aboeleneen *et al,* 2018; Rhodes and Alexander, 2018; Alexander *et al,* 2019). A contemporary device used to quantify eccentric hamstring strength parameters is the Nordbord® (Opar *et al,* 2013). With its use becoming more apparent in sport and subsequently applied research, the addition of the Nordbord® for quantifying eccentric hamstring strength parameters post cooling for recovery responses have been investigated (Alexander *et al,* 2020). Only one publication to date however uses the device to report the effects of cooling over the hamstring region on eccentric strength metrics following induced fatigue protocols (Alexander *et al,* 2020) and is discussed further in THEME 5 (Section 1.7).

1.4.3 Intra-muscular Temperature (T_{im}) *and Strength Response to Cryotherapy*

It seems pertinent to consider the relationship between T_{sk} and T_{im}, denoted in current literature to provide a comprehensive understanding of deeper tissue cooling response from superficial cryotherapy applications at this point (Chesterton *et al,* 2002; Janwantanakul, 2004; Kanlayanaphotporn and Janwantanakul, 2005; Kennet *et al,* 2007). Although Jutte *et al,* (2001) proposed that T_{sk} is weak predictor of T_{im} indicated though a multiple regression model, Hardaker *et al,* (2007) suggests a quadratic relationship between T_{sk} and T_{im} temperature exists (Figure 3. pg. 93). Publication 4 in this body of work alludes to this quadratic relationship when investigating the effects of joint vs muscle cooling on strength parameters over a rewarming period of up to 30-minutes (Alexander and Rhodes, 2019). Suggesting that as T_{sk} rewarmed, deeper muscle tissues continued to decline, contributing to the strength loss noted in the findings over such a rewarming period. Reasons, however, are only assumptive, as T_{im} was not quantified in study 4 directly. T_{sk} being more applied in nature provides a suitable proxy measure to aid the understanding of muscle strength responses to cooling application in a sporting context through the consideration of underpinning theories presented by Hardaker *et al,* (2007) in earlier research.

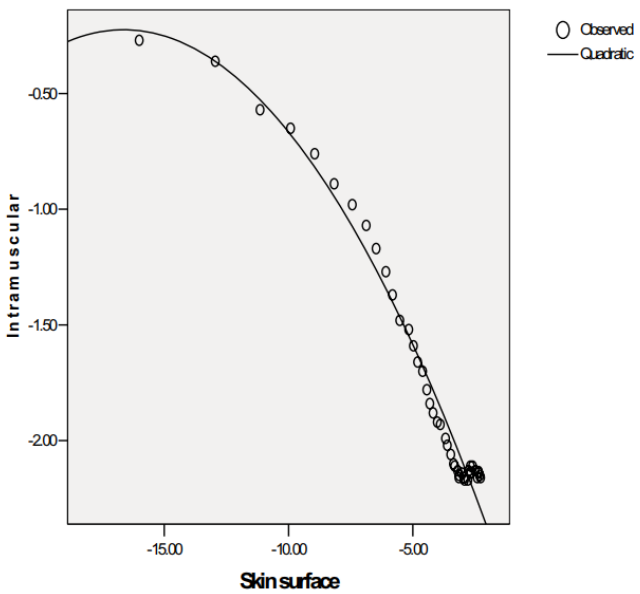


Figure 3. Demonstration of the quadratic relationship between skin surface temperature (T_{sk}) and Intramuscular temperature (T_{im}) reductions following local cooling (Hardaker *et al,* 2007).

The response of muscle strength to local cooling applications, typical of applied practices in sport demonstrate immediate and prolonged changes resulting in performance deficits attributed to decreases in dynamic contractile force (Point *et al,* 2018). Differences in the magnitude of changes in muscle force are associated with location of cooling (joint / muscle) and modality efficacy. Yet, an association between T_{sk} and T_{im} is acknowledged and considered in the attempt to understand safe parameters of return to functional performance following cooling where muscle strength deficits are identified. Muscle mechanical properties and architectural responses to cooling are often alluded to the potential reductions in stretch capacity that muscle tissue requires to sustain without consequential injury risk. As a result, increased stiffness in soft tissue structures following cooling pose reductions in available ROM and consequently predisposing athletes to injury mechanisms. These are important considerations practically reflecting the safe application of cryotherapy, and to minimise potential functional deficits through optimisation of cooling protocols prior to performing functional sporting demands.

Taylor *et al.* (2014), explains how thermal gradients radiated in muscle tissue supports heat loss through conduction. Muscles that anatomically are situated distally are smaller or present with limited thermal insulation from other structures can be influenced by environment (Booth *et al,* 2004; Taylor *et al,* 2014). In addition to this adipose tissue influences the ability to affect heat transfer and subsequently muscle temperature reductions (Otte *et al,* 2002; Petrosky and Laymon, 2009; Bleakley and Hopkins, 2013). Levels of which are measured commonly through skinfold quantification via skinfold calliper measurements at common sites (Otte *et al,* 2002). The direct relationship between adipose thickness and required cooling time is clinically important and should be considered in practical application of cooling methods (Otte *et al,* 2002). Skeletal muscles are a heat source during exercise (Todd *et al,* 2014), and previous studies have shown inter-site variability in intramuscular temperatures across segments due to increases in metabolic variations (Kenny *et al,* 2008). This may be important to consider in relation to the efficiency of cryotherapeutic applications used in sport over muscular sites, as response via the extraction of heat may be affected by intramuscular temperatures. Variation across sites therefore in consideration of suggestions by Taylor *et al,* (2014) are of interest in consideration for cooling applications for recovery post exercise for example. Further presentation of $T_{sk,}$ and the effect of cooling is discussed in THEME 3 (Section 1.5).

CRITICAL EVALUATION OF THE EVIDENCE

1.5 THEME 3: THERMOGRAPHY AND SKIN SURFACE RESPONSES TO CRYOTHERAPY

The responses of superficial tissue to cooling are critically analysed for THEME 3, Section 1.5, in respect to publications 6-8 (Appendix 3). Relevant topics in the following section include skin surface temperature (T_{sk}), skin surface sensitivity (SSS), nerve conduction velocity (NCV) and their responses to cryotherapy applications in sport. Quantification thereof through thermography is also critiqued. In addition, perceptual measures in response to cryotherapy applications are appraised.

1.5.1 *Skin Surface Temperature (T_{sk}) Responses to Cryotherapy*

Reductions in T_{sk} initiate the first responses to cooling applications. Considerations such as metabolic state of the body, temperature of modality and stimulus are important factors in skin temperature reductions (Taylor *et al,* 2014). The ability of any cryotherapy modality to simultaneously achieve an effective analgesic effect and avoid adverse reaction is often determined by the magnitude of skin surface tissue cooling achieved by the cryotherapeutic modality applied (Costello *et al,* 2012a). T_{sk} over rewarming periods after cold removal in both clinical and sporting settings are of interest (Costello *et al,* 2012a). Both the dynamic (response) and absolute (temperature) profile of T_{sk} can be affected by multiple factors, including subcutaneous adiposity, tissue damage, ethnicity, age and gender (Inoue *et al,* 1992) and addition of compression discussed further in THEME 4 (Section 1.6). The influence of subcutaneous tissue thickness on deeper tissue temperature variances following local cooling applications have been previously investigated (Myrer *et al,* 2001; Otte *et al,* 2002; Selkow, 2019). Physiological changes in deeper structures are often understood via the presentation of T_{sk} and extensively reported throughout literature in relevance to efficacy of cooling modalities (Jutte *et al,* 2001; Chesterton *et al,* 2002; Breslin *et al,* 2015; Costello *et al,* 2012a; Alexander *et al,* 2019). Yet, we must be conscious that by only measuring peak changes in T_{sk} optimal cooling of other structure may be compromised if T_{sk} is the only measure to provide understanding and development of optimal dose exposure as one example. Hence the importance of quantifying multi measures of response.

In accordance with PRICE guidelines, T_{sk} reductions of 5-15°C are required to achieve an analgesic physiological response. Deemed important in terms of acute injury management, and T_{sk} maintained between 10-15°C are required for deeper therapeutic physiological changes to ensue (Bleakley and Hopkins, 2010; Bleakley *et al,* 2011). Introduced in section 1.1.2 (pg. 71), the acronym POLICE (Bleakley *et al,* 2012) is suggestive that the role of ICE via cold-induced analgesia is still acknowledged in the acute management of soft tissue injury. Most recently, the development of PEACE and LOVE acronym questions the application of cryotherapy in the early inflammatory phases yet recognises the positive analgesic response to cooling (Dubois and Esculier, 2019). Studies investigating analgesia responses to local cooling applications refer to earlier PRICE guidelines (Bleakley *et al,* 2011) suggesting an analgesic response in T_{sk} of 12°C is required (Bleakley and Hopkins, 2010; Bleakley *et al,* 2011). T_{sk} lower than the therapeutic range <10°C are thought to increase potential injury or induce negative responses such as function disturbance and motor or sensory loss to peripheral nerves and therefore should be avoided (Bleakley and Hopkins, 2010). Physiological responses to cooling are known to differ between cryotherapy modalities and T_{sk} is not exempt as the initial reaction following cryotherapy application through peripheral cutaneous vasoconstriction (Johnson *et al,* 2005). This was further examined in publication 7 (Alexander *et al,* 2020), whereby positional differences also demonstrated variances in T_{sk} response between modalities and positional factions in a rugby union population. It is not always possible however to control accurately the temperature of some cooling modalities, hence the interest around the investigation of traditional and contemporary cooling modalities and quantification of their efficiency through thermology.

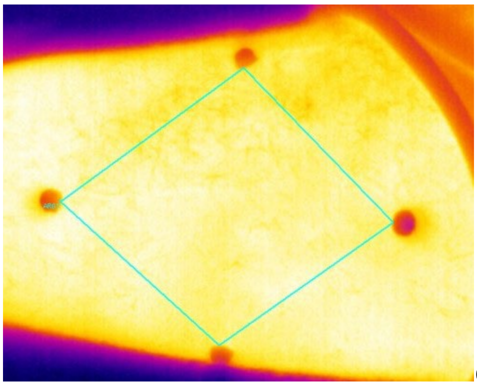
T_{sk} is of note in the literature specifically observed over rewarming recovery periods after cryotherapy removal (Costello *et al,* 2012a; Alexander *et al,* 2018; Alexander and Rhodes, 2019). Several studies allude to this type of investigation through thermology for both immediate T_{sk} response (Alexander *et al,* 2019) and suggest its importance as a measure of cryotherapy efficiency followed up over a period of timepoints (Kim *et al,* 2002; Kennett *et al,* 2007; Klimek *et al,* 2011; Alexander *et al,* 2018; 2019; Alexander and Rhodes 2020). The majority reporting that T_{sk} does not return to baseline after cryotherapy exposures over variable rewarming periods (20-120 minutes). Common applications apply cooling intermittently; to achieve therapeutic benefits research agrees this process should consider the cycles of skin temperature rewarming. Costello *et al,* (2012a) suggests therapists to be cognisant of this and the subsequent potential for injury due to deeper tissue changes that continue through a rewarming period that may be monitored through T_{sk}. Several relationships between T_{sk} and other structures have been highlighted in the literature, such as T_{im} (Hardaker *et al,* 2007) and NCV (Halar *et al,* 1980; Greathouse *et al,* 1989). Differences in relationships are reported however with a negative quadratic relationship for intramuscular temperatures in relation to T_{sk}, compared to a linear relationship noted for NCV. Evidently, this contributes to the confusion in the field of cryotherapy, with practitioners unaware of this relationship to decipher what are optimal applications.

1.5.2 Quantification of T_{sk} *Responses*

T_{sk} is illustrative of the interface between environment and body (Taylor *et al,* 2014). The rationale for the measurement of T_{sk} is partly to quantify thermal gradients and often perturbations following local cooling to assess vascular responses (Davey *et al,* 2013; Taylor *et al,* 2014). Furthermore, clinically relevant investigations in relation to superficial tissue temperatures are reflective of pathological state of injury, with the extent of thermal presentation associated with severity of injury condition (Eglin *et al,* 2013; Taylor *et al,* 2014). In sports and exercise medicine the measurement of T_{sk} following cooling is deemed important as a diagnostic parameter pertaining to physical attributes (Cholewka *et al,* 2012). That said, it is not always an applicable or accessible method used commonly within a sport environment per se. It is acknowledged that systemic bias between infrared and conductive measures exists (Bach *et al,* 2015), although the quantification of T_{sk} through infrared thermography (IRT) following cryotherapy applications is an accepted measure to enumerate the effectiveness of cooling modalities (Kanlayanaphotporn *et al,* 2005; Costello *et al,* 2012a). The presence of sweat and environmental heat influences on infrared thermal imaging was considered for those studies that are conducted with an applied perspective in mind. Further, blood flow, adipose tissue and metabolic rate contribute to the properties of subcutaneous tissue layers ensuing the dynamic nature of tissue temperature and variations in T_{sk} (Manier *et al,* 2015). That said, to ensure consistency across the thesis, quantification of T_{sk} appears useful to consider in the investigation of cryotherapeutic effects and acknowledges methods explored in literature (Selfe *et al,* 2006; Matos *et al,* 2015). Evidence supports the use of IRT for the assessment of cryotherapy applications in research (Costello *et al,* 2012a) to quantify physiological functions (Bandeira *et al,* 2012). Matos *et al.* (2015) reports thermography through thermal imaging technology an efficient method to monitor T_{sk} by detection of infrared radiation emitted from the skin surface (Moreira *et al*, 2017). Costello *et al.* (2012a) in agreement recommend thermal imaging due to its accuracy and reliability in collecting skin temperature data.

A non-invasive method of quantifying $T_{sk,}$ thermal imaging, non-ionizing with no contrast and painless providing high-resolution images subsequently results in high accuracy output (Herrera *et al,* 2010; Matos *et al,* 2015). Although thermocouples, and wireless sensors provide other methods that access $T_{sk,}$ these are classified as contact devices (Merrick *et al,* 2003; Gregson *et al,* 2013; Manier *et al,* 2015; Matos *et al,* 2015). In contrast, non-contact methods such as thermal imaging via infrared cameras often pose advantageous compared to these methods as they are non-invasive (Matos *et al,* 2015). Errors in data often noted when applying subjective or contact methods should be considered prior to choosing the quantification technique of cooling (Manier *et al,* 2015). Other benefits of T_{sk} measurement through IRT is the ability to collect a large area of temperature data and quick quantification without any disruption of accuracy that may occur through other TI devices that are in contact with the skin during data capture (Boetcher *et al,* 2009).

Rather than a spot measurement to calculate temperature over an anatomical area post cooling, studies often present a region of interest(s) (ROI) when using IRT methods (Plassman *et al,* 2006; Selfe *et al,* 2014; Costello *et al,* 2012a; Alexander *et al,* 2018; Vellard *et al,* 2016). A ROI is a consistent anatomical frame that used to assess temperature between and within subjects, usually constructed as a quadrilateral region over a pre-determined area of skin devised using inert markers over anatomical landmarks (Selfe *et al,* 2006; Costello *et al,* 2012) (Figure 4). Defining a ROI is a popular method of analysis (Gold *et al,* 2004; Owen *et al,* 2018) whereby the mean temperature from within the ROI area is extracted (Selfe *et al,* 2006; Owen *et al,* 2018). Emissivity of the camera used for thermal imaging is important and literature suggests an emissivity setting of 0.97-0.98 (Steketee, 1973; Cholewka *et al,* 2012; Costello *et al,* 2012a; Moreira *et al,* 2017). In addition, the distance of the camera in relation to the region being assessed and environmental ambient temperature are factors that should be considered during IRT (Ring and Ammer, 2000; Moreira *et al,* 2017). Distance between camera and the area being thermographed affects resolution of pixels, whereas ambient room temperature may induce sweating or shivering of the subject and likely to affect recorded T_{sk} (Moreira *et al,* 2017). Although these three factors inevitably affect the erroneous recording of accurate skin temperature (Moreira *et al,* 2017), several studies fail to report such settings. As a result, the requirement of method standardisation to assess T_{sk} are advocated in many previous publications (Plassman *et al,* 2007; Costello *et al,* 2012a; Moreira *et al,* 2017).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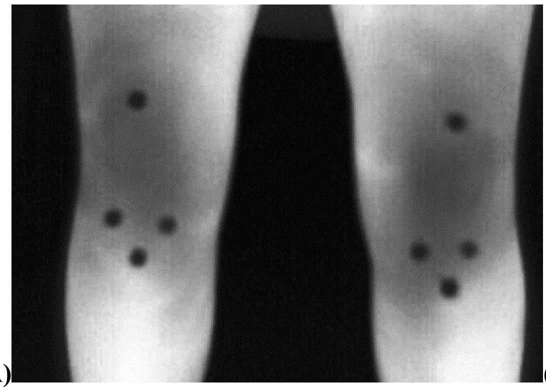
(B)

Figure 4. (A) Region of Interest (ROI) over the anterior aspect of the non-dominant limb determined by percentage circumference and anatomical location points (Taken from: Alexander *et al,* 2020). (B) An example of an anatomic marker system (AMS) over the anterior knee (Taken from: Selfe *et al,* 2006).

Several variables can impact on thermoregulation, such as physical characteristics, fitness, medicinal treatments, application of acclimatisation periods, ambient environment temperature, emissivity, calibration, setup and maintenance of the camera (Plassman *et al,* 2007; Formenti *et al,* 2013; Marins *et al,* 2014; Moreira *et al,* 2017). Guidelines have developed recently to ensure the most efficient use of IRT in sports and exercise medicine research (Moreira *et al,* 2017). The proposal of a 15-point checklist entitled "Thermographic Imaging in Sports and Exercise Medicine" (TISEM) (Figure 5) devised following a Delphi study, to help standardise analysis of skin temperature and collection of data across studies using IRT (Moreira *et al,* 2017). Publication 8 in the current body of work provides a commentary on the use of thermography for defining efficiency of cryotherapy modalities. The narrative of that work supplements the positive acknowledgement of this technique with reference to applications of cooling in sporting populations and environments to underpin the commonality of thermology application throughout most publications presented in this thesis. Studies produced in the thesis prior to the guidelines produced by Moreira *et al,* (2017) ensured the control of IRT through replication of previously validated methods of T_{sk} quantification through IRT (Matos *et al,* 2015).

1) The relevant individual data of the participants must be provided. Note: These could include, but are not limited to, age, sex, body mass, height, body mass index, ethnicity and whether they are smokers or not. An indication of physical activity profile (e.g. frequency, duration, intensity, and activity description) should be reported.
❑ Yes ❑ No ❑ Unclear
2) Participants should be instructed to avoid alcohol beverages, smoking, caffeine, large meals, ointments, cosmetics and showering for four hours before the assessment. Also, sunbathing (e.g. UV sessions or direct sun without protection) should be avoided before the assessment. Note: This should be confirmed verbally before the assessment. The use of any medicinal treatments or drugs should be recorded. Any condition that could not be avoided should be reported.
❑ Yes ❑ No ❑ Unclear
3) Extrinsic factors affecting skin temperature (e.g. physical activity prior to the assessment, massage, electrotherapy, ultrasound, heat or cold exposure, cryotherapy) should be clearly described.
❑ Yes ❑ No ❑ Unclear
4) Ambient temperature and relative humidity of the location where the assessment took place must be recorded and reported as mean ± standard deviation.
❑ Yes ❑ No ❑ Unclear
5) The assessment should be completed away from any source of infrared radiation (e.g. electronic devices, lightning) or airflow (e.g. under an air conditioning unit). Note: Any condition that could not be controlled should be reported.
❑ Yes ❑ No ❑ Unclear
6) The manufacturer, model and accuracy of the camera used should be provided. Note: When available it is recommended to provide the maintenance information of the equipment (e.g. when and where it was completed the last calibration).
❑ Yes ❑ No ❑ Unclear
7) An acclimation period in the examination room should be completed. Note: This item is only applicable for initial baseline measurements or basal analysis.
❑ Yes ❑ No ❑ Unclear
8) If necessary the camera should be turned on for some time prior to the test to allow sensor stabilization following the manufacturer's guidelines.
❑ Yes ❑ No ❑ Unclear
9) Conditions of image recording such as mean distance between object and camera, percentage of the region of interest within the image should be detailed.
❑ Yes ❑ No ❑ Unclear
10) The camera should be positioned perpendicular to the region of interest.
❑ Yes ❑ No ❑ Unclear
11) Emissivity settings of the camera must be reported. Note: 0.98 of emissivity is suggested for a dry clean skin surface.
❑ Yes ❑ No ❑ Unclear
12) The time of day at which the images were taken should be reported.
❑ Yes ❑ No ❑ Unclear
13) The standard body position of the subject and the regions of interest must be well described and appropriately selected. A visual example (with temperature scale presented and scale of colors properly configured) is recommended.
❑ Yes ❑ No ❑ Unclear
14) If the skin is dried (e.g. to remove surface water), the drying method should be clearly described.
❑ Yes ❑ No ❑ Unclear
15) The evaluation of thermograms and collection of temperature from the software should be clearly described.
❑ Yes ❑ No ❑ Unclear

Figure 5. The Thermographical Imaging in Sports and Exercise Medicine (TISEM) 15-point checklist (Moreira *et al,* 2017).

1.5.3 Skin Surface Sensitivity (SSS) Responses to Cryotherapy

Somatosensory mechanisms in relation to proprioceptive feedback are of importance when contemplating the effect that local cooling applications may have. Knowledge on the effect of cooling via common cryotherapeutic modalities on skin surface sensitivity (SSS) is lacking, although reductions in SSS following crushed ice application over the anterior knee are reported in publication 6 (Alexander *et al,* 2019) reducing the gap of knowledge in this area. Specifically, results demonstrated an anticipated larger reduction over the medial aspect of the knee, compared to other regions and SSS did not return to base line measures following a 20-minute rewarming period. In addition, T_{sk} did not return to baseline either over the rewarming period of investigations. In another study, tactile threshold sensitivity found to decrease followed cryotherapy applications of varied dose exposures to the upper limb (Gregório *et al*, 2014). Studies report the use of crushed ice (Alexander *et al,* 2019), and gel pack (Gregório *et al,* 2014) respectively, therefore further investigations are advised due to the lack of comparable studies. Alexander *et al,* (2019) conclude reductions in SSS and T_{sk} is of importance and sports medicine practitioners should consider the implications of such reductions on the demands of functional movement post-cooling, however further investigations are required.

The impact of impaired neuromuscular feedback mechanisms via reduced SSS may elevate injury risk in the lower limb, caused by modifications to neural pathways facilitating detrimental influences on JPS. Evaluation of this relationship is debated; presumptions however may speculate that compensation from deeper joint receptors may counteract the hypothesis that increased injury risk is heightened due to reduced SSS thresholds, a consideration important to sports medicine and performance practitioners and one which requires further investigations to determine in sports populations.

1.5.4 Quantification of SSS Response

Sensitivity levels of the skin surface following cooling is quantifiable through esthesiometers, which consist of nylon monofilaments of varied thickness relating to a scope of predetermined sensitivity levels, through reproducible buckling stress (Moharic and Vidmar, 2014). An inexpensive and portable test for tactile thresholds, monofilaments are well documented as reliable and widely used (Dros *et al,* 2009; Moharic and Vidmar, 2014). Typically, monofilaments range from 0.05g to 300g, and recent publications allude to their use in the measurement of SSS following local cooling to determine perceived tactile intensity (Georgio *et al,* 2014; Alexander *et al,* 2019). Other sensitivity mapping acknowledged in the literature base include the foot (Hennig and Sterzing, 2009) and commonly this method / location of tactile threshold appears useful in the assessment of peripheral neuropathy (Dros *et al,* 2009) and diabetic presentations (Baraz *et al,* 2015). The quantification of sensitivity and tactile feedback through monofilaments following interventions such as cryotherapy supports investigation of another physiological effect following cooling. The intention behind study 6 in this thesis investigated SSS over a rewarming period alluded to the uncertainty of how cooling may affect SSS response and thus have an impedance over feedback mechanisms at the knee on return to play following cooling. The study supported the use of monofilaments (Aesthesio® Precise Tactile Sensory Evaluator, Dan Mic Global, LLC, USA) in the measurement of SSS after cooling application.

1.5.5 Perceptual Responses to Cryotherapy

Regardless of applying cryotherapy locally or systemically for sports injury management or as a recovery strategy, psychological factors influence the mediation of individual response to various types of cooling (Schaal *et al,* 2015). Psychological monitoring following cooling interventions have included the perception of cold and emotional reaction through thermal comfort (TC) and sensation (TS) assessment (Costello *et al,* 2012b; 2014a) and consistent throughout THEMES 3, 4 and 6, or the subjective perceived recovery status (Heidari *et al,* 2019), and perception of delayed onset muscle soreness (DOMS) (Holmes and Willoughby, 2016) represented in THEME 5 (Section 1.7).

The subjective assessment of cold, in terms of TC or TS response to local or systemic cryotherapy applications are reported across several studies (Smolander *et al,* 2004; Costello *et al,* 2012b; 2014; Selfe *et al,* 2014; Cuttell *et al,* 2017; Alexander *et al,* 2020b; 2020c). TS response to cold exposures is quantified through questions with answers reported on a nine-point standardised scale (ISO 10051). The protocol of asking, '*How are you feeling now?',* and options of response being; *4 = very hot, 3 = hot, 2 = warm, 1 = slightly warm, 0 = neutral, -1 = slightly cool, -2 = cool, -3 = cold, -4 = very cold.* Thermal Comfort is rated on a five-point scale after asking *'Do you find this,'* with the options to answer being *0 = comfortable, 1 = slightly uncomfortable, 2 = uncomfortable, 3 = very uncomfortable, and 4 = extremely uncomfortable.* Costello *et al,* (2014b) reported a significant reduction in thermal sensation following exposures of WBC and CWI, in line with previous investigations by Westerlund *et al.* (2003), and Somolander (2004). These perceptual scales have been useful indicators of such differences in gender response to WBC due to body composition factors for example (Cuttell *et al,* 2017). Demonstrations of greater insulating responses in females consequently result in significant differences in TS compared to males immediately following WBC exposures (Cuttell *et al,* 2017). In other studies, TC and TS responses have differed significantly between cryotherapeutic modalities (Alexander *et al,* 2020b; 2020c). Findings as such implicate the choice of modality for optimal beneficial response to cooling in sport, determined by perceptual preference in association with modality efficiency for example. Perceptual response to cooling is not limited by the perception of temperature sensation or comfort. Perceptual wellbeing responses to cryotherapy as a recovery strategy are appraised in THEME 5 (Section 1.7), as a key contributory factor when considering the multifaceted responses to cooling, introduced at the beginning of the work.

1.5.6 Nerve Conduction Velocity (NCV) Responses to Cryotherapy

The study of nerve conduction (NC) as a physiological effect in relation to and response of skin temperature changes have an important role in evaluation of cooling effect. Quantified generally through electromyogram, NC studies quantify nerve conduction velocity (NCV) in peripheral nerves from the speed of propagation of action potentials along large, myelinated axons (Kane and Oware, 2012). Location application of superficial electrodes to quantify NCV is dependent on neural anatomy and study interest with previous investigations (Herrera *et al,* 2010) referring to Oh *et al.* (2002). Previous quantification of NCV provides literature on objective and qualitative data on neural function (Dhavalikar *et al,* 2009; Kane and Oware, 2012). The velocity of nerve impulse can be influenced by temperature changes (Dhavalikar *et al,* 2009; Herrera *et al,* 2010). Therefore, the assessment of NC represents a reliable and established method of analysis for cryotherapeutic modality efficacy, as nerve tissue is a direct target for the intervention of cooling for the management of muscle pain (Herrera *et al,* 2010). NCV is reported to reduce following superficial cooling at the ankle (Algafly and George, 2007), and amplitude increases in muscle and nerve potentials are noted (Dofman and Bosley, 1994; Dhavalikar *et al,* 2009). In a practical sense understanding the effects of decreased NCV attributes to the support of cryotherapy application for pain management (Sauls, 1999; Algafly and George, 2007). That said, disruption of neuromuscular response is not well understood and important to underpin functional response for emphasis in practice. The slowing down of NCV following cooling is thought to be due to a delay in sodium channel opening, subsequently producing a slower sodium influx and increased latency of conduction, which consequently reduces the permeability of nerve axons during the excitation phase (Kimura, 1989; Dhavalikar *et al,* 2009). The linear relationship between T_{sk} and NCV reported in previous electrophysiological studies (Halar *et al,* 1980; Greathouse *et al,* 1989), make suggestions as to factors which influence such a relationship. These include nerve depth, age, subcutaneous surrounding tissue and type of cryotherapy modality applied in practice (Herrera *et al,* 2010). Different responses occur dependent on nerve fibre type, such as motor and sensory. Per degree of skin temperature reduction, motor NCV reduces by 1.1-1.5 m/s/°C and sensory by 1.4-2.6 m/s/°C (Knight, 1995). This knowledge challenges the understanding of achieving optimal physiological outcomes in response to cryotherapy applications, influencing future studies. In addition, the proposal of a linear relationship between T_{sk} and NCV contrasts with the quadratic relationship observed in deeper tissues as proposed by Hardaker *et al,* (2007) discussed earlier. Electrophysiological investigations suggest an inverse linear relationship between skin temperatures and NCV, in relation to compound action potential (Halar *et al,* 1980; Halar *et al,* 1981; Greathouse *et al,* 1989). This association subsequently achieves resultant inverse response in action potential, latency and amplitude (Dofman and Bosley, 1994). Ultimately, different tissues have different relationships in response to cold, which is one of the reasons for confusion in the field of cryotherapy.

A body of literature investigating differences in cold modalities and their effect on nerve parameters exists (McMeeken *et al,* 1984; Nadler *et al,* 2004; Algafly and George, 2007; Herrera *et al,* 2010; 2011). The impact on variability in NCV response to cold however suggests dissimilarities between cooling modalities are important to quantify to determine optimal applications that affect neural responses. Herrera *et al,* (2010) reported CWI to be an optimum modality to induce change in motor conduction and hypertonicity, when compared to ice massage and ice pack, but the authors confirm all three modalities caused a hypoalgesia response, supporting previous literature (Chesterton *et al,* 2002; Kennet *et al,* 2007). The impact of such findings for sports medicine practitioners are important for the informed choice of application based on physiological or therapeutic desires of treatment. As analgesia is indicative of a response to cold and a therapeutic benefit, it is critical to determine the subsequent effect of analgesia, especially pitch side following local cooling applications. The findings by Herrera *et al,* (2010) are therefore important two-fold; CWI is unlikely to be used within a competitive fixture pitch side; 2) therefore, investigation here focuses on ice pack application and neural responses including analgesia reflecting the resultant effect on proprioceptive input and maintenance of dynamic stability, not only pain relief in relation to decreased NCV.

Several studies discuss the mechanisms behind the physiological response of analgesia induced by cryotherapy (Bugaj 1975; Westerlund *et al,* 2003; Nadler *et al,* 2004; Algafly and George, 2007). The hypoalgesia response is hypothesised around various contexts such as the pain gate theory (Melzack and Wall, 1984) via 'closing of the gate', the activation of inhibitory control mechanisms, nociceptor activation threshold increases or modulation of pain through central nervous system (CNS) descending pathways (Herrera *et al,* 2010). Increased pain threshold and tolerance are associated with decreases in NCV following cryotherapy (Algafly and George, 2007), and although a desired therapeutic benefit of acute sports injury management, the deleterious effects of reduced nerve parameters are evident from prolonged cooling (Malone *et al,* 1992; Herrera *et al,* 2010). Consequently, it is the effect of reduced NCV following local cooling in respect to maintaining dynamic stability that is of interest here, (section 1.5.6 pg. 106), as this may have significant implications on injury risk if returning an athlete to the field of play in such circumstances whereby local cooling has induced analgesia. Consensus in the literature is still lacking and therefore investigations that observe functional control responses of stabilising structures in the lower limb following cooling applications are essential to optimise cooling protocols in sport. Furthermore, it is essential that contemporary cryo-compressive methods of cooling within a sporting context are investigated, of which the following section addresses.

1.6 THEME 4: CONTEMPORARY CRYOTHERAPY APPLICATIONS AND RESPONSES

This section critiques the contemporary applications of compression and cryotherapy, recognised as cryo-compression, common practice in the management of sports injuries and recovery. Physiological and psychological responses in relation to the topic scope of THEME 4 are appraised here extracted from the current evidence base, representing the publications in Chapter 3, (pg. 139). When collapsed into context this refers to the physiological responses to cryo-compression devices, including T_{sk} and SmO_2; and psychological responses to cryotherapy applications recognising the perceptual wellbeing of the athlete.

1.6.1 *Contemporary Cryotherapy Approaches for Sports Injury*

In an applied setting confusion still exists around optimal applications of local cryotherapy to ensure maximal benefits and outcomes for the athlete. The translation of research into applied practice is one of the greatest barriers (Buchheit, 2017; Sandbakk, 2018; Haugen, 2019; Coutts, 2020; Buchheit *et al,* 2021). Contemporary perspectives on when or if to apply cooling for sports injury management remain controversial with opposing literature refuting (Dubois and Esculier, 2020) or supporting (Long and Jutte, 2019) applications in acute sport injury management. There is a clear need to clarify 21st century applications of this modality. Publication 9 (Alexander *et al,* 2021) presented as part of THEME 4 presents a communication around these discussions, drawing on those recent propositions (Long and Jutte, 2019; Dubois and Esculier, 2020) and suggests the need for rigorous examination of real-world practices of cryotherapy in sporting contexts. This is not just representative of study designs which reflect modern day application of cooling, such as cryo-compressive devices, periodisation or dose-response. Individual athlete response alongside the demands of the competitive season, team ethos, philosophies and tactical demands should be considered to provide research in topics that support the needs of the working practitioner. Most recently this approach to research development in the field was highlighted by Buchheit *et al,* (2021). In brief findings suggest research outputs that are useful to high-performance environments and those that work in them must, and most importantly, reflect the assessment of injury risk and the improvement of mitigation strategies (Buchheit *et al,* 2021). In consideration for future approaches in applied cryotherapy research the same should likewise be applied. To determine this, quantification of cryotherapeutic effects on the four categories of response (*biomechanical, biochemical physiological, psychological*) are important considerations for future work. At the time of writing no studies fully address this or implement this approach to their study designs.

1.6.2 *Physiological Responses to Cryo-Compression Applications*

The art of combining cooling and compression is not new, although technological advancements in cryo-compressive devices are a common application in sport environments. Literature advocates that magnitude of cooling on the reduction of skin surface and intramuscular temperature (T_{sk}, T_{im}) can be aided with the addition of external static compression (Merrick *et al,* 1993; Knobloch *et al,* 2006; Janwantanakul, 2006; Tomchuck *et al,* 2010). A lack of understanding regarding optimal protocols regarding collective cryotherapy and compression however is evident despite technological developments in cryo-compressive modalities (Alexander *et al,* 2020). Such examples include the Game Ready®, SquidGo, and Swellaway® devices that provide pneumatic compression options alongside cooling (Alexander *et al,* 2020c). Other adaptations of compression include fabric wrap adapted to joints or muscular regions such as the Cryo/Cuff® or HyperIce manual compression, or traditional cling wrap used to hold ice packs in place, frequently acknowledged for its effectiveness during investigations of cryotherapy applications (Merrick *et al,* 1993; Janwantanakul, 2009). Although the pressure (mm Hg) of fabric or cling wrap cannot be controlled such like electronic devices, consequently magnitude or quantification of compression via those applications is underreported in studies. Confusion therefore exists on the differences between cryo-compressive devices for optimal application.

There are several aims of compression that traditionally stem from the established physiological influences it has on the lymphatic system (Kraemer *et al,* 2004; Ostrowski *et al,* 2019). An early scientific study on human patients by Martin *et al.* (2001) documents significant declines in knee T_{ia} following the combination of ice and compression. Agreement demonstrated more recently in a meta-analysis by Song *et al.* (2016), also suggests early combined cryotherapy and compression benefits postoperative knee surgery management. In the latter stages of rehabilitation however, the authors report no differences among studies comparing cryotherapy with compression to cryotherapy alone for intra-articular joint cooling but the recommendation for more studies is emphasised (Song *et al,* 2016). Translated into the expectations of enhancing local cooling modalities, Kraemer *et al,* (2004) acclaims that compression is thought to reduce space for the accumulation of swelling and provide mechanical support for injured structures. Other literature advocates that compression increases the magnitude of reduction in T_{sk} targeted by local cooling modalities (Capps, 2009; Tomchuck *et al,* 2010; Du Pont *et al,* 2017). Consequently, it is considered that different levels of pressure (mm Hg) therefore may influence the magnitude of cooling (Tomchuck *et al,* 2010; Rigby *et al,* 2017), whereas other studies report no differences (Kwiecien *et al,* 2019) revealing further controversy in the impact of concurrent applications of cryotherapy and compression.

Given the need for further investigation, publication 11 in this thesis investigated various levels of pressure in two contemporary cryo-compressive applications (Chapter 3, Theme 4, pg. 185). Findings from that publication support greater magnitudes of cooling quantified through $T_{sk,}$ of which are associated with greater compression settings (mm Hg) and changes in physiological measures including Muscle Oxygenation (SmO_2) (Alexander *et al,* 2020b). SmO_2 is identified in several other investigations which explore the effects of cryotherapy indicating reductions in SmO_2 following cold-water immersion (CWI) (Ihsan *et al,* 2013; White and Wells, 2013; Yeung *et al,* 2016; Hohenauer *et al,* 2019). Conversely, isolated external compression without cooling is reported to increase SmO_2 (Neuschwander *et al,* 2012; Nandwana *et al,* 2019). Combining cooling and compression and its effect on a physiological parameter such as SmO_2 is therefore of interest and under contention, yet useful to inform current practices where cryo-compressive devices are applied. Indicators of metabolic muscular activity can be collected through non-invasive techniques with such devices as MOXY Sensors (MOXY, Swinco, Zurich, Switzerland) which offers ratio of oxyhaemoglobin concentration to total haemoglobin in the muscle as a useful real-time indicator for physiologic feedback. Publication 10 identified initial increases in SmO_2 following cryo-compressive exposure in both modalities (Game Ready® and Squid®) followed by declines, compared to an application of no compressive adjunct. Greater changes in SmO_2 were associated with higher compression levels highlighting important dose-response relationships for cryo-compressive applications. That said, no other literature at the time of writing was available to support or refute these findings, and therefore further investigations are required to be able to develop understanding of such responses which implicate development of optimal cryo-compressive applications for sporting environments that are advantageous to the athlete.

Various types of compression are reported within recent studies such as intermittent, consistent, pneumatic, with different pressure settings (low, medium, high) recorded (Mora *et al,* 2002; Knobloch *et al,* 2007). Inconsistencies or nil reporting of such details are evident when comparing study methods, highlighted in publication 10 (scoping review) in this thesis (Alexander *et al,* 2021c). Despite several studies reporting on these parameters of combined cryotherapy and compression, a failure to recognise the non-existent panacea of individual protocols somewhat curbs the true understanding of the implications of cryo-compressive combinations. It is difficult due to high variability in the approach of scientific enquiry and complexity of contrasting methods to fully elucidate interaction effects (Alexander *et al,* 2021c). The agreement however alludes to the suggestion that compression, as an adjunct to cryotherapy is positive in nature. Consideration of the technological advancements in cryo-compressive devices should be recognised and further examined in future research. Without however, a clear understanding on dose-response in individual concepts of cryotherapy and compression the same challenges will continue to limit the current evidence base for cryo-compression applications in sport to develop optimal protocols.

1.7 THEME 5: MULTIFACETED RESPONSES TO CRYOTHERAPY AS A RECOVERY STRATEGY IN ELITE SPORT

Recovery facilitation in sport often alludes to the application of cryotherapy in its various forms, with the aim to strategically maximise an athlete's readiness to train or compete. A multifaceted restorative process and relative to time, recovery is modulated by individual response to stress, external load and can be dictated by the demands of sport and competition (Kellman *et al,* 2018). Yet a lack of consensus or guidelines contribute to the practicality of cryotherapy for optimising recovery response. The current stance on cryotherapy as a recovery strategy in sport is critiqued in the following section relevant to THEME 5. The evidence reviewed includes modes of cooling and the effects on multi-measures of performance, such as inflammatory markers, muscle oxygenation, skin and core temperature, psychological comfort and sensation measures in terms of thermal temperature, perceptual and individual considerations to quantify the effectiveness of cryotherapy for recovery; and the impact of its application on an athlete's readiness to play and train or reduction of injury risk in elite sport. In response to the large gap apparent in the scientific evidence, THEME 5 builds on the preceding themes by considering the inclusion of all 4 categories of response (*biomechanical, biochemical, physiological, psychological*) (Figure 1, pg. 41) utilising elite sport populations.

1.7.1 Cryotherapy Strategies for Recovery and Performance in Elite Sport

Physiological impairments, fatigue, EIMD and reduced muscle function following prolonged exercise are acknowledged (Mawhinney and Allan, 2018). A fundamental principle of exercise training is recovery and optimal strategies to maximise it are essential for the training-adaptation cycle, with the goal of homeostasis restoration (Peake, 2017; Kellman *et al,* 2018). Consequently, investigations with a focus on strategies for recovery are of interest including the role and effects of cryotherapy (Peake, 2019; Nogueira *et al,* 2020). Modalities used for recovery are vast and varied between individual athletes and teams (Altarriba-Bartes *et al,* 2020). Post-exercise recovery strategies commonly include the popular application of cryotherapy in its various forms (White and Wells, 2013; Hohenauer *et al,* 2015; Bongers *et al,* 2017; Peake, 2019; Ihsan *et al,* 2020), with the theoretical basis being to reduce perception of fatigue in biomechanical markers (Dupuy *et al,* 2018), delayed onset muscle soreness (DOMS) (Machado *et al,* 2016; Dupuy *et al,* 2018) skin (Alexander *et al,* 2020) and core body temperature (Stephens *et al,* 2018). Many physiological effects of cooling for recovery of performance in sport are reported (Poppendieck *et al,* 2013; White and Wells, 2013; Hohenauer *et al,* 2015; Rose *et al,* 2017; Lombardi *et al,* 2017; Nogueira *et al,* 2020), yet it is the enhanced perceptual responses following recovery that substantiate the positive evidence for recovery implementation strategies (Broatch *et al,* 2014). Although the coherence between evidence and practice can be confusing and consequently the optimisation of prescribed strategies and the design of multifaceted recovery protocols are limited (Thorpe, 2021). Consequently, the impact on decision making related to applying optimal protocols of cooling for recovery is evident.

Typical modes of cryotherapy for recovery in elite practice often include cold-water immersion (CWI), whole-body cryotherapy (WBC) or pneumatic cryo-compressive devices such as the Game Ready® as one example. CWI and Game Ready® are investigated in publications 5, 11-13 in the thesis, through a variety of methodologies which determine their effects on multi-measures of performance post fatiguing exercise in elite athletes. To date publication 12 (Alexander *et al,* 2021d) is the first to explore the immediate effects of the Game Ready® device in an elite youth population on multiple performance metrics mid-competitive season. Reductions in performance metrics following cooling in this study are indicative of supporting further research on periodisation and frequency of this recovery strategy if effective neuromuscular responses are required in the immediate short term.

1.7.2 Recovery Responses to Cryotherapy Strategies in Elite Sport

The application of CWI aims to reduce exercise-induced muscle soreness (EIMS), skin, muscle tissue temperature and restore metabolic, neural or mechanical processes (Hohenauer *et al,* 2015; Mawhinney and Allan, 2018). Reductions in delayed onset muscle soreness (DOMS) through the utilisation of CWI (Machado *et al,* 2016) is considered to provide functional recovery benefits and improved performance (Allen and Mawhinney, 2017). A passive recovery method of cooling such as CWI, does not induce muscle activation, and is considered a positive adjunct for recovery of glycogen stores post-exercise (Gregson *et al,* 2013; Mawhinney and Allan, 2018). Recently Mawhinney and Allan, (2018) reported that an increase in studies relating to temperature changes have tried to quantify the impact this has on glycogen kinetics to help determine the effects on muscle recovery. The authors conclude that an increased rate of glycogen synthesis resulting in improvements in muscle function correlate to higher intramuscular temperatures, compared to cooler. This would support recent findings in literature reporting on the effects of superficial cooling on muscle function, whereby muscle function is negatively affected by lower intramuscular temperatures (Torres *et al,* 2017; Rhodes and Alexander, 2018; Alexander and Rhodes, 2019).

These findings denote a lack of impact of CWI on the post-exercise inflammatory and cellular stress response and need careful attention when translated into practice. Although some findings suggest cooling presents inadequate cellular responses post-exercise in recent investigations for recovery (Peake *et al,* 2017), others indicate that CWI may be useful within competition settings, particularly those requiring a short turn-around (such as tournament situations, athletic meets and cycling tours), or in high environmental temperatures, to reduce inflammatory responses (Allan and Mawhinney, 2017). There remains however, a lack of justification for using CWI regularly during a 'pre-season' or preparation phase, particularly where the goal includes a hypertrophic response, due to the potential of dampening the adaptive response to training (Roberts *et al,* 2015). Consideration of the aims of a recovery session presents a determining factor in the suitability of cold modalities options to aid optimum post-exercise recovery (Peake, 2017; Mawhinney and Allan, 2018). Currently, further investigation into the correct periodisation of CWI with recovery programmes requiring individualised approaches. Noted in recent research perceived muscle soreness is reduced consistently after exposure to CWI protocols (Glasgow *et al,* 2014; Fonseca *et al,* 2016; Lindsay *et al,* 2017). Furthermore, the effect of cryotherapy on the cardiovascular system induces physiological responses, which include reductions in cardiovascular strain, limb swelling and increases in cardiac parasympathetic activity and muscle oxygenation (Ihsan *et al,* 2016). All considered these parameters of post-exercise restoration are vital and positively correlated to a greater recovery.

Secondary effects of CWI as suggested by Peake *et al,* (2017) remain speculative with regards to optimum recovery through adaptation to exercise. Cumulative strength training effects may be depleted due to the attenuation of muscle adaptation following CWI protocols; however, Peake (2017) suggests that endurance performance may be enhanced due to the stimulation of molecular response. Controversy therefore over the immediate application of CWI, following fatigue induced training sessions may cause attenuation of adaptive physiological responses. The aim of application however differs by contrast and purpose here. Applications of cooling immediately after adaptive training for greater 'recovery' may subsequently affect desired player adaptations required for the demands of the sport (Crystal *et al*, 2013) or strength gains required for improved performance (Roberts *et al,* 2015). During periods of competitive fixtures, this differs, with timing of protocols aimed at performance recovery and/or damage recovery. Previously authors have reported improvements in sport-specific activities such as sprint performance (Ingram *et al,* 2009). Most recently Peake *et al,* (2017) reported CWI to have no impact on inflammatory physiological measures compared to active recovery, and Roberts *et al*, (2015) suggested CWI can dampen the response to resistance exercise training. Periodisation of CWI and individual approaches for this type of application in practice is advised (Allan and Mawhinney, 2017). Publication 13 in the thesis considers periodisation in terms of CWI within a competitive season and findings of that study support the recommendation that multi-measures of performance alongside analysis of individual response should be considered to optimise applications of such mode (Alexander *et al,* 2021e).

Recommendations for the use of CWI based on biochemical, morphological and molecular responses in athletes suggests that medical and performance practitioners might reconsider its application following resistance training (Roberts *et al,* 2015; Peake *et al,* 2017). The effects of cryotherapy on biochemical markers however remain unclear due to several limitations noted in the evidence; with indirect blood markers employed, high risk of bias and limited comparisons of cooling to other forms of recovery (Méline *et al,* 2017). In contrast it appears that practitioners should not jump to the conclusion that CWI should be ruled out as a beneficial recovery strategy in practice altogether (Allan and Mawhinney, 2017; Ihsan *et al,* 2020). It appears that often the translation of findings into practice are not clearly defined across study conclusions, leading to inappropriate applications or periodisation of cooling in sporting contexts from mechanistic approaches. Current practices are often reliant on cryotherapy as part of readiness to train and play recovery approaches in elite sport settings. Contemporary studies recommend the investigation of biochemical responses to cryotherapy in its various forms to help determine optimal application and periodisation for recovery strategies in sport (Allan *et al,* 2019). In practice however this is less feasible to obtain within mid-competitive seasons. Further to this, Peake (2019) advises that investigation into optimal recovery should encompass the effects of multiple interventions captured in applied practice with the adoption of systematic comparisons of exercise protocols. This approach was considered in publication 13 in the thesis (Alexander *et al,* 2021e), yet it should be considered that characteristics in mode be controlled in early explorations to identify potential differences attributable to the differences in characteristics between modes. Henceforth the consideration to investigate one recovery mode and multi-measures of performance, in addition to individual response in terms of data analysis in publication 13 (CWI) and 15 (WBC). Findings from this publication suggest that group analysis may not optimally identify nor account for individual responses to recovery strategies such as CWI or passive recovery (PR) in this case (Alexander *et al,* 2021e). Furthermore, results in publication 13 advocate the application of multiple components of testing aligning to the recommendations in other literature (Chrismas *et al,* 2019).

Analgesic and placebo properties considered in sport recovery and are important physiological responses to consider, often induced through modalities such as CWI or whole-body cryotherapy (WBC) (Lombardi *et al,* 2017) (THEME 5, Section 1.7). Variability in the literature surrounding CWI for post-exercise recovery is noted by Stephens *et al,* (2016), suggesting a one-size fits all approach does not work. Parameters such as physical traits, individual characteristic responses to cooling suggest several factors may influence the efficacy, efficiency and effectiveness of CWI as a recovery strategy. A focus on the goals of the athlete, their training/competition schedule and environment is proposed alongside dose, duration and frequency of such applications. The period between CWI application and performance should be considered to maximise positive response and the objective of recovery prior to applications such as CWI should be specific to the desired outcome (Stephens *et al,* 2016).

Contemporary perspectives on the value to measuring psychological response for optimising recovery strategies in elite sport suggest the consideration of mental fatigue monitoring in athletes as a beneficial marker (Russell *et al,* 2019). Evidence implies that mental fatigue is undervalued in sporting performance analysis and research (Russell *et al,* 2019). Investigations on the effectiveness of cryotherapy recovery strategies should consider utilising such parameters alongside those of physical intention to identify whether relationships between levels of mental fatigue and the effectiveness of cryotherapy recovery strategies are influenced. This may support the development of individual approaches to the use and periodisation of cryotherapy as a recovery tool in elite sport settings.

To summarise, cryotherapy as a recovery strategy in sport is popular yet lacks definitive protocols advantageous for athlete performance demands required for readiness to train and / or play. This is due to variations in exercises protocols, modes of cooling, implementation of strategies, single measures of performance or physiological response or non-elite populations in laboratory settings. Frequency, dose-response and mode of cryotherapy require further investigation to optimise strategies of recovery using this intervention through a battery of applicable performance measures to optimise chronic adaptations to training, which may differ between sports and their demands. This would provide beneficial knowledge to practitioners in the field when devising protocols of cryotherapy for recovery.

1.7.3 Whole-Body Cryotherapy in Elite Sport

The therapeutic application of cold air in the region of between -110°C-140°C is a technique that most recently has dominated emerging literature in the remit of cryotherapy in sport from an injury, preparation and recovery perspective (Selfe *et al,* 2014; Bouzigon *et al,* 2016; Lombardi *et al,* 2017; Polidori *et al,* 2018; Haq *et al,* 2018; Jaworska *et al,* 2018; Hohenauer *et al,* 2019; Partridge *et al,* 2019; Wilson *et al,* 2019; Louis *et al,* 2020). Known as whole-body cryotherapy (WBC), this modality is described whereby the subject is entirely exposed to cold treatment via cryochambers that are usually divided into two or three compartments of varying temperatures between -10-160°C, with exposures of between 1-4 minutes common (Lombardi *et al,* 2017). Chambers can usually accommodate multiple athletes. Alternatively, PBC exposes the human body to roughly the same temperature ranges; however, the head/neck are not exposed to the cold conditions (Bouzigon *et al,* 2016). Previously thermal responses between WBC and PBC were reported as similar, with the fundamental differences being PBC can be less expensive and portable (Bouzigon *et al,* 2016), although portable WBC units are now commercially available and utilised within elite sport.

The application of WBC of extreme cold air for up to 4-minutes at temperatures noted above, are reported (Hausswirth *et al,* 2011; Fonda *et al,* 2014; Selfe *et al,* 2014; Louis *et al,* 2020). Evidently, dose-response relationships are an important factor in optimal protocol development for WBC applications (Haq *et al,* 2018). Dosage differs across the evidence, and the approach in publication 14 (Selfe *et al,* 2014) was to investigate dose-response, reporting a 2-minute exposure at -135°C optimal to induce changes for physiological responses to ensue, compared to 1 and 3-minute exposures. Fonda *et al,* (2014) agreed stating an exposure for longer than 2.5 minutes failed to induce any further thermal response or beneficial effects, and exposure over 4-minutes are not recommended due to safety (Bleakley *et al,* 2014; Bouzigon *et al*, 2016). Interestingly, Haq *et al,* (2018) questioned the rationale for proposing a 2-minute exposure as being ‘optimal’ compared to 3 minutes. This was due to peripheral limb venous shutdown, and despite T_{sk} being lower after a 3-minute exposure, other variables demonstrated minimal change (tissue oxygenation) (Selfe *et al,* 2014). Consequently, the same benefits can be achieved across several variables without having to reduce tissue temperatures greater or cause peripheral venous shutdown, the approach is surely therefore more advantageous to the athlete. The longest dose of WBC reported in literature is 3-minutes and 40 seconds (Costello *et al,* 2012b), though similar physiological changes were again noted after shorter durations of exposure (Hausswirth *et al,* 2013; Mawhinney *et al*, 2017). Studies typically report a 3-minute dose, although optimal dose and number of exposures are debated that influence the beneficial performance or recovery of an athlete (Malone *et al,* 2021). Further research is required taking consideration of multiple variables and measures that appropriately represent relevant key performance indicators (KPI). The use of WBC is becoming a typical feature within elite or high-performance sport environments and protocols often developed through trial-and-error approaches. This is likely due to several combinations of pre-performance, post competition or training scenarios, subjective and objective measures and studies owing to the controversy or limited guidelines for the provision of this tool in practice. The difficulty in developing such investigations that aim to impact practice begin with the limited underpinning knowledge around key categories of response (*biomechanical, biochemical, physiological, psychological*) and initially require methodologies to provide the building blocks for future research in this sense. A simple approach of exposure duration was investigated in publication 15 to understand critically the effects of different single exposure durations before considering multiple exposures. Measures of performance chosen in that study helped guide current practice around the decision making of how long to expose an athlete to WBC and the effects on KPI's representing real-world environments with data captured mid-competitive season. Since, several studies have alluded to those findings, examining further the effects of various WBC protocols and dose-response durations on performance measures in sporting populations to further the knowledge in this area (Jaworska *et al,* 2018; Hohenauer *et al,* 2019; Wilson *et al,* 2019; Louis *et al,* 2020). In contrast, there has been an increase in review-based studies aiming to capture the current stance of this recovery strategy (Lombardi *et al,* 2017; Haq *et al,* 2018; Nogueira *et al,* 2020). Unsurprisingly the consensus from those studies suggest further investigations of WBC is required that reflect the multifactorial approaches and pressures of the elite sport environment.

1.7.4 Recovery Response to Whole Body Cryotherapy in Elite Sport

One example includes the response to cooling for the promotion of recovery in sport include athlete wellbeing and psychological assessment. Investigations around sleep levels and pattern response in elite athletes after cooling such as WBC/PBC are becoming increasingly prominent in the literature (Hausswirth *et al,* 2013; Schaal *et al,* 2015; Douzi *et al,* 2019). With adequate sleep required for mental and physical performance levels in sport (Chennaoui *et al,* 2015), strategies used to improve recovery are of interest. Normal sleep patterns often disrupted due to training schedules or travel in elite sport can subsequently induce negative effects on performance thereafter (Meyer *et al,* 2014; Douzi *et al,* 2019). Studies report positive correlations between exposure to WBC following training sessions and improvement in sleep quality (Douzi *et al,* 2019). A reduction in movements during sleep via Actigraph technology in professional footballers after PBC (Douzi *et al,* (2019). In addition, Schaal *et al,* (2015) report beneficial effects on sleep quantity during a period of intensive training in elite female synchronised swimmers after exposure to daily bouts of WBC (−110°C, 3-minutes). This improved athletes' tolerance to training load (Schaal *et al,* 2015). Further beneficial effects of WBC on psychological recovery are reported by a recent review (Lombardi *et al,* 2017) suggesting post-exercise studies generally report a decreased perception of muscular tiredness and pain compared to other recovery techniques (Pournot *et al,* 2011). Despite an increasing body of evidence that leads towards suggestion of improved sleep and perceived stress, the mechanisms by which this occurs are still evolving in scientific literature. In addition, there is little evidence available that agrees on optimal exposure durations in elite settings (Selfe *et al,* 2014). Most recently Malone *et al,* (2021) reported that no additional benefit on subjective recovery were noted by increasing the level of WBC exposures in a population of elite premier league footballers. Future considerations that explore the dampening of stress response post-match following exposure to WBC that may increase the rate of relaxation for example is of key interest and more evidence is required to produce recommendations for the use of WBC in high-performance sport.

Generally, the use of WBC/PBC in sport is accepted post-exercise with a key measure in its ability to reduce ratings of muscle soreness, swelling and to negate effects of fatigue on maximum voluntary contraction (MVC) or functional performance (Bleakley *et al,* 2012; Costello *et al,* 2015). Most available literature tends to compare WBC/PBC to CWI due to the rationale for application being post-exercise recovery rather than to treat acute sports injury (Holmes *et al,* 2016; Hohenauer *et al,* 2017; Rose *et al,* 2017; Wilson *et al,* 2018). Evidence however appears supportive toward minimising symptoms of inflammatory conditions that affect athletes because of injury or performance (Lombardi *et al*, 2017). With others suggesting the use of PBC between-training sessions is useful to enhance the recovery of eccentric muscle performance (Ferreira-Junior *et al,* 2015). The key purpose for WBC/PBC application relates to recovery responses and the potential for injury management in sport. The therapeutic effects recognised may be comparable to those of local cooling applications, due to the ability of this modality to induce physiological effects such as analgesia or reduction in inflammatory response (Lombardi *et al,* 2017), however literature is limited despite common use in elite level and high-performance sport for this reason.

Lombardi *et al,* (2017) acknowledge that response to WBC can be dependent on percentage of fat mass and fitness levels and subjective responses in terms of pain, stress, recovery and soreness for example were significantly improved, mitigating the effects of EIMD through reductions in perceived soreness (Hohenauer *et al,* 2017). The only other study available that compares PBC to CWI demonstrated a failure to accelerate the performance of a CMJ over a 72-hour period post-exercise (Abaidia *et al,* 2017). Alternatively, studies investigating either WBC or PBC in comparison to passive recovery suggest these modes of cryotherapy to be effective in accelerating recovery (Hausswirth *et al,* 2011; Ferreira-Junior *et al,* 2015). The development of future studies into WBC in elite sport would provide sport science and medicine practitioners the knowledge to support rationale of its use and optimal protocol information. The effectiveness of such interventions compared to passive recovery and other cryotherapy applications such as CWI for instance is one recommendation noted in the literature (Hohenauer *et al,* 2017).

1.7.5 Quantification of WBC effectiveness in elite sport

A topical review on the current consensus of WBC in sport by Lombardi *et al.* (2017) suggests this cryotherapeutic modality significantly decreases T_{sk} below that of CWI supporting the effectiveness in reducing symptoms of inflammatory conditions in athletes. The response of T_{sk} to cooling is presented in THEME 3 (Section 1.5). In terms of core temperature response, evidence is available on the measurement of such physiologic measure with relevance to during / post-exercise, temperate environments (Campbell, 2008) or in response to cooling interventions (Costello *et al,* 2012b; Selfe *et al,* 2015). Difficulties exist however in the numerous sites of investigation available, and with that in mind known differences in temperature, quantification is evident therefore throughout studies (Campbell, 2008; Taylor *et al,* 2014). Commonly tympanic, rectal or auditory meatal temperature is measured as it most closely reflects the temperature of the hypothalamus (Campbell, 2008), whereby body temperature is controlled. This is not always feasible or applicable in a practical setting to determine the effectiveness of WBC, where functional performance measures would typically override this physiological measure. Other measures of core temperature include the use of core temperature pills (CorTemp®, Wireless Ingestible Temperature Sensor-Product No. HT150002 HQInc. Florida. USA) recorded via a handheld device (CorTemp®, Data Recorder-Product No. HT150001). Publication 15 used this method to successfully record core temperature in elite rugby league players after various exposures of WBC (Selfe *et al,* 2014). Findings of the study noted a significant and predicted increase in core temperature (Selfe *et al,* 2014), representative of vascular shunting to maintain normal function of vital organs in response to extreme temperatures. Although useful in understanding deeper physiological affects the feasibility of ingesting core temperature pills has implications on the demands of which an elite athlete may face mid-competitive season. These include being unsafe to expose an athlete to MRI scanning post ingestion, or the risk of the pill passing through the body before data can be obtained.

The utilisation of biochemical markers for evaluating the efficiency or effects of cryotherapy as a recovery strategy in sport are reported across with application of CWI as a common example, demonstrating varying approaches to data collection, analysis, output, and implications on recovery

(Pournot *et al,* 2011; Roberts *et al,* 2015; Peake *et al,* 2017; Allan *et al,* 2019). Reported earlier, studies suggest that the modality of CWI does not appear to be more efficient than active recovery in limiting muscle damage when quantifying biochemical markers (Peake *et al,* 2017) with inconsistent findings noted when comparing studies (Bailey *et al,* 2007; Pournot *et al,* 2011). Similar differences are demonstrated in a review by Holmes and Willoughby (2016) between WBC effects on indices of muscle damage. It is difficult to directly compare findings or observe synonymous effects due to methodological differences in studies; often represented by variances in cryotherapeutic protocol, objective markers or the time point of which they are collected. Although indices of muscle damage affected by WBC are of keen interest practically to optimise player recovery and performance. Biochemical parameters however appear to suggest WBC protocols are ineffective to instigate positive or beneficial changes (Lombardi *et al,* 2017). Several biological functions within the body are considered to constitute 'biochemical' responses. For the purpose and relevance of this thesis and the coinciding publications in THEME 5, blood marker components of creatine kinase (CK) and levels of inflammation of muscle damage, such as interleukin-6 (IL-6) and their response to cryotherapy are evaluated. Suggestions for further research here is warranted, with the demand for effective WBC protocols that might induce positive biochemical responses that may be advantageous to athlete performance through recovery.

Biochemical markers are utilised in sport to monitor fatigue and recovery (Heidari *et al,* 2019) discussed previously within this chapter. Information gained from multiple biochemical markers can include nutrition, hydration, inflammation, muscle status, injury risk and CV performance (Lee *et al,* 2018). Biomarkers do have their limitations and although they can assess several aspects of sport performance or recovery, challenges are noted over several factors. One example is single biomarkers which are poor for collating broad physiological function in relation to sports recovery (Lee *et al,* 2018). Often the immune signalling molecule IL-6 is used to determine inflammatory responses both pro- and anti-inflammatory indicators, and CK levels as another example provides reliable indicators for muscle damage (Lee *et al,* 2018; Heidari *et al,* 2019). Biological markers however are pleiotropic in nature and therefore relying on one marker is an unrealistic determinant of meaningful information on an athlete's health. Multiple and simultaneous measures are therefore advocated in sports persons. Practically this is important to consider when determining response to recovery strategies such as WBC on performance, in pre-training or competition status.

Since the review by Lombardi *et al,* (2017) studies have investigated the effects of WBC on performance (Le Meur *et al,* 2017) for post-training recovery (Rose *et al,* 2017) and pre-competition preparation (Partridge *et al,* 2019). From the perspective of readiness for competitions, Partridge *et al,* (2019) indicated the potential for enhancements in athletic performance using acute passive WBC pre-competition. Although the lack of effectiveness or viability of such modality in the current available literature is acknowledged (Partridge *et al,* 2019). Despite the increase in research around the topic of WBC / PBC significant debate as to its effectiveness for athlete recovery is still evident and methodological differences make comparison of WBC studies difficult. As an emerging method of recovery in sport further research is desirable on WBC to accurately inform current practice especially in elite performance settings. Several variables such as those highlighted in Figure 1 (pg. 41) affect the efficacy of WBC protocols. In agreement with Haq *et al,* (2018), to devise an optimal WBC protocol is challenging; and although the coinciding publication 15 considers multi-measures within its design, research needs to continue to consider multiple variables, utilise appropriate performance indicators and investigate relationships between such parameters. Longitudinal studies that consider dose, frequency and periodisation of WBC in team-based sports or elite settings where fixture congestion increases the pressure on shorter recovery time may be beneficial. For benefits to performance, academically driven research needs to consider exploring current protocols of WBC utilised in elite settings to truly represent and determine whether benefits across multifaceted responses exist and on an individual athlete basis. This approach will better inform and impact real-world practices of sports medicine and performance practitioners. As a common yet contemporary recovery strategy, the evidence base for WBC use as an advantageous strategy for performance is still in its infancy with significant opportunity for applied research to develop.

1.8 SUMMARY

It is apparent from the literature that cryotherapy in the broad sense of the term is a common part of sports injury, rehabilitation and recovery and performance in sports settings and varying standards of competition. The evidence however, to support or refute common practices is developmental, lacks agreement on optimal applications or recommendations that reflect current practices and is limited in its translation into applied practice. That said, the topic has for a long time been buoyant with relevant questions including, *'Is ice right? Does cryotherapy improve outcome for acute soft tissue injury?'* (Collins *et al,* 2008), *'Should athletes return to sport after applying ice?'* (Hubbard and Denegar, 2004) and debates whether cryotherapy in the broadest sense can provide strategic advantages in the recovery-fatigue and readiness to perform continuum. Collectively these gaps in the scientific and translational EBP provide a platform for ongoing contemporary critical examination of the effectiveness of cryotherapy applications. This is important for the development of cryotherapy applications in sport for the active practitioner, respective of the intention behind its use. Collectively if we don't consider the multifaceted responses and variables that influence cryotherapy application in a practical real-world setting then inadequate use leading to heightened injury risk or poor recovery protocols with negative implications on performance are among the potential outcomes. Sustaining studies that aim to impact current practice however remains disjointed through limited knowledge on the principles that influence the development of optimal cryotherapy protocols in practice (Figure 1, pg. 41). Moreover, despite the physiological benefits of cryotherapeutic applications widely considered in the evidence, knowledge is limited by a lack of consideration around moderating variables (Figure 1, pg. 41), and the concurrent effects on *biomechanical*, *psychological* and *biochemical* responses. The five themes in which the publications of this thesis sit, respectfully aim to reduce some of the gaps identified by the debates extracted from current literature.

Summary of key issues from the current evidence:

Despite a long-term theoretical basis for cryotherapy use in terms of inflammation management and (Knight, 1976: Merrick *et al,* 1999), how much of a decrease in temperature is required for optimal response is still debated (Hawkins *et al,* 2017). Due to limited knowledge surrounding target tissue temperature reductions, practitioners can only consider the therapeutic goal of application or recovery strategy and when to adjust based on limited recommendations (Hawkins *et al,* 2017). Opposition to the use of cryotherapy use is also evident in the literature for acute injury management, (Hawkins et al, 2017; Dubois and Esculier, 2019). The impact cryotherapy has on slowing down natural inflammatory processes necessary for the inflammatory process to ensue through a decrease in blood flow is considered (Linsay *et al,* 2016). Furthermore, the volume of inconclusive literature surrounding the therapeutic benefits of cryotherapy are reported as confusing (Hubbard and Denegar, 2004; Hawkins *et al,* 2017). Since the last key systematic review by Bleakley *et al,* (2004) and a review by Hubbard *et al,* (2004) dated almost 15 years, considerations for updates in the scope of cryotherapy for sports injury management were warranted. An editorial by Dubois and Esculier (2019) acknowledges the established acronyms of ICE, RICE, PRICE and most recently POLICE, but emphasises the lack of contemporary thought around subacute and chronic stages of tissue healing in relation to sports injury management. Interestingly the authors scrutinise the benefits of anti-inflammatory on pain and function, suggesting an updated approach presented as the acronym of "PEACE and LOVE" which omits cryotherapy from acute injury management is thought to alternatively enhance acute rehabilitation of sport injury. How much the advancement of knowledge has moved on practically in consideration of this collectively is unknown and debatable. None more so than the confusion these discussions may lead to in respect to practical pitch-side applications of cryotherapy for acute injury management and / or the potential deleterious effects on performance and injury risk when returning to functional competitive activity following cooling exposures.

Biomechanical responses and mechanisms, both in kinematic and strength considerations, continue to be of interest. Laboratory and sophisticated methods of quantification are useful to understand these responses, however for practitioners to engage with scientific research, investigation on the effects of contemporary cryotherapy modalities that reflect typical applications and functional demands of sport performance post-exposure are important for impact in the field. The same approach is also noted with regards to physiological and biochemical responses. Although these concepts may be well established in some respects, these responses feature across many of the themes in the thesis through the publications that aim to reduce the dearth of applied research in sporting applied contexts. In terms of psychological responses, "under recovery" often leads to psychological or wellbeing issues in athletes (Kellmann *et al,* 2018) impacting performance. The role in which cryotherapy plays for recovery purposes in sport continues to be imperative in high-performance settings and of interest in the literature base. The obvious argument for individualisation of athlete recovery protocols is key to support athlete readiness to train or compete. This needs to come from individualised monitoring and measurement of recovery response including perception of recovery modalities (Kellmann *et al,* 2018). Consequently, study design therefore needs to acknowledge individual analysis, multi-measures of performance that consider several mechanics and typical applications of cooling to determine this. Contemporary applications of pneumatic cryo-compressive devices or WBC lack evidence around dose and periodisation in elite sport that may be beneficial for recovery purposes, despite their anecdotal and widespread use. Further exploration of such applications is needed to support potential advantageous benefits of athlete recovery. Ultimately the effects of cryotherapy on simultaneous responses underpin the development of acute applications and recovery protocols in applied practice where cryotherapy modalities are implemented. Publications in this thesis intend to encompass this approach.

Finally, thermography continues to be the gold standard in quantifying T_{sk}, which contributes to the efficacy of cryotherapy modality applications in sports medicine. There are significant gaps in current evidence, acknowledged in recent publications, surrounding compression, often an adjunct to cryotherapy anecdotally found positive for the rehabilitation of sports injury or recovery. Most of the available research quantifies the effectiveness of modalities in normative populations, and predominantly male populations, focussing on the analgesic effects alongside skin and intramuscular temperature responses to cooling. Limited studies have investigated injured populations and the effect of cryotherapy on injured tissues. That said, the underpinning justification for studies published in this body of work originate exclusively from the fact that optimal protocols cannot be designed without the extensive investigation into the individual variables presented earlier (Figure 1, pg. 41) affecting the efficiency of cryotherapy applications on uninjured, normative populations initially.

To conclude, current evidence recommends developing research that is representative of applied practices in sport for greater impact on practice. To achieve this, the investigations in this thesis aimed to address contemporary issues through the consolidation of multiple responses with relevant performance measures (subjective and objective in nature) and several interventions in sporting populations to optimise cryotherapy application for injury, rehabilitation, recovery and readiness to perform. With pressure on medical and performance teams to enhance acute injury management, recovery of athletes, reducing time loss through injury or enhancing readiness to train or compete, the establishment of advantageous protocols are paramount. Consequently, the justification of research around individual athlete response and concurrent assessment methods underpins many of the studies across several of the five themes presented in the body of work.

Chapter 2

~ Methodological Approaches ~

CHAPTER 2 – METHODOLOGICAL APPROACHES

2.0 Research Approach and Design

In brief this section provides a summary of the overarching research approach of the body of work alongside study designs, data collection protocols, methods and analysis strategies across the publications. An outline of the philosophical positioning and justification of research approaches are presented and considered in association with the thesis aim.

The approach which led into the design of the collective works was always an applied focus. Therefore, the philosophical position was not constricted to a positivism / interpretivism style or solitary ontological and epistemological position for example, which would have restricted the breadth of scope of the overall thesis. Further to this, to purely present fundamental research would not have generated comprehensive findings to impact current applied practice. That said, it may be argued that underpinning to the earlier studies in this body of work a fundamental approach might be acknowledged in part driven through curiosity and the desire to expand knowledge in a specific research area, however the overarching premise of the studies individually and collectively was an applied research perspective, pragmatically approached with the aim to solve problems and those questions highlighted as a practitioner earlier in section 0.3 (*The Researcher Journey*), and the lack of applied research around cryotherapeutic applications in sport, with practical implications for optimising applications. In the short commentary publication (publication 9) however, methodological stance and approaches around theory-driven translation research, or 'discovery research' (Owoete *et al,* 2020) are deliberated for the purpose of developing future studies in the topic area. That said, a single philosophy, approach to theory development, methodology or strategy replicated across all studies would not have provided the appropriate outcomes to answer the overall aim of the thesis. Consequently, a pragmatic approach appropriately represents the body of work overall in this thesis, given the aim and applied nature of the investigations.

2.1 Summary of Study Designs and Methods

Robust methods were essential for the publications to meet the research aims and objectives of each study, driven by issues or questions identified from practice. Fundamentally, all methodologies required consideration of both laboratory-based outcomes measures and the attention to the applied nature of the research context in the field. Approaches to the development of methods considered the multiple potential impacts cryotherapy may have when utilised in sport, such as understanding acute *biomechanical, biochemical, physiological and psychological* responses to cooling, minimising time-loss through injury, recovery and readiness to perform for training and fixture demands. With that in mind it was felt that several different 'methods' (type of study, data collection, strategy of analysis) would help answer the research questions outlined in Table 1 (pg. 26-28). Types of study designs included randomised controlled trial, experimental / observational, scoping review, editorial and short commentary pieces. Naturally these approaches developed over time to capture the contemporary issues that arose. The approach of utilising elite sports populations and multiple performance or physiological markers in some of the publications (Selfe e*t al,* 2014; Alexander and Rhodes, 2020; Alexander *et al,* 2020f) provided stronger ecological validity to applied research and the intended impact of the findings to those high-performance environments. A pure mixed-methods approach is not entirely accurate in its description of the studies where psychological measures of thermal comfort, sensation and overall wellbeing were captured in addition to objective measures, as qualitative responses were quantified through quantitative scoring. It did however provide qualitative data to inform quantitative findings, or subjective to support objective data interchangeably. In publications 11, 13 and 14 this proved a valuable addition to the objective data of functional movement that provided comprehensive answers to the original research questions in those studies. Overall methodologies varied across each publication in this thesis, in terms of the data collection, protocol and consequently analysis applied. Consequently, this highlights that to achieve the aims of the research studies, innovative study designs and methods were adopted and adapted as the body of work progressed and no solitary approach could best represent the nature of enquiry. The following section discusses examples of key methodological approaches to data capture, protocols and justification of measures in the body of work.

Replicating a method of rewarming (publications 2-7, 11) contributed to developing a depth of understanding around some of the latent effects that occur in response to cooling. Initially, data was predominantly captured at pre and immediately post intervention timepoints (publication 1 and 15) without the consideration of delayed, adaptive or latent responses across physiological, biomechanical, psychological or biochemical markers. The process of ongoing mutual shaping between researcher and research represents a reflexive approach to methodology growth (Attia and Edge, 2017). The design of methodologies through the studies in this thesis develop the applied nature particularly demonstrated in the latter publications 13 and 14. With a reflexive research attitude in mind, the development of publication methodologies in this thesis is representative of a retrospective reflexivity approach in which the research effects the researcher (Attia and Edge, 2017). In this case, to ensure development of future robust methodological design considerations. By quantifying the responses to cryotherapy applications over rewarming periods through methodological design, key lessons highlighted the importance of determining safe periods to return to functional activity post local cooling. Methodologies in the subsequent studies continued to capture biomechanical, psychological and physiological parameters of data over prolonged rewarming periods of up to 10-, 20- and 30-minutes post-cooling intervention (publications 2-7, 11). From this, it became evident that periodisation of cooling for recovery was a variable for consideration (Theme 5) and timepoints for data capture were extended over a 24-hour period within a mid-season micro-cycle (publication 14).

The shifting focus of research toward functional movement patterns with objective measures that reflect neuromuscular control and the quantification of the effect of cooling on proprioceptive components, such as JPS is represented in publications 1-4, 13,14. Methodological developments in these studies particularly demonstrated a closer relationship to the applied practices of cryotherapy in the field than may often be apparent in laboratory-based investigations. This was achieved through functional measures of movement commonly utilised in sports environments. In addition, this approach supported the consistent recommendations in the evidence base to inform optimal practices for cryotherapy protocols in sport, particularly around the relationship with proprioception (Furmanek *et al,* 2014). A reflection of the applied practice evidenced through the methods demonstrated in the publications reinforce the initiation of research findings into practice and the translation of evidenced based research.

The design of a scoping review study became vital to determine current agreement on the specific topic and helped shape successive study designs in the thesis (publications 12 and 13). The scoping review methodology in publication 10 followed a typical framework suggested by Arksey and O'Malley (2005). Many methodologies for experimental studies were designed to reflect the typical protocols of these modalities applied in elite sports performance settings, acknowledged as a significant gap in the literature reported in the findings of the scoping review. This was important to be able to present meaningful studies that reflect real-world practices. Although the scoping review was published after publication 11-14 due to the length of time taken for reviewer's comments. The combination of contemporary cryo-compressive devices, rewarming periods and investigation into dose-responses were demonstrated in the study designs of subsequent publications 11-14. Simultaneously components of dynamic stability in the lower limb continued to underpin the key objective measures of these publications, building on earlier study designs.

Methods applied in publications 1 and 2 considered the importance of recognising how cooling affects JPS (a key component of proprioceptive acuity) (Hillier *et al,* 2015), in order to represent an understanding of the effector response of the body to adapt to changes in afferent input. This was quantified via 3D movement analysis to help identify potential detrimental effects local cooling may have on mechanoreceptor responses. As reductions in dynamic stability are a contributing aetiological factor to injury in sport (Ogard, 2011; Changella *et al,* 2012), development of research methodologies utilising appropriate tests to measure parameters of neuromuscular control was key in the progression of the research themes in this thesis. Previously literature has assessed these parameters individually with many studies attempting to quantify the effect of cryotherapy on various components of proprioception, including dynamic stability (Douglas *et al,* 2013) and JPS for example (Surenkok *et al,* 2008; Oliveira *et al,* 2010). Arguably, within study protocol design multiple parameters that measure multiple components of dynamic performance output should be measured simultaneously to further the understanding of the effect of cooling on proprioceptive components collectively. Sequential studies aim to therefore reflect methodologies that demonstrated this (publications 13 and 14).

The concept of including a subjective response to some protocols stemmed from a statement by Tremb *et al,* (2001) strongly suggesting that proprioceptive acuity following cooling over the anterior thigh remained largely unaffected when quantifying participant perceptions. Furmanek *et al,* (2014) report that components of proprioceptive acuity are affected by cooling, although many studies fail to quantify perceived stability in their methodological approaches for example. These latter research strategies in theme 5 were clearly focussed with an approach to the type of data collected crucial for bringing together physiological, biomechanical and psychological performance multi-measures, acknowledged as methodological triangulation. Three publications in the thesis succeed in demonstrating this multi-factorial approach to methodological design (publication 13-15). Multiple measures collected over a time-period within the mid-competitive season in elite sport incorporating a rewarming period of investigation represented the complex protocols executed in these publications (Figure 6).

		Weekly Post Match Day Training Schedule			
		Match Day +1	**Match Day +2**	**Match Day +3 Scheduled Training**	**Match Day +4 Scheduled Training**
Time Point (1-4)		No data collected	No data collected	1. Pre-Training 2. Post Training 3. Immediately Post Intervention	4. 24 Hours Post Intervention
GROUP	**Group 1 CWI**	No data collected	No data collected	Baseline measures taken (Pre-training) * GPS Post training data collected* Immediately post CWI data collected*	24 hours post CWI intervention data collection prior to scheduled training*
	Group 2 PR	No data collected	No data collected	Baseline measures taken (Pre-training) * GPS Post training data collected* Immediately post PR data collected*	24 hours post PAS intervention data collection prior to scheduled training*

**Data collection across all timepoints consisted of; Performance measures = Eccentric Hamstring Strength (EHS), Isometric Adductor Strength (IAS), Hamstring Flexibility (HF). Psychological = Wellbeing Questionnaire (WB) (McLean et al, 2010). Physiological =Skin Surface Temperature (T_{sk}) (ROI = hamstring and adductors). GPS = Monitoring of training load during scheduled training session.*

Figure 6. Taken from publication 14 (Alexander *et al,* 2021f) demonstrating an example of multiple measures collected across a training micro-cycle typical of elite football and incorporating a rewarming period.

Chapter 3

~ Presentation and Critique of Publications ~

CHAPTER 3 – PRESENTATION AND CRITIQUE OF PUBLICATIONS

3.0 Overview

This chapter introduces a critique of each study (publications 1-15) to provide a comprehensive evaluation of the investigation, methodologies, results, implications and considerations for future research, building on the summaries provided earlier in Table 2. (pg. 42-52). Individual presentation of the abstract and critical account is demonstrated per publication, within each theme, although each study aims, objectives, summary of findings, original contribution to knowledge are previously presented in Table 2 (pg. 42-52) and consequently are not repeated in this chapter. The purpose of this section is to present the significant contribution to knowledge and scholarship in understanding the multifaceted responses to cryotherapy in sport through research and practical implications. Limitations of the studies are presented in the synopsis chapter. Full copies of each publication are presented in Appendices 1-5.

3.1 THEME 1: KINEMATIC RESPONSES TO CRYOTHERAPY (PUBLICATIONS 1-2)

3.1.1 Publication 1.

Alexander, J., *et al,* (2016). An exploratory study into the effects of a 20-minute crushed ice application on knee joint position sense during a small knee bend. *Physical Therapy in Sport*, 18(1); 21-26. (Appendix 1a).

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Original research

An exploratory study into the effects of a 20 minute crushed ice application on knee joint position sense during a small knee bend

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ABSTRACT

Objectives: The effect of cryotherapy on joint positioning presents conflicting debates as to whether individuals are at an increased risk of injury when returning to play or activity immediately following cryotherapy application at the knee. The aim of this study was to investigate whether a 20 min application of crushed ice at the knee immediately affects knee joint position sense during a small knee bend.
Design: Pre- and post-intervention.
Setting: University movement analysis laboratory.
Participants: Eleven healthy male participants.
Main outcome measures: Kinematics of the knee were measured during a weight bearing functional task pre and post cryotherapy intervention using three-dimensional motion analysis (Qualisys Medical AB Gothenburg, Sweden). Tissue cooling was measured via a digital thermometer at the knee.
Results: Results demonstrated significant reductions in the ability to accurately replicate knee joint positioning in both sagittal ($P = .035$) and coronal ($P = .011$) planes during the descent phase of a small knee bend following cryotherapy.
Conclusion: In conclusion a 20 min application of crushed ice to the knee has an adverse effect on knee joint repositioning. Team doctors, clinicians, therapists and athletes should consider these findings when deciding to return an athlete to functional weight bearing tasks immediately following ice application at the knee, due to the potential increase risk of injury.

1. Introduction

The application of ice for the treatment of soft tissue injuries is common practice within sport and clinical settings (Bleakley, Costello, & Glasgow, 2012; Bleakley, McDonough, & MacAuley, 2004; Costello & Donnelly, 2011). Cryotherapy in this instance is generally applied to provide cold induced analgesia by aiming to reduce tissue temperatures to 13.6 °C (Bleakley et al., 2012; Bugaj, 1975; Jutte, Merrick, Ingersoll, & Edwards, 2001) in order for physiological changes to occur (Algafly & George, 2007; Fishman, Ballantyne, Rathmell, & Bonica, 2010; Knight & Draper, 2013; Nadler, Weingand, & Kruse, 2004; Rice, McNair, & Dalbeth, 2009). It has been previously established that cellular metabolism is reduced by 10% when skin surface temperatures (Tsk) are between 10 and 11 °C (Bugaj, 1975). Other research suggests a reduction in nerve conduction velocity (NVC) occurs at 12.5 °C (Jutte et al., 2001), and hypometabolism onset at 15 °C (Knight & Draper, 2013). Algafly and George (2007) reported a 33% reduction in nerve conduction velocity (NCV) when Tsk was cooled to 10°, supporting earlier work by Chesterton, Foster, and Ross (2002). Kennett, Hardaker, Hobbs, and Selfe (2007) suggest Tsk between 10 °C and 15 °C can therefore define an optimum therapeutic Tsk range. It is interesting that although the effects of cryotherapy on proprioception and joint position sense (JPS) are largely unknown (Costello & Donnelly, 2010), clinicians and therapists continue to apply cold modalities such as ice in a clinical or pitch side setting (Bleakley et al., 2011). Anecdotal evidence suggests that ice is applied during rehabilitation to facilitate joint movement. Athletes therefore often perform exercises immediately after cryotherapy. There is however, little consensus in the literature on how functional performance and joint range of movement is affected by the application of cold, with recent systematic reviews (Bleakley et al., 2012; Bleakley & Costello, 2013) reporting varying conclusions.

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Figure 7. Abstract taken from, Alexander *et al,* (2016). An exploratory study into the effects of a 20-minute crushed ice application on knee joint position sense during a small knee bend.

3.1.1 Publication 1 Critical Account

Study 1 investigated the effect of local knee joint cooling on JPS. Commonly in sport, local applications of cryotherapy are applied notably during short intermittent breaks in play or tactical substitutions with players often returning to the field of competitive play shortly after cold exposure. This publication corresponds with Theme 1 (Table 1, pg. 26-28) and Research Questions; *What are the effects of local cryotherapy applications on dynamic stability at the knee?* And *do changes in kinematic response to cooling affect safe return to functional activity in sport?* (Table 2, pg. 42-52) identified for exploration.

Publication 1 Rationale

There is ongoing debate as to whether an increased risk of injury follows cooling applications, especially when applied to the lower weight bearing limbs / joints. To understand this, further research into the effect of JPS was required aligned with Costello's *et al.* (2010) recommendations where previous studies with poor methodology presented conflicting results. Since that review conflicting findings still appear in the evidence base as to whether proprioceptive components are positively or negatively affected by cryotherapy (Table 8). Generally, evidence on the effects of cryotherapy applications on proprioception responses are often contradictory and inconclusive. Findings from publication 1 have implications on the pitch side management of an athlete that may return to competitive play post cooling.

Table 8. Examples of literature which investigate or review the effects of cryotherapy applications on proprioceptive components, to illustrate the lack of conclusive agreement.

Effects of Cryotherapy on Proprioceptive Components			
NO DETRIMENTAL EFFECTS		**POTENTIAL DETRIMENTAL EFFECTS**	
Reference	**Conclusion in Summary**	**Reference**	**Conclusion in Summary**
Houten and Cooper, (2017).	*Results suggest that 15 min of Cryo-cuff treatment does not significantly affect proprioception. Although the effect of cryotherapy on proprioception depends on cooling modality used, time frame applied, and joint applied to.*	Costello and Donnelly, (2010)	*Limited and equivocal evidence is available to address the effect of cryotherapy on proprioception in the form of JPS. Until further evidence is provided, clinicians should be cautious when returning individuals to tasks requiring components of proprioceptive input immediately after a cryotherapy treatment.*
Khanmohammadi *et al,* (2011)	*These findings suggest that 15-minute water immersion at 6°C dose not significantly alter the middle range of plantar flexion/ dorsiflexion JPS at the ankle and is not deleterious to JPS.*	Douglas *et al,* (2013)	*The results suggest that cryotherapy to the ankle has a negative effect on the ML component of dynamic balance following ice water immersion. Immediate return to play following cryotherapy application is cautioned given the decreased dynamic ML balance and potential for increased injury risk.*
Costello *et al,* (2012c)	*No increased risk of proprioceptive-related injury following WBC.*	Macedo *et al,* (2014)	*After cold water immersion of the ankle, special care should be taken in activities that require greater neuromuscular control.*
Fukuchi *et al,* (2014)	*Results indicated that cold water immersion appears safe prior to running activities.*		

Publication 1 Results and Conclusion

Results demonstrated a significant reduction in JPS through knee joint positioning in the decent phase of the SKB for sagittal ($p<0.35$) and coronal ($p<0.011$) planes. T_{sk} was significantly reduced over the anterior, medial, and lateral portions of the knee to within therapeutic ranges following a 20-minute application of crushed ice ($p<0.05$). The results confirmed that a clinically relevant dose of cryotherapy in the form of crushed ice to the knee had negative effects on proprioception such as JPS or dynamic balance.

Publication 1 Practical Implications

This study was the first of its kind, that assessed knee joint motion in all three planes of motion during a functional closed-chain task following a local cryotherapy application. The shift in valgus movement following cooling may present implications during sport, whereby the ability to control through the medical structures of the knee highlight concerns around further non-contact injury if an athlete returns to functional play. Although a series of subtle arguments are presented through the discussion section of the publication, it is evident that the mechanisms behind mechanoreceptor response to cooling were of key interest, nevertheless not determined. It was postulated that through neuromuscular adaptation to cold, negative effects on the ability to maintain or replicate knee joint position following cooling occurred with a desensitisation of receptors contributing to a reduced awareness and control of position. Findings recommended that considerations should be taken around the decision making of when to return an athlete to functional movement following knee joint cooling based on the reduction in the ability of participants to replicate knee joint positioning in the sagittal and coronal planes of movement. To reduce injury risk following cryotherapeutic applications, the implications of these findings should be considered by sports medicine and performance practitioners when developing safe and effective applications of cooling protocols in sport.

Publication 1 Research Implications

Inevitably, several questions were stimulated from this exploratory study and although the effected outputs are quantified, the fundamental mechanisms behind why adverse responses to local cryotherapy application occurred at the knee joint require further investigation. Appropriately, the conclusion suggests sports medicine or performance practitioners to be aware of the potential detrimental effects local cooling application may have on injury risk. The methodology in this study, however, falls short of observing a rewarming period post-cooling to determine any latent effects which influences return to sport / functional activities after this type of application / protocol. Observations of JPS over a rewarming period following cooling may provide further understanding to a greater depth surrounding the mechanistic responses to cooling in sport.

Given the hesitation to generalise these findings to other modalities, the study presents a platform of research questions to pursue. Not inclusive to a range of modalities; outcomes measures, application protocol and populations. Furthermore, demonstrating not only the importance of further investigation of JPS, but the parameters that contribute to dynamic stability, such as muscle strength. This also highlights the need for further rigorous studies that compare multiple modalities and objective measures to help develop optimal protocols of cryotherapy applications in sport.

With a purely critical take on the findings, this study emphasises the need to consider what objective measures are chosen in future publications to answer the research questions outlined in Table 1 (pg. 26-28), and consideration of multifaceted categories of response to cryotherapy, presented in Figure 1 (pg. 41). It is important to consider the specific mechanisms through which cooling altered knee joint control in this early exploratory study, yet this may be speculative as it is the response outputs that are quantified. Considerations as to which physiological variations led to changes in the adaptations seen here to knee joint mechanics were considered post-publication. These included NCV, muscle strength and sensory skin surface feedback for example. To develop further depth of understanding, the proposal to observe functional movements post cooling over rewarming periods was presented, with the aim to determine what the potential lasting effects from local cryotherapy applications are. The focus of the subsequent publication (Alexander *et al,* 2018) replicated a similar methodological approach to study 1, however JPS response, after knee joint cooling was observed both immediately after cooling removal and over a rewarming period of 20-minutes.

THEME 1: KINEMATIC RESPONSES TO CRYOTHERAPY (PUBLICATIONS 1-2)

3.1.2 Publication 2.

Alexander, J., *et al* (2018). Delayed effects of a 20-min crushed ice application on knee joint position sense assessed by a functional task during a re-warming period. *Gait and Posture,* 62;173-178. (Appendix 1b).

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Full length article

Delayed effects of a 20-min crushed ice application on knee joint position sense assessed by a functional task during a re-warming period

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ABSTRACT

Delayed effects of a 20-min crushed ice application on knee joint position sense assessed by a functional task during a re-warming period.

Introduction: The effect of cryotherapy on joint positioning presents conflicting debates as to whether individuals are at an increased risk of injury when returning to play following cryotherapy application at the lower limb.

Objectives: The aim of this study was to investigate whether a 20 min application of crushed ice at the knee affects knee joint kinematics immediately post and up to 20 mins post ice removal, during a small knee bend.

Method: 17 healthy male participants took part in the study performing a functional task. Using three-dimensional motion analysis (Qualisys Medical AB Gothenburg, Sweden), kinematics of the knee were measured during a weight bearing functional task pre and immediately post, 5, 10, 15 and 20 min post cryotherapy intervention. Skin surface temperature (T_{sk}) cooling was measured via infrared non-contact thermal imaging (Flir Systems, Danderyd, Sweden) over the anterior and medial aspect of the knee.

Results: Results demonstrated significant reductions in the ability to accurately replicate knee joint positioning. A significant increase ($P \geq 0.05$) in rotational movement in the transverse plane occurred, 20 min post ice removal.

Discussion: A 20-min application of crushed ice to the anterior aspect of the non-dominant knee has an adverse effect on knee joint repositioning and dynamic stability, 20 min after ice is removed. In consideration of returning a land-based athlete to dynamic functional activities, post cryotherapeutic intervention at the knee, clinicians should consider these findings due to the potential increase risk of injury.

Figure 8. Abstract taken from, Alexander *et al,* (2018). Delayed effects of a 20-min crushed ice application on knee joint position sense assessed by a functional task during a re-warming period.

3.1.2 Publication 2 Critical Account

Publication 2 investigated the effect of local knee joint cooling on JPS over a rewarming period. This publication corresponds with Theme 1 (Table 1, pg. 26-28) and Research Question; *What are the latent effects of local cryotherapy applications on dynamic stability at the knee over a rewarming period?* (Table 2, pg. 42-52) identified for exploration. The temptation was to include investigation of multiple variables in this subsequent study to the Alexander *et al.* (2016) work, however the key message from the exploratory study was the need for observation of JPS over a rewarming period. To this point literature was scarce as to the longevity of such effects after knee joint cooling (Ribeiro *et al,* 2013).

Publication 2 Rationale

It is common practice to see athletes returned to the field of play following cryotherapy applications pitch side, applied initially for analgesic purposes (Bleakley *et al,* 2011; Costello *et al,* 2012a). To this point little was known about the effects of local cryotherapy applications to the lower limb on proprioceptive parameters, including JPS and as to how long the effects of knee joint cooling last post-removal. The potential for increased risk of injury due to negative effects of local joint cooling on functional stability is considered following immediate removal of cooling at the knee (Costello *et al,* 2010; Bleakley *et al,* 2012), but it was unknown at the time of study development as to the extent of delayed effects in relation to JPS.

Publication 2 Results and Conclusion

After a 20-minute exposure of crushed ice to the anterior aspect of the non-dominant knee a significant increase in rotational movement through the transverse plane was reported. Knee joint positioning could not be replicated to pre-cooling measures at the end of the 20-minute rewarming period. Findings highlight the consideration of safety when returning an athlete to functional tasks, immediately and up to 20 minutes later, following cooling at the knee joint. With the heightened risk of injury at the knee increased, sports medicine or performance practitioners should be cautious to return an athlete to the field of play or functional weight-bearing activity post local knee joint cooling without considering the length of rewarming periods. Results support the application of crushed ice to reduce T_{sk} to within therapeutic ranges over the anterior knee, and the use of TI to quantify T_{sk} following local cooling applications.

Publication 2 Practical Implications

Considering the movement patterns for non-contact ACL injury, the findings in this study might suggest that by returning an athlete to closed chain functional activity following knee joint cooling, the risk of structural injury to the ACL is increased. In addition to the potential risk of injury, the implications pose further interest around the application of joint cooling to facilitate movement during rehabilitation.

At the time of publication, literature failed to observe rewarming periods of investigate following local cooling applications that combined T_{sk} and kinematic analysis of JPS. The study draws attention to the decrease in rotational stability in the knee following cooling and notes this may have been because of insufficient neuromuscular changes. The significant argument throughout the discussion of this publication denotes back to the influence local cooling applications have on neuromuscular responses and highlights the fundamental lack of agreement in research available at the time regarding this. Although the publication acknowledges the viewpoint of Khanmohammadi *et al,* (2011) that suggests deeper regions of a joint are not affected by cryotherapy through the sensorimotor system, or that a level of compensation in deeper structures of the joint counteract the changes in receptor response superficially (Wassinger *et al,* 2007), findings would disagree with these proposals. Over the rewarming period T_{sk} followed a typical rewarming curve and considering the ideas by Hardaker *et al,* (2007) it might be assumed that deeper structures continue to cool following the removal of crushed ice. The suggestion was made that superficial joint cooling may continue to affect structures that are important for proprioceptive feedback mechanisms to function optimally, such as JPS or dynamic stability, after cooling is removed. Findings were therefore pertinent to the rationale for observing responses over a rewarming period in future publications. The impact of this affects current practice and methodological considerations of future studies.

Publication 2 Research Implications

Some caution is required when considering the design of future methodologies in terms of the objective measure chosen to quantify and subsequently understand the physiological effects of cryotherapy, especially in terms of proprioceptive components such as JPS or dynamic stability. Components of proprioception are quantified in many studies relating to the effects of cryotherapy (Ribeiro *et al,* 2013; Furmanek *et al,* 2014; Kalli and Fousekis, 2019), although the accuracy and misinterpretations of the term used (proprioception) is challenged within contemporary research in respect to how it is understood and importantly optimally quantified (Hillier *et al,* 2015).

Neuromuscular responses initiate muscle contractions that help maintain optimum body position in response to changes in joint loading (Williams *et al,* 2001; Cordeiro *et al,* 2014). Dynamic stability is therefore different to JPS in terms of observing movement patterns, and therefore the role of muscle strength to maintain functional control is important to consider. Abnormal movement patterns that may be due to delayed neuromuscular responses to cold are therefore important to observe, as reductions in dynamic stability due to inefficient neuromuscular pathways, is an aetiological factor of injury occurrence in the lower limb (Croix *et al,* 2015). Ultimately, the most appropriate measures to effectively quantify responses are important to develop optimal protocols for cryotherapy applications. If neuromuscular pathways provide efficient feedback and muscles work effectively in terms of strength to withstand load, then dynamic stability is deemed effective (Greig, 2009; Adachi *et al,* 2009; Small, 2009). The significance of this understanding should not be understated in terms of future methodological considerations for cryotherapeutic investigations. With that in mind, the findings of the current study support the progression of research questions relating to Theme 2 - *Cryotherapy and the Effects on Muscle Strength Parameters* (Table 1, pg. 26-28).

The findings from Alexander *et al,* (2016; 2018) provide an informative overview of changes that occur post-cooling in relation to the proprioceptive system and of which implicate future study designs. Changes in JPS, as measured in these two publications may only be indicative of why performance of functional movements are negatively affected following cooling. In consideration of this, several performance parameters were contemplated in terms of objective measures. Future publications in the thesis were designed to develop further understanding around the effects of local cooling on biomechanical, psychological and physiological parameters and considered these measures. Future studies observing perceived stability and muscular activity during single limb balance tasks for dynamic stability and eccentric / concentric contractions for muscle strength in response to cooling were carried out, although not represented in the thesis.

3.2 THEME 2: MUSCLE STRENGTH RESPONSES TO CRYOTHERAPY (PUBLICATIONS 3-5)

3.2.1 Publication 3.

Rhodes, D and Alexander J. (2018). The effect of knee joint cooling on isokinetic torque production of the knee extensors; considerations for application. *International Journal of Sports Physical Therapy,* 13(6); 6-8. (Appendix 2a):

IJSPT

ORIGINAL RESEARCH

THE EFFECT OF KNEE JOINT COOLING ON ISOKINETIC TORQUE PRODUCTION OF THE KNEE EXTENSORS: CONSIDERATIONS FOR APPLICATION

David Rhodes, PhD
Jill Alexander

ABSTRACT

Background: Cryotherapy is commonly used in sport for the management of injury or during recovery, however the effects on concentric isokinetic strength appear unclear when considering the effect of joint cooling distal to the anterior thigh.

Purpose: The purpose of this study was to investigate the effect of cooling of the knee joint on quadriceps concentric isokinetic torque production. The results will inform the use of cryotherapy in practice.

Study Design: Observational cohort, Repeated Measures

Methods: Fourteen healthy male participants volunteered to take part in the study, all of whom regularly played competitive sports (mean age 20.24 ± 1.51years; body mass 80.34 ± 11.34Kg and height 179.45 ± 6.59cm). 800 g of crushed ice was applied over the anterior knee joint for 20 minutes. Concentric quadriceps strength was measured using an isokinetic dynamometer (IKD) by measuring concentric peak (PkT) and average torque (AvT) outputs at pre-, immediately post and 20 minutes post cooling intervention. Additionally, skin surface temperature (T_{sk}), was measured using a hand-held thermometer at the patella at the same time intervals. Measurement was taken at the mid-point of each participant's patella, which was ascertained by measuring between the base and apex.

Results: Significant main effects reported for PkT, for time post-ice application ($p = 0.02$, $\eta^2 = 0.161$). Post-hoc analysis revealed pre-ice application PkT to be significantly higher ($p \leq 0.003$) than all other timepoints. Quadratic regression analysis revealed a strong correlation between reductions in quadriceps torque production and time post application ($r = 0.82$). The quadratic pattern of recovery displays a minima of 17.28-minutes and maxima of 34.56-minutes post ice application. AvT post-ice application demonstrated significant main effects for time post-ice application ($p = 0.03$, $\eta^2 = 0.152$). Post-hoc analysis revealed pre-ice application AvT to be significantly higher ($p \leq 0.005$) than at all other timepoints. Quadratic regression analysis revealed a strong correlation between reductions in quadriceps torque production and time post application ($r = 0.80$). The quadratic pattern of recovery displays a minima of 18.38-minutes and maxima of 36.76-minutes post ice application. T_{sk} reduced significantly, immediately post intervention ($p \leq 0.05$) without returning to baseline measures at 20-minutes post ($p \leq 0.05$).

Conclusions: Isokinetic peak torque values of the quadriceps diminish after cryotherapy application to the knee joint and are not fully recovered at 20 minutes post application on the knee. These findings could have potential implications for participation in activity immediately following ice application.

Level of Evidence: 2b

Keywords: Cryotherapy, Isokinetic Dynamometry, Knee, Quadriceps

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The authors declare no conflict of interest within or related to the present work.

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Figure 9. Abstract taken from, Rhodes and Alexander, (2018). The effect of knee joint cooling on isokinetic torque production of the knee extensors; considerations for application.

3.2.1 Publication 3 Critical Account

Publication 3 investigated the effect of local knee joint cooling on isokinetic torque production of the knee extensors. This publication corresponds with Theme 2 (Table 1, pg. 26-28) and Research Question, *"Do differences occur in temporal isokinetic strength production patterns following anterior thigh compared to direct knee joint cooling, over a rewarming period?* (Table 2, pg. 42-52) identified for exploration. The rationale behind the study was to advance earlier kinematic publications (1-2) through further investigation of muscle strength parameters, known to be affected by cooling but vitally important for joint stability and feedback at the knee (Zhou *et al*, 1998; Abulhasan and Grey, 2017). The investigation focussed on concentric contraction performance of the quadriceps muscle group, which provides posterior-anterior stability at the knee joint (Zhou *et al*, 1998; Abulhasan and Grey, 2017). With the increased risk of non-contact musculoskeletal injury based on the inability to control rotational or valgus motions demonstrated in publications 1-2, the central theme of this study was to investigate whether cooling distally to the belly of the quadriceps muscles presented deficiencies in strength parameters adjacent with negative changes found in JPS (Alexander *et al,* 2016; 2018). It was important to continue the observation of functional markers over a rewarming period reinforcing earlier methodology from publication 2.

Publication 3 Study Rationale

Although several studies present convincing evidence around the relationship between T_{sk} rewarming as T_{im} decline post cooling, previously the strength of this type of relationship was questioned (Jutte *et al,* 2001). Later investigated by Hardaker *et al,* (2007), evidently a strong negative quadratic relationship between T_{sk} and T_{im} was proposed. Since that study however little progression that challenges that relationship has progressed in the literature making the understanding of physiological responses to cooling and consequently the mechanisms in which cryotherapy affects muscle physiology difficult to translate in an applied nature. With many solely reporting T_{im} without measurement of simultaneous T_{sk} both prior to and following Hardaker *et al,* (2007) recommendations. Evidence surrounding muscle strength following cryotherapeutic applications at the time presented conflicting information on magnitude of change (Ruiz *et al,* 1993; Sanya *et al,* 1999; Thornley *et al,* 2003; Pietrosimone *et al,* 2009; Point *et al,* 2018) and were limited in their analysis of muscle strength in relation to T_{sk} (Kennet *et al,* 2007; Rupp *et al,* 2012; Selkow *et al,* 2012). Investigation of muscle strength responses to cold over a rewarming period using these methods of strength assessment did not exist to the authors' knowledge.

Changes in performance post cooling is arguably influenced by dynamic stability. With effective dynamic stability required for optimal stabilisation of weight baring joints such as the knee (Williams *et al*, 2001), investigations into the effect of cooling on muscle strength parameters were therefore warranted. Whether neuromuscular responses resulted in the same output following cooling to only the joint was of interest. It was considered that results may provide only an indication into the mechanisms by which dynamic knee stability are affected through cooling as again it was only the affected output reported and quantified in the investigation. Thus, investigation into the effect of cooling on muscle strength in relation to T_{sk} and location of cooling was required for the progression of optimal cryotherapeutic applications. With protocol development to optimise cryotherapy application being an underlying consideration throughout all publications in this thesis.

Publication 3 Results and Conclusion

Overall analysis demonstrated significant reductions in T_{sk} over the anterior knee joint in line with previous literature (Alexander *et al,* 2016; 2018) following the application of crushed ice. When measured immediately post-cooling application, T_{sk} fell to within the desired therapeutic range of cooling (10-15°C), for physiological changes to ensue (Kennet *et al,* 2007), displaying a 51% reduction in T_{sk} from baseline. A rewarming curve was displayed supporting the increase in T_{sk} over the 20-minute rewarming period but failing to return to pre-intervention levels at 20-minutes post exposure. This was expected in consideration of earlier literature (Alexander *et al,* 2016; 2018), and emphasised the demand for further research into T_{sk} comparison against other contemporary cooling modalities commonly applied in sport.

An acute influence of ice application on concentric muscle strength of the quadriceps demonstrated for both AvT and PkT production displayed significant main effects for time ($p=0.03, n^2$

$= 0.152; p=0.02, n^2 = 0.161$) respectively. With significant reductions noted in isokinetic torque for concentric quadriceps up to 20 minutes post cooling (rewarming period ended at this point) results accentuated the lasting effects that joint cooling may have on the mechanical properties that contribute to muscle strength superior to the area of cooling. These findings correlate to large effect sizes indicating the strength of the immediate effect of joint cooling on strength parameters. Regression analysis suggested a maximum of between 34.56-36.76 minutes for normalisation of PkT and AvT values back to baseline respectively. It may have been useful in hindsight to continue data collection for up to this point post cooling to determine whether these suggestions are substantiated. There is much controversy however as to when muscle strength is affected to this point based on intramuscular temperature data. For example, Selkow *et al,* (2012) reported intramuscular temperatures that did not return to baseline measures up to 140 minutes post ice application. Although, strength measures were not quantified and results from publication 3 cannot be directly compared due to numerous methodological differences. This was consistent across several available studies at the time. Furthermore, dose-exposure times differ significantly, with applications of up to 60 minutes compared to a standardised 20-minute application in publication 3. Although not examined in this study, it sparked interest and opportunity to develop in future investigations. Dose-response being another underpinning variable playing a key role in protocol development of cryotherapeutic applications in sport. In publication 3, observation of strength over a rewarming period was important to understand the extent of peripheral joint cooling on proximal muscle strength, T_{im} however were not measured in this investigation, considering the location of cooling it felt irrelevant to quantify.

In conclusion results of publication 3 displayed reductions in concentric muscle strength of the quadriceps and proposed important considerations as to location of cooling and the negative effects on surrounding neuromuscular structures. Even though the muscle belly was not cooled in this experimental protocol, concentric strength was still negatively affected and did not fully recover at 20-minutes post cryotherapy intervention.

Publication 3 Practical Implications

The practical implications of such findings support previous suggestions (Shultz *et al,* 2015) of an increase in predisposing injury risk to knee joint structures due to a lack of stability caused by reductions in the stabilising structures at the knee, i.e., muscles. Despite some literature being available at the time suggesting that reductions in muscle strength (Bleakley *et al,* 2012) and increases in muscle stiffness (Point *et al,* 2018) occur following cryotherapeutic applications, it was difficult to compare results across variable methodologies. This made it problematic to establish whether the current findings reinforced or disputed previous scientific knowledge due to a lack of comparable methodologies, specifically in location of cooling and over rewarming periods. Most studies typically cooled the muscle belly reporting on strength deficits that seem plausible (Ruiz *et al,* 1993; Zhou *et al,* 1998; Pietrosimone *et al,* 2009; Csapo *et al,* 2017). Results are thought to be due to cold-induced reductions in receptor firing rates and muscle spindle activity (Algafly and George, 2007), leading to an effect on performance in terms of strength output.

Several explanations may explain the reduction in concentric torque output reported in this study. It is presumed that the mechanisms of which knee joint cooling altered concentric quadriceps strength response should consider the additional involvement of deeper joint structures. With structures continuing to remain cool after the intervention removal and because of the effect of cooling on golgi tendon organs (GTO) and afferent feedback mechanisms neuromuscular response may have been compromised through the desensitisation of joint mechanoreceptors. Further, differences in type of receptors located at a joint (rafinni endings), musculotendinous junction (GTO) or muscle (muscle spindles) (Table 7, pg. 84), provide further mechanistic understanding as to why joint cooling may influence torque production compared to isolated application at the muscle belly. This, and in respect to earlier literature by Schepers and Ringkamp (2010), findings from publication 3 support the assumption that proprioceptive deficits occurring post knee joint cooling are not only isolated to JPS, affecting the strength output of surrounding musculature too. Contradicting earlier suggestions by La Riviere and Osternig (1994) that suggested joint receptors can compensate for reductions in muscle afferent feedback caused by superficial cooling.

The findings of the study propose several implications to current practice when investigating knee joint cooling protocols; 1) optimal injury management; 2) understanding the impact of strength deficits post cooling and 3) development of safe return to sport criteria following joint cooling. Practically this study contributes to the further applied understanding of the effect of cryotherapy on muscle strength responses and results here challenge previous literature that fails to account for neuromuscular changes that affect biomechanical responses.

Publication 3 Research Implications

A development of this research theme mentioned later in publication 5 would be the investigation of eccentric muscle strength following cooling through comparison of joint and direct muscle cooling across both genders in similar tests. Results from this study indicate strength changes when local cryotherapy is applied distally to the muscle belly, it was considered important therefore to expand this concept into further comparisons of direct muscle belly versus direct joint cooling over a rewarming period. Whether strength outputs in response to the same cooling application over different locations are the same, remained to be determined at this point. Although it was reported recently by Selkow (2019) that similar cooling (T_{sk} measures) occurs in multiple thigh muscles (rectus femoris, hamstrings, gastrocnemius) when subcutaneous tissue thickness determined intervention length. Future studies should consider combining investigation of multiple variables that determine optimal treatment applications of ice and consider analysis of individual response to determine if group results accurately reflect individual responses of participants.

The results in publication 3 have implications on the design and implementation of future studies in terms of functional measures obtained. In future studies, the combined observation of JPS and myoelectrical activity through dynamic movements would support the understanding of biomechanical responses that may be affected by cryotherapy. This would provide a profound understanding around the factors that contribute to control required for dynamic stabilisation around the knee joint and the implications of such cooling protocols, specifically, potential timescales on the safe return to functional movement tasks related to sporting scenarios may benefit. To date it was unclear from the available evidence whether investigation has been undertaken with such multiple parameters, particularly around the knee joint, thus, providing a limited consensus on the subject. Whilst some related literature using an electromyographic (EMG) approach demonstrate the interest in this biomechanical marker, studies tend to focus on the ankle joint rather than the knee and under different circumstances of cooling application (Halder *et al*, 2014). This makes it difficult to compare studies to draw a consensus.

Based on the results of publication 3 and the available evidence base at the time of publication, strategies for future studies appear to require a multifactorial approach. This includes consideration around design, population and outcomes measure(s) to ensure useful data is generated in order to minimise the knowledge gap around the effects of cryotherapy modalities on multiple biomechanical, psychological, and physiological parameters relevant to sport injury and recovery. Further large-scale research across genders would reduce the risk of statistically underpowered studies and reflect a wider population group, currently underrepresented in this field of research.

THEME 2: MUSCLE STRENGTH RESPONSES TO CRYOTHERAPY

3.2.2 Publication 4.

Alexander, J and Rhodes, D. (2019). Temporal patterns of knee extensor isokinetic torque strength in male and female athletes following comparison of anterior thigh and knee cooling, over a rewarming period. *Journal of Sports Rehabilitation,* 18: 1-7. (Appendix 2b).

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Human Kinetics
ORIGINAL RESEARCH REPORT

Temporal Patterns of Knee-Extensor Isokinetic Torque Strength in Male and Female Athletes Following Comparison of Anterior Thigh and Knee Cooling Over a Rewarming Period

Jill Alexander and David Rhodes

Context: The effect of local cooling on muscle strength presents conflicting debates, with literature undecided as to the potential implications for injury, when returning to play following cryotherapy application. ***Objective:*** To investigate concentric muscle strength following local cooling over the anterior thigh compared with the knee joint in males and females and the temporal pattern over a 30-minute rewarming period. ***Design:*** Repeated-measures crossover design. ***Method:*** Twelve healthy participants randomly assigned to receive cooling intervention on one location, directly over either the anterior thigh or the knee, returning 1 week later to receive the cooling intervention on opposite location. Muscle strength measured via an isokinetic dynamometer at multiple time points (immediately post, 10-, 20-, and 30-min post) coincided with measurement of skin surface temperature (T_{sk}) using a noninvasive infrared camera. ***Results:*** Significant main effects for time ($P \leq .001$, $\eta^2 = .126$) with preice application higher than all other time points ($P \leq .05$) were demonstrated for both peak torque and average torque. There were also significant main effects for isokinetic testing speed, sex of the participant, and position of the ice application for both peak torque and average torque ($P \leq .05$). Statistically significant decreases in T_{sk} were reported in both gender groups across all time points compared with preintervention T_{sk} for the anterior thigh and knee ($P < .05$). ***Conclusions:*** Reductions reported for concentric peak torque and average torque knee-extensor strength in males and females did not fully recover to baseline measures at 30-minute postcryotherapy interventions. Sports medicine practitioners should consider strength deficits of the quadriceps after wetted ice applications, regardless of cooling location (joint/muscle) or gender.

Keywords: isokinetic dynamometry, cryotherapy, quadriceps, thermal imaging

The therapeutic technique of cooling commonly used for the treatment of musculoskeletal conditions and recovery in sport is widely debated.[1–3] Deliberation around when athletes may return to activity safely following local cooling applications is recognized,[1,2] in consideration of potential neuromuscular deficits.[4] However, methodological differences reduce the strength of consensus across current studies in this area. Within sporting situations, cryotherapeutic application is often associated with pitch-side or half-time management of injuries to induce analgesic responses.[2] Other known physiologic effects include reduced cellular metabolism,[5] receptor firing rate,[6] nerve conduction velocity,[7] and inhibition of muscle spindles[8,9] are well reported.[2,3] Reduction of tissue temperatures through local cryotherapy applications occurs through contact of cryotherapeutic modalities via skin surface initially to achieve physiological responses.[10] A therapeutic skin surface temperature (T_{sk}) target range of between 10°C and 15°C is essential to initiate those essential responses to aid acute injury management.[11] Modalities of cooling differ in thermodynamic properties and therefore cooling efficiency.[10] Efficient in phase change modalities such as crushed or wetted ice noted numerously throughout cryotherapy literature as the most efficient for inducing physiological changes.[12–14] The known effects of cryotherapy on performance and reinjury/further injury risk lack consensus with methodology difficult to compare outcome measures across studies. Previous studies discuss changes in muscle force depending on cryotherapy location and report increases, decreases, or no change.[8,15,16,17] Emerging literature[1] recognized the importance of further study in muscle strength response postlocal cooling application, applicable to sporting situations.

Although rate of temperature change between modalities presents fluctuations, the consensus agrees on a relationship existing[12] that being a highly significant quadratic association between T_{sk} and intramuscular temperatures postlocal cooling applications.[12] The gold-standard protocol to measure T_{sk} is through infrared thermal imaging.[18,19] Due to the multifactorial considerations that can affect deeper soft tissues, such as duration,[20] gender,[21] adipose tissue levels,[22] and location of cryotherapy applications, knowing the optimum protocol for reduction in muscle temperature to induce physiological changes can be challenging. Furthermore, inconsistencies in methods across studies consequently implicate the ability to compare outcomes or effects accurately. This said literature clearly displays physiological changes as a result of various cryotherapy applications[20–22] and has indicated the importance of exploration of cryotherapy on neuromuscular function.[23]

Literature indicates performance deficits as a result of cooling,[2] and these have been attributed with decreases in dynamic contractile force.[1] These conclusions were drawn based on measures of ultrasound shear wave elastography and myoelectrical activity; no output measures of strength were ascertained. It is important to note that the changes in dynamic contractile force were strongly related to muscle stiffness, which resulted in acute change in muscle mechanical properties after air-pulsed cryotherapy intervention.[1] The authors propose this may reduce the amount of stretch available to sustain by the muscle without resulting in injury. The evaluation of muscle strength with isokinetic

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Figure 10. Abstract taken from, Alexander and Rhodes, (2019). Temporal patterns of knee extensor isokinetic torque strength in male and female athletes following comparison of anterior thigh and knee cooling, over a rewarming period.

3.2.2 Publication 4 Critical Account

Publication 4, situated in Theme 2 (Table 1, pg. 26-28), investigated the relationship between torque-production of the concentric quadriceps in male and female athletes over a rewarming period following local crushed ice cooling and tackled some of the questions raised in the preceding publication (Rhodes and Alexander, 2018). This study attempted to investigate a comparison between direct muscle belly cooling (quadriceps) to joint cooling (knee) to determine whether differences in exposure response occurred in muscle strength due to location of cooling and between genders. A longer rewarming period of up to 30-minutes was observed. The change from a 20-minute rewarming period applied in previous publications (2-4) was considered noteworthy as previous biomechanical markers of interest did not return to pre intervention baseline measures at 20 minutes post cooling application. Publication 3 (Rhodes and Alexander, 2018) proposed minima of between 17-28-18.38 and maxima of between 34.56-36.76 minutes for normalisation of PkT and AvT values back to baseline respectively, through post-hoc regression analysis. Therefore, with the latter end of this being around the 30-minute time point, it was considered a reasonable time point to investigate in consideration that dose exposure length would stay consistent with previous publications (1-4) of 20 minutes cooling. That said the decision was to reduce the dose of cooling to only 10-minutes in publication 4. It was felt that this length of dose was representative of pitch-side or half time application where athletes are more likely to return to the field of play following exposure. Comparison between preceding publications to this study therefore is difficult when considering differences in dose. A shorter dose application was also considered in respect to recommendations in previous literature (Bleakley *et al,* 2012). On reflection, it may have been useful to consider a two-dose comparison of 10- and 20-minute exposures in the study protocol. A challenge for practitioners in the field is to provide optimum dosage and application to gain physiological benefit dependent on treatment aim / recovery goal. This may have provided further insights into dose-response, considered important to optimise cryotherapeutic protocols in sport, although the focus of the study was to detect changes in muscle response to cooling and between genders rather than dose-response comparison at this stage.

Publication 4 Study Rationale

Within any evidenced-based protocol for therapeutic modality use in sport, knowledge of the physiological responses is necessary to aid protocol development and application of adequate injury and recovery strategies. Indeed, research in cryotherapy and the effects on muscle strength parameters has shown performance deficits because of cooling (Bleakley *et al,* 2012) and attributed to decreases in contractile muscle force (Ruiz *et al,* 1993; Point *et al,* 2018). Yet to draw a robust conclusion from the available evidence is difficult as literature only highlights the fundamental lack of contemporary research to provide a thorough understanding of the effects of cooling on muscle strength. The main purposes for cryotherapy application in sport appears generally two-fold; 1) for injury management (including rehabilitation) and 2) recovery for performance. These 'therapeutic' demands of cryotherapy application in sport can be broken down further into a myriad of goals referring to optimising treatment and healing, reducing time-loss through injury or minimising impact of damaging exercise that are essential for optimal athlete participation in competitive sports. Accordingly, a thorough understanding of the physiological and biomechanical effects of cooling on neuromuscular components as this study attempted to investigate, may provide sports medicine and performance practitioners with practical direction for decision making around optimum protocol applications of cryotherapy.

Publication 4 Results and Conclusion

Across all timepoints, statistically significant decreases in T_{sk} were displayed for whole group data and individual gender data following knee joint cooling ($p \leq 0.05$). At 30-minutes post cooling, T_{sk} displayed reductions over the anterior thigh, and although this was not significantly reduced compared to baseline, T_{sk} had not returned to baseline temperatures at this point. Significant differences in T_{sk} between males and females were reported at 30 minutes post intervention however, for males but not females and over the anterior thigh only. The immediate effects and temporal pattern of recovery of PkT and AvT demonstrated significant reductions for concentric strength of the quadriceps in both males and females ($p \leq 0.05$). By continuing the observation of muscle strength parameters over a rewarming period a better understanding of the impact cooling applications may have for their use in sport pitch side may be explained by T_{sk} and T_{im} relationships. T_{im} however was not quantified in this study, as this was not the target aim of the investigation. It was only assumed that the relationship proposed earlier by Hardaker *et al,* (2007) partly justified the effects displayed in muscle strength data post analysis in this study.

Unlike previous studies, where joint or muscle cooling has been compared individually, this study simultaneously observed physiological and biomechanical markers across multiple locations. The only other study to investigate the comparison of location cooling quantified JPS not muscle strength, with crushed ice, not wetted (Oliveira *et al,* 2010). Results in publication 5 noted reductions in torque production that failed to return to baseline at 30 minutes post removal of wetted ice for both locations. The strength reductions noted at similar locations despite differences in modality or dose of cryotherapy support findings by Oliveira *et al,* (2010) that report impairments of JPS from applications of cryotherapy at the anterior thigh and knee joint on separate occasions. The trend toward greater percentage reductions in muscle strength response noted from knee joint cooling immediately post rather than directly over the muscle are of interest and may be justified through several mechanisms. One consideration is the application of cold over superficial bony prominences such as the anterior knee that may produce variable physiological effects as to the extent of cooling rate compared to areas of soft tissue such as muscle (Pietrosimone *et al,* 2009). Thus, an initial response of lower torque production occurring at the knee compared to muscle cooling may be because of the greater effect on neuromuscular response around the knee complex required for optimal feedback. After this, at all other timepoints over the rewarming period greater reductions in strength were noted for muscle cooling compared to joint, suggesting that the region of muscle may be continuing to cool post-exposure influencing the strength parameters measured. Findings have implications both clinically, but more importantly of an applied nature, affecting safe return to play following similar cryotherapy exposures and potentially performance in terms of recovery. What these findings do reinforce is the importance of detrimental effects on adjacent muscle strength (quadriceps) when cooling distally at the knee joint. Findings that were previously reported in publication 3. Collectively conclusions from publication 3 and publication 4 highlight that this response occurs from two different types of cooling modality over the knee, in publication 3 crushed ice was applied, in publication 4, wetted ice. What is different from these modalities is the length of dose exposure, publication 3 being 20-minutes and publication 4, 10-minutes. Comparison of dose-response here reinforces the agreement in existing literature that wetted ice has a greater thermal conduction ability than a dry interface (Lide 1994; Kwiecien *et al,* 2019) resulting in lower T_{sk} over a shorter application duration. This has implications on protocol design for cryotherapy applications in sport. A certain cryotherapy technique may be advantageous through a greater or rapid cooling rate to minimise cellular metabolism or the extent of, which is associated with secondary injury (Merrick *et al,* 2003; Janwantanakul, 2004). Future publications should aim to compare multiple modalities and length of dose exposure on muscle strength parameters to generate further evidence-based literature for optimal protocol development of cryotherapy in sport.

Publication 4 Practical Implications

The decision to include female as well as male gender participants acknowledges the suggestions by Costello *et al,* (2014a) whereby sports medicine practitioners should be conscious to minimise gender disparity in current research. The benefits of including both male and female athletes provided further comparison analysis between gender groups in response to cooling.

A plethora of studies over the last two decades comparing multiple cryotherapeutic modalities in sport, has progressed in part what may be the most beneficial reflecting objective responses to cooling (Chesterton *et al,* 2002; Merrick *et al,* 2003; Dykstra *et al,* 2009; Hamid *et al,* 2013; Kwiecien *et al,* 2019). The decision to apply wetted ice instead of crushed ice as per earlier publications (Alexander *et al,* 2016; 2018; Rhodes and Alexander, 2019) reflected the recommendations from the evidence base for optimal cryotherapy modalities, suggesting greater thermal conduction from wetted ice applications occurs (Kwiecien *et al,* 2019). The limitations to this restrict the comparison of findings directly to publication 3 due to different modality choice. That said, an underpinning consideration of this thesis was to report on contemporary applications of cooling, therefore reflected in the choice of modality of wetted ice. Conclusively the clinical implications of findings in publication 4 concentrates on the responses of strength that were affected by cold application regardless of location or gender to some extent. The physiological responses that may have contributed to strength reductions observed due to cooling in this study remain open for some interpretation however, as findings refute (Hopkins *et al,* 2002; Pietrosimone *et al,* 2009) and agree with previous reports (Bleakley *et al,* 2012; Point *et al,* 2018; Rhodes and Alexander, 2018). Although it is acknowledged that neuromuscular responses to cooling play a part in making sense of the findings, it is the effect of strength reductions on performance and further injury risk that are of interest. Reflecting an applied nature of the study approach and results. Further consideration around the appropriate measures of function that are useful practically and the biomechanical effects of cryotherapy were considered in successive publications. Evaluation of the results in this study centred on the impact of reduced muscle strength that may predispose athletes to non-contact injury at the knee complex. From the point of dose-response the publication highlights that even shorter (<20 minute) exposures can have meaningful impact, be it negative, on strength ability that contributes to potential reductions on dynamic stability required for safe return to the field of play or performance.

Publication 4 Research Implications

Future research should consider the lack of investigations of female athletes for cooling effects utilising contemporary and portable methods of cryotherapy reflecting current practice of sports medicine practitioners. Moreover, the evaluation of the effects of multiple contemporary cooling modalities used in sport aside from the typical crushed/wetted ice protocols would be beneficial. This could have been considered in this publication however other factors in protocol development were thought of as higher priority, such as dose and location of cooling. As to which variable is most important remains debateable. The multifaceted response to cryotherapy application in sport are considered in Figure 1 (pg. 40) and feature a panacea of themes pertinent to the progression of optimal cryotherapy protocols in sport. With consideration to keep a focus of the publications and thesis acknowledging contemporary modalities, comparison of such were integrated in subsequent studies presented in this thesis. Interestingly, the development of contemporary cooling devices typically combined the adjunct of compression as a suggestion to increase magnitude of cooling (Tomchuk *et al,* 2010). To this point minimal studies investigated these devices (Hawkins *et al,* 2012) and subsequently this avenue is examined in the publications that follow.

THEME 2: MUSCLE STRENGTH RESPONSES TO CRYOTHERAPY

3.2.3 Publication 5.
Alexander, J., *et al,* (2021). Exploratory evaluation of muscle strength and skin temperature responses to contemporary cryotherapy modalities in sport. *Isokinetics and Exercise Science.* In Press. (Appendix 2c).

Exploratory evaluation of muscle strength and skin surface temperature responses to contemporary cryotherapy modalities in sport

Cite

Article type: Research Article

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Abstract: BACKGROUND: The effects of contemporary cryo-compression devices on function are limited compared to traditional applications of cooling. Development of cooling protocols are warranted. OBJECTIVE: To investigate the effects of three different cryo-compressive modalities applied at the knee on the isokinetic strength of the quadriceps over a re-warming period. METHODS: Eleven healthy male participants took part (23 ± 14 years; 78.3 ± 14.5 Kg; 180 ± 9.5 cm) randomly assigned to receive all modalities (Game Ready® (GR), Swellaway® (SA), Wetted Ice (WI)) applied for 15-min, separated by 1-week. Skin surface temperature (Tsk) via thermography and the concentric peak moment (PM) of the quadriceps at 60 and 180°/s were collected pre-, immediately-post and at 20-min post-intervention. RESULTS: Significant reductions occurred in Tsk across all timepoints for all modalities ($p=\leqslant 0.05$). Significant reductions in PM for WI were noted across all timepoints and PM for GR and SA immediately-post ($p=\leqslant 0.05$) only. CONCLUSION: Precaution for immediately returning to sport following cryotherapy is required and influenced by type of cooling on muscle strength responses. Alternate targeted treatment modalities to minimise deferred deleterious effects on muscle strength may be considered. Research into length of application, periodisation and location is warranted for the development of such contemporary cryo-compressive modalities in applied practice.

Keywords: Cooling, knee, isokinetic dynamometry, performance, sport injury

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Figure 11. Abstract taken from, Alexander *et al,* (2021a). Exploratory evaluation of muscle strength and skin surface responses to contemporary cooling modalities in sport.

3.2.3 Publication 5 Critical Account

Publication 5 compared the effects of three cryotherapy modalities at the knee on isokinetic strength over a re-warming period. This publication sits within Theme 2 (Table 1, pg. 26-28) alluding to answer the research question; *Do differences occur between current technological cooling devices when investigating the effect on isokinetic strength of the knee extensors over re-warming periods?* (Table 2, pg. 42-52). Prior to this study single modes of cooling had been observed (Publications 1-4). With a conscious eye on contemporary developments within cryotherapy, that included cryo-compressive devices, naturally the investigation to compare between such modalities and replicate protocols applied in sport commenced. This study evaluated muscle strength and T_{sk} parameters, that constituted biomechanical and physiological responses, key themes which continuously evolved from investigations of traditional methods of cooling to include pneumatic cryo-compressive devices.

Publication 5 Study Rationale

The three modalities examined in publication 5 included the Game Ready®, Swellaway and wetted ice. Findings from publication 3 and 4 suggested muscle strength deficits exist following cooling using wetted ice, and in publication 4 regardless of whether cooling was applied directly to joint or over the muscle belly. Between the two pneumatic devices, two main differences were the circumferential application of the Game Ready® compared to the targeted cooling of the Swellaway device through Peltier cell technology. To grow the evidence and development of optimal protocols, the investigation of these devices and their effects on biomechanical components was important as many elite sport settings utilise these cooling devices without any clear directives on the most appropriate protocols from research. Consequently, the justification to explore differences between traditional and contemporary devices with different application styles seemed logical.

Publication 5 Results and Conclusion

This publication demonstrated consistent acute reductions in strength following cooling however significant differences in the amount of strength loss between devices was evident when applied for the same dosage time of 15-minutes. Significant reductions in T_{sk} were confirmed and in line with previous literature for all modalities and baseline T_{sk} did not return at 20-minutes post removal for any of the applications. The greatest effect on strength and for the longest time into the rewarming period was through the application of wetted ice. Compared to the two pneumatic cryo-compressive devices where PkT was reduced only on immediate removal time point not 20 minutes post application.

The study continues to advocate the use of thermal imaging for measures of T_{sk} in cryotherapeutic investigations. Overall, the findings provide evidence to suggest the importance of dose-response considering previous durations of cooling exposures. The choice to apply a shorter duration in this study compared to previous study design was to reflect common application periods in sport. Undoubtably, biomechanical measures of strength provide an insight into the strength loss differences between devices, supporting a fundamental message from the investigation around circumferential and targeted treatments of local cooling. To minimise deleterious effects of cooling on concentric muscle strength, dose and application type are important in the development of optimal cryotherapy protocols to be advantageous to the athlete. Practitioners may utilise the findings of this study for decision making reflecting the decisions around targeted or circumferential cooling applications besides alterations of dose for physiological changes to occur, without the consequences of muscle strength reductions.

Publication 5 Practical Implications

From the results of this study the greatest impact practically is the effect of targeted treatment vs circumferential. It may be obvious that greater size of area cooled may affect more neuromuscular structures that aid stability and control input around a weight baring joint, resulting in deleterious effects on concentric strength, although this has not been investigated before using contemporary cooling devices. Sports medicine and performance practitioners can, based on these findings, start to recognise the differences and benefits of utilising circumferential versus targeted cooling treatments or traditional wetted ice applications. The benefits of a targeted treatment approach as demonstrated by the Swellaway device (using small Peltier cell contact with the skin) offer the ability to cool within therapeutic range with reduced impact on concentric strength when applied to the medial and lateral aspects of the knee joint. That said, and with a critical standpoint, eccentric and kinematic data in terms of dynamic stability were not quantified within the study. Furthermore, although correlation relationships are considered within the evidence base between T_{sk} and T_{im} it is still under contention as to the true reliability of this measure (T_{sk}) to accurately define muscle temperature decreases (Ostrowski *et al,* 2019). Collectively, we can only assume that greater deficits in dynamic stability or JPS may have been noted after wetted ice or the circumferential cooling over the rewarming period. Clinically this has implications on the correct time and considerations over adequate rewarming periods before returning to functional activity for athletes, sports medicine and performance practitioners to reflect in their management and safety. Future research however is required to confirm this.

Publication 5 Research Implications

It is evidenced that intra-muscular structures continue to decrease in temperature through a rewarming period following removal of cooling from contact with the skin (Rupp *et al,* 2012). The duration of cooling in this study was shorted than that of previous publications in the thesis (1-4), and one of the main considerations as to the reasons behind the findings at 20-minutes post cooling when measures were observed over the rewarming period. The other consideration is phase change capability of the modality. Although several variables affect phase change it is notwithstanding that this played a part in the outcomes reported in the study between modalities. Future studies and research design should consider the investigation of multiple applications, variable dosages and apply protocols to athletes in an injured (musculoskeletal sports injury) or fatigued state for example to truly progress the evidence-based practice of such cryo-compressive devices. Further investigation of targeted treatments, such as the Swellaway device and use of Peltier cell technology for cooling is warranted as the benefits of targeted and controlled cooling may be advantageous to athlete rehabilitation or recovery. The same should also be considered for the circumferential cooling abilities of the Game Ready® device. The choice of cooling modality may be based on the aim of treatment; however, this is only one variable that is considered to influence the design of optimal applications of cooling. At various phases of injury rehabilitation external compression is recommended to influence greater magnitudes of cooling and reduced oedema establishment (Ostrowski *et al*, 2019). What is worthy of further research here is the compression adjunct which these pneumatic cryo-compressive devices offer. Future research design should consider the effect of additional controlled compression to cooling and the effects on the four categories of response within themes highlighted in Figure 1. (pg. 41).

It became apparent to this point that although the findings have impact on current practice, multiple measures to quantify variables that influence optimal protocols of cryotherapy applications are required. Generally, land-based sports are multidirectional, requiring variable physical qualities and several feedback mechanisms that overlap across responses categorised in this work (*biomechanical, biochemical, physiological, psychological*) that one measure cannot solely provide. To understand the full extent of such cryo-compressive modalities on multifaceted responses (*biomechanical, biochemical, physiological, psychological*) future research design needs to include a multi-factorial study approach within the methodology to capture this to relate findings to current practice simultaneously developing the evidence base for optimising cryotherapy applications.

3.3 THEME 3: THERMOGRAPHY AND SKIN SURFACE RESPONSES TO CRYOTHERAPY (PUBLICATIONS 6-8)

3.3.1 Publication 6.

Alexander, J., *et al,* (2019). Mapping of skin surface sensitivity and skin surface temperature at the knee over a re-warming period, following cryotherapy. *PRM+ Journal of Quantitative Research in Rehabilitative Medicine*. 2(1): 1-5. (Appendix 3a).

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Mapping knee skin surface sensitivity and temperature following cryotherapy

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Abstract

Objectives

To investigate the effects of cryotherapy on knee skin surface sensitivity and temperature using monofilaments and thermal imaging.

Methods

Following a 20-minute cryotherapy exposure (crushed ice), knee skin surface sensitivity and temperature was mapped in 19 healthy participants using infrared camera and tactile sensory evaluation. The data were collected before and up to 20 minutes after cryotherapy exposure.

Results

Comparing to baseline, in women, significant decrease in skin surface sensitivity in the upper medial section of photographic knee pain map was observed up to 20-minutes after cryotherapy exposure. In men, the respective difference was observed only immediately after the explosion.

Conclusions

Crushed ice application may reduce skin surface sensitivity around a knee medial aspect and result in impeding return to play due to affected joint position sense following cryotherapy.

Keywords:

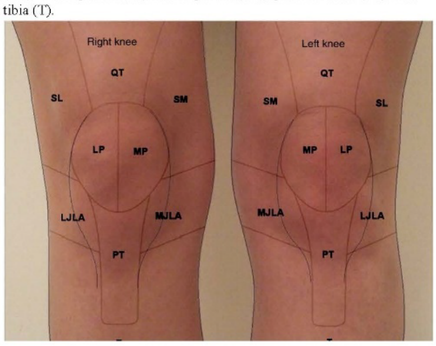
cryotherapy; cooling; knee; thermal imaging; skin sensation

INTRODUCTION

Cryotherapy decreases superficial tissue temperature via the removal of heat from the body (1). The pathophysiologic effects of topical modalities such as local cryotherapy include reductions in metabolism (2), pain, spasm, blood flow, inflammation, edema and tissue extensibility (1). It has been widely reported that nerve conduction velocity (NVC) is also decreased by local cooling (2,3). There has been conflicting evidence on the effects of local cooling on joint position sense (JPS) and the multifaceted stimuli of cutaneous receptor feedback in joint and soft tissue structures (4-6). The application of cryotherapy techniques is common in clinical practice and sport injury management (7,8). The therapeutic range for cooling has often been defined as skin surface temperature (T_{sk}) from 10°C to 15°C measured using non-invasive infrared thermal imaging (9). That temperature can be achieved by using crushed ice, wetted ice, gel pack, and cold-water immersion (10). The thermal properties of modalities vary in their cooling abilities and efficiency.

Afferent information feedback from skin receptors via tactile stimulation plays an important role in proprioceptive responses (11). Cutaneous receptors regulating a response to thermal and pressure changes include nociceptors, mechanoreceptors, and thermoreceptors (1). Tactile sensitivity has been reported to vary across different parts of the body (12). Cooling may penetrate to a depth of 2 to 4 cm decreasing the activation threshold of nociceptors and

Figure 1. Photographic Knee Pain Map developed and kindly agreed to be utilized in the study by Elson et al (2011) (21) for original use in collecting knee pain data.
Nine anterior zones: lateral joint line area (LJLA), medial joint line areas (MJLA), superior lateral (SL), superior medial (SM), quadriceps tendon (QT), lateral patella (LP) medial patella (MP), patella tendon (PT), and tibia (T).



subsequently reducing painful stimuli (1). Cooling might affect the response from mechanoreceptors as well (1). Slowed impulse conduction and cutaneous sensation has been considered to reduce pressure stimuli following cooling (13). Although cutaneous receptors may play a lesser role in proprioceptive feedback than muscle spindles

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Conflicts of interest: None to declare

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Figure 12. Abstract taken from, Alexander *et al,* (2019). Mapping knee skin surface sensitivity and temperature following cryotherapy.

3.3.1 Publication 6 Critical Account

Publication 6, situated in Theme 3 (Table 1, pg. 26-28), investigated the effects of cryotherapy on knee skin surface sensitivity (SSS) and T_{sk}. This publication corresponds with Research Question; *What is the impact of local cryotherapy application on skin surface sensitivity at the knee?* (Table 2, pg. 42-52) identified for exploration. The continuation of including male and female participants continued to support earlier recommendations by Costello *et al*, (2014a) and is became an indispensable consideration of the contemporary studies represented in this thesis. The investigation to establish whether differences occurred in SSS following a local cooling application of crushed ice was developed to address one of the variables presented in Figure 1 (pg. 41). Evidently, SSS represents a key physiological response to cooling that may help to explain earlier findings in relation to kinematic changes in knee JPS.

Publication 6 Study Rationale

To this point, research was limited and representative of upper limb peripheral neuropathy assessments in diabetic populations (Baraz *et al,* 2015). The quantity of studies in relation to the lower limb on tactile feedback responses was therefore relatively low. Further justification for this study was based around the consideration of how cutaneous receptors may play a part in JPS response to cryotherapy. The reduction of T_{sk} through superficial cooling and the effect on afferent feedback from skin receptors may have implications on understanding proprioceptive acuity responses and their role in JPS at the lower limb (knee). Therefore, quantification of SSS after cooling was considered an optimal measure to determine such responses. While there is a strong relationship suggested between accuracy of knee joint control response and reductions in muscle spindle or joint receptor feedback, the same cannot be said for the role in which cutaneous receptors may play. Although it was known to be less of an influence at this point no literature explored this component post cooling applications.

Publication 6 Results and Conclusion

T_{sk} fell to within therapeutic range (10-15°C) following the cryotherapy application over the patella region but unsurprisingly not for the tibialis anterior region. Although a reduction in T_{sk} was noted despite cooling location being superior to this ROI of the lower limb. It was unclear as to the reasons behind the large spread of cold observed for T_{sk} so distally over the tibialis anterior region when cooling was not directly applied to that area. This was considered important to acknowledge as implications to other structure responses such as muscle strength may be indirectly affected from superior or inferior location cooling through wider dissemination spread of cooling. Parameters of muscle strength were not objectively measured in this study, we can only speculate such a response and consider previous findings (Alexander and Rhodes, 2019). Neither ROI's (patella / tibia) returned to pre-intervention T_{sk} at the end of the rewarming period (20 minutes) observed for either gender.

Significant decreases in SSS for the superior medial and medial joint line regions of the PKPM (Figure 13) were displayed at immediately post and timepoints of up to 10-minutes post intervention. Between genders, significant differences in SSS were also observed. The findings displayed differences in SSS response between medial and lateral regions of the anterior knee. An explanation of this considered the known anatomical structures of the knee complex, specifically, the differences in neural pathways over medial and lateral regions suggesting that anatomical influences and may explain earlier findings in publications 1 and 2 that explored JPS noting changes in valgus control post cooling. Components of proprioceptive control, such as JPS and dynamic stability are required for optimal functional weight-bearing activities (Williams *et al,* 2001). Although these components were not simultaneously measured in this study, the findings in publication 6 present useful data with interpretation of how superficial sensory deficits at skin level may relate to other physiological and biomechanical responses to local cooling over peripheral weight-bearing joints.

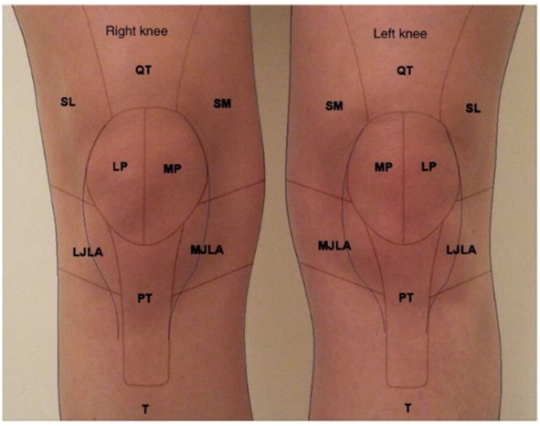

Figure 13. Photographic Knee Pain Map (Elson *et al,* 2011).

Publication 6 Practical Implications

Despite the questionable importance or minimal role thought to be contributed to proprioceptive feedback via cutaneous receptors, findings in this study presented interesting considerations to take forward in understanding the complex response mechanisms to cryotherapeutic applications. Medial regions of the knee compared to that of the lateral side (as depicted by the PKPM), demonstrated different responses to crushed ice application, reducing SSS significantly ($p<0.05$). These findings represented whole group (i.e., male, and female subjects together) and when collapsing groups by gender ($p<0.05$). The results highlight key anatomical differences when considering neural pathways that cross medial compared to lateral aspects of the knee. A reasonable 'physiological' explanation for the larger reduction in SSS reported for the medial side of the knee being the superficial locations of the saphenous nerve branches at the knee. These differences in tactile receptor feedback were considered and it was postulated that with larger reductions in SSS occurring over the medial aspect of the anterior knee joint, the deficiencies in valgus knee control as reported in earlier publications (Alexander *et al,* 2016; 2018) may be influenced by reduced cutaneous SSS feedback responses. SSS levels did not return to pre-cooling scores over a 20-minute rewarming period, and to date is the only study that observes a rewarming period which investigates tactile sensitivity of the lower peripheral limb rather than the upper (Moharić *et al,* 2014), therefore findings in the current study are difficult to compare or generate consensus.

Results may suggest adaptation of cooling dose between genders in terms of providing analgesia response. From a practical perspective, findings are limited in their contribution towards the understanding the extent of reduced cutaneous response through tactile response as acuity of JPS or muscle strength parameters in the same region were not quantified. Indeed, methods that incorporate all three parameters of measures (physiological, biomechanical, perceptual responses) may be interesting in future research but warrant justification as to the depth of relevance this information may contribute to the body of evidence around development of optimal cooling protocols using contemporary methods of cryotherapy. What may be of interest would be SSS levels in relation to dose response in terms of cooling duration, reflective of shorter cooling applications pitch side in sport for example. Whether SSS is affected to the same or lesser effect in terms of variable dose-response (duration of cooling) may provide vital information to develop optimal cryotherapy application protocols in sport.

Publication 6 Research Implications

Conclusively the study presents an interesting insight into cutaneous response to local cooling relatable to some of the known neuromuscular responses. Differences reported in findings between genders have implications on future investigations and methodological development of studies that investigate tactile response post cooling. It may be valuable for the development of cooling protocols in sport to investigate correlations between T_{sk} and SSS per section of the PKPM, however complex ROI would be required to determine precooling exposures for thermography analysis. This also highlights other statistical considerations for future studies. The statistical analysis approaches used in this study, being a repeated measures ANOVA and paired T-Test in hindsight may only provide a basic method of analysis, although useful to consider whether significant differences in SSS across the timepoints occurred. Consideration of analysis using a univariate method might have provided further information of interactions between 'gender*timepoint' interaction for example.

Fundamentally the interpretation of findings provides an interesting insight into SSS responses over a rewarming period following local cryotherapy not established previously. This study is the first of its kind to use the PKPM to represent and consider tactile parameters using monofilaments to quantify SSS over the anterior knee following cooling and over a rewarming period. Evidently the results have implications on the development of understanding surrounding the multifaceted responses of cryotherapy applications in sport in relation to related proprioceptive components that may be affected by local cooling. This approach became useful in several ways, to help identify relevant anatomical influences with regards to the findings and interpretation of results.

THEME 3: THERMOGRAPHY AND SKIN SURFACE RESPONSES TO CRYOTHERAPY

3.3.2 Publication 7.

Alexander, J., *et al,* (2020). Comparison of cryotherapy modality application over the anterior thigh across rugby union positions: A crossover randomized controlled trial. *International Journal of Sports Physical Therapy.* 15(2): 210-220. (Appendix 3b).

IJSPT

ORIGINAL RESEARCH

COMPARISON OF CRYOTHERAPY MODALITY APPLICATION OVER THE ANTERIOR THIGH ACROSS RUGBY UNION POSITIONS; A CROSSOVER RANDOMIZED CONTROLLED TRIAL.

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Daniel Birdsall BSc[1]
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ABSTRACT

Background: In deliberation of the diverse physical traits of rugby union and the known interference adipose tissue has on the ability to cool deeper tissues, evidence is required to understand the effect of cryotherapy modalities to provide optimum outcomes post-injury.

Purpose: To investigate differences in the cooling ability of three different cryotherapy modalities in a rugby union population in an attempt to describe optimum cooling protocols for the anterior thigh.

Study Design: Within-subjects randomized control crossover.

Methods: Twenty-one healthy male rugby union players took part. Skin surface temperature measured via thermal imaging camera (ThermoVision A40M, Flir Systems, Danderyd, Sweden) alongside Thermal Comfort and Sensation questionnaires following interventions of either Wetted Ice (WI), Crushed Ice (CI) applied in a polythene bag secured by plastic wrap, or CryoCuff® (CC), applied for 20-minutes over the anterior thigh. Participants were grouped by their typical playing position for the sport of rugby union; i.e. forwards and backs.

Results: Significant differences ($p = < 0.05$) in T_{sk} for all modalities compared to baseline and comparing post T_{sk} between CI and CC ($p = 0.01$) and WI to CC ($p = 0.01$) were displayed. Significantly greater reductions in T_{sk} noted immediately-post in the *'forwards'* group ($p = \leq 0.05$) compared to the *'backs'* group for, all modalities ($p = \leq 0.05$). Thermal Comfort and Sensation scores demonstrated significant changes baseline compared to post for all modalities ($p = < 0.05$). No significant differences were found when comparing between modalities for Thermal Comfort ($p = 0.755$) or Sensation ($p = 0.225$) for whole group or between positional groups.

Conclusions: Physiological responses to cooling differed across modalities with WI producing the greatest decrease in T_{sk}. Significant variability in T_{sk} was also displayed between positional factions. Results uphold the importance of the individualization of local cooling protocols when considering physical traits and characteristics within a rugby union population. Findings provide further understanding of the physiological responses to cooling through T_{sk} quantification in specific populations, helping to guide sports medicine practitioners on optimal cooling application development in sport.

Level of Evidence: Level 2b

Keywords: Cryotherapy, Rugby Union, Thermal Imaging, Movement System

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Figure 14. Abstract taken from, Alexander *et al,* (2020a). Comparison of cryotherapy modality application over the anterior thigh across rugby union positions: A crossover randomized controlled trial.

3.3.2 Publication 7 Critical Account

This publication corresponds with Theme 3 (Table 1, pg. 26-28) and Research Question; *Do different physiological responses occur in skin surface temperatures across multiple cryotherapeutic modalities utilised in sport?* (Table 2, pg. 42-52) identified for exploration. As part of the diverse physical traits found within a rugby union playing squad developed from the demands of the sport, consequently levels of adipose tissue vary across positional factions. The study therefore investigated whether differences in response to multiple types of cryotherapy modalities occurred and considered groups of playing positions, i.e., 'forwards' and 'backs' to describe and develop optimal cooling protocols over the anterior thigh region. The comparisons of three different modalities were examined relative to playing position and comparisons were made between the modalities using the same outcomes measures.

Publication 7 Study Rationale

The choice and application of cryotherapeutic modalities in sport vary, with optimum exposure protocols still in debate in practice when considering clinical effectiveness and thermodynamics (Jutte *et al*, 2001; Kennet *et al*, 2007; Hardaker *et al,* 2007; Bleakley *et al,* 2012). Key cellular and physiological changes following cryotherapy are well reported (Knight *et al,* 2000; Jutte *et al,* 2001; Algafly and George, 2007) and the efficacy of cryotherapy is often investigated through the quantification of T_{sk} via thermal imaging (Selfe *et al*, 2009; Costello *et al*, 2012a; Selfe *et al*, 2014; Alexander *et al,* 2016; 2018). Early literature considers temperature change in deep tissue inversely relates to skinfold and limb circumference (Lowden and Moore, 1975). Many latter sources agree that adipose tissue levels implicate the clinical effectiveness of cooling (Otte *et al,* 2002; Bleakley *et al,* 2011; Hawkins and Miller, 2012) and therefore should be considered when deciding on a cooling dose or modality. Otte *et al*, (2002) reported a clinically important relationship between adipose thickness and required cooling durations, suggesting that length of duration requires adaptation to different levels of skin fold measures to produce similar T_{im} temperatures. Despite this no study had considered quantifying these claims in a sporting population, nor compared this in respect to positional differences or demands of team-based sports. From this perspective, it seems appropriate to question whether sports medicine or performance practitioners are implementing knowledge according to evidence (or the lack of) and based on historical entities such as familiarity of modality, ease of application, or tradition proposed by Hawkins and Hawkins (2016). The justification for this study most definitely stemmed from this perception, complementary to the underpinning necessity for more applied research to provide appropriate evidence that can be transferred into practice.

Publication 7 Results and Conclusion

Analyses showed that in a population of semi-professional rugby union players (20±2.9 years, body mass 96.2±16.7 kg, height 179.9±7.1 cm, BMI 29.7±2.6 kg/m2 and thigh circumference 62.5±7.1 cm), statistically significant reductions in T_{sk} occurred and varied significantly between playing positions (forwards vs backs). Greater magnitudes of cooling across the anterior thigh were displayed in the 'forwards' group compared to the backs on immediate removal of the intervention, and for all three modalities this transpired. Overall WI proved most effective at reducing T_{sk} when comparing all three modalities over the same region (anterior thigh). These results corroborate available data in studies that compared WI with other forms of cryotherapy (Dykstra *et al,* 2009; Hamid *et al,* 2013), and findings are thought to be due to optimal phase change capability achieved by this mode of cryotherapy (Merrick *et al,* 2003). Perceptual responses in relation to TC and TS were as predicted, with colder temperatures resulting in reduced comfort and sensation scores. Interestingly when collapsing the data for analysis between groups the insulating effects of increased adipose tissue levels in the forwards group had a profound effect of the level of sensation/comfort in comparison to backs response. Consequently, backs reported a larger reduction in TC, but forwards reported a larger reduction in TS which can only be rationalised by the cooler T_{sk} reported in the forwards group. This is clearly represented in the WI exposure particularly.

Publication 7 Practical Implications

It was predicted that differences would occur between groups in terms of the influence adipose tissue levels have on superficial cooling efficacy. These findings were contrary to what was expected with regards to the way each positional group responded. As forwards typically present with higher body fat percentage and larger thigh circumference (and anthropometric data displayed no difference in this study compared to previous characteristic analyses in this population group) (Duthie *et al,* 2003; 2005; Cahill *et al,* 2013), it was thought that thermal imaging would show superficially warmer T_{sk} temperatures in the forwards groups compared to the backs. Yet, T_{sk} data indicated the opposite. When considering the interference of adipose tissue on thermodynamic mechanisms that occur from superficial cooling it seems sensible to appreciate that the insulating effects of adipose levels in the forwards group prevented the direct extraction of heat thus resulting in cooler superficial T_{sk} temperatures. A logical response, nevertheless, this potentially challenges former theories relating to the proposed relationships between T_{sk} and T_{im} (Hardaker *et al,* 2007). If we consider the quadratic relationship proposed by earlier work (Hardaker *et al,* 2007) it may be assumed that cooler T_{sk} temperatures indicate T_{im} follows in a quadratic fashion (Figure 3, pg. 93), by which we can assume T_{im} is decreasing and at a specific degree of reduction. If the proposed rationale for the results presented in publication 7 suggest however, that adipose tissue is consequently restricting the extraction of heat from deeper tissues, the relationship between T_{sk} reductions would not be representative of T_{im} temperatures necessarily. Therefore, relationships of cooling applications on deeper muscular temperatures may be questioned though the physiological responses demonstrated here. T_{sk} responses present in an altogether different manner depending on adipose tissue levels, which in succession relates directly to playing characteristics across a rugby union playing squad. This has direct implications on protocol development of optimal cryotherapy applications in sport. Additional investigations which incorporate measures of T_{im} are imperative and beneficial to the design of optimal cooling protocols confirming the effects of superficial cooling on deeper structures, specific to a sporting population. Although only superficial physiological measures were collated in this study the results demonstrate that several variables impact the desirable outcome of cooling applications and different modes present different capabilities, due to several influential factors.

Publication 7 Research Implications

Unlike previous research designs in the thesis, the methodology was specific to a sporting population where dichotomies between player characteristics occur in response to the demands of the sport. At the time no other research of similar standing was available. This provided an opportunity to reduce the ravine of knowledge for protocols of cryotherapeutic treatment within specific populations and highlight future research considerations that are required. While expected results occurred between optimal cooling efficiency of modalities at this point per se, the proportional differences in T_{sk} results between within-population groups were interesting. The findings of this study have had direct implications on the design of subsequent research to advance understanding around optimal protocols of cooling for injury management or recovery.

The main contributing factors to research from this study are the obvious impact on physiological responses that different modalities of local cooling have. The impact of such dictates to some extent modality choice via decision-making for sports injury or rehabilitation that comprises the use of cooling. In hindsight the publication should have elaborated further on the different positional demands and consequential levels of residual fatigue and demands of the sport rather than only the physiological differences that contributed to the differences in responses that were reported. That said, the conclusions strongly correlate to previously literature through comparison of modalities and consequential T_{sk} (Kennet *et al,* 2007), and results demonstrate new evidence regarding specific population groups in sport not explored in this style before. With that in mind, irrespective of modality choice, further studies that investigate sport specific responses to contemporary cooling methods should consider multiple measures of physiological responses in cohort groups representative of elite populations. The benefits of this would be two-fold; 1) develop research that represents physiological, biomechanical or psychological measures relevant to industry, and 2) present useful findings that increase the impact of research into practice to the benefit of sports medicine and performance practitioners. A study associating different contemporary methods of cooling that incorporate compression is warranted to demonstrate this. A related study from theme 4, publication 11, considers modern methods of cooling and examines other physiological measures aside from those investigated here. Furthermore, the basis of this investigation prompted the expansion of future studies into elite populations and the development of a triad of measures with the addition of kinematic and strength measures deemed useful in the development of recovery strategies that utilise cryotherapy. Examples of this are shown in publications 13 and 14. Finally, research that ties in the contributions of historical knowledge on optimal cryotherapeutic modalities (through reduction magnitude of T_{sk}) and considers objective, measurable parameters of contemporary devices beneficial to current practice would provide additional analysis needed in this field. Those results may indicate the value of modality choice in performance settings when time-loss to injury or recovery demands are heightened.

THEME 3: THERMOGRAPHY AND SKIN SURFACE RESPONSES TO CRYOTHERAPY

3.3.3 Publication 8.
Alexander, J and Rhodes D (2020). Editorial Commentary - Thermography for defining efficiency of cryotherapy modalities in sport. *Temperature.* 8(2):105-107. (Appendix 3c).

TEMPERATURE
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Front Matter: Discovery

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Thermography for defining efficiency of cryotherapy modalities in sport

Comment on: Alexander, J., Selfe, J., Birdsall, D., Rhodes, D. The effects of three different cryotherapy modalities on skin surface temperature across squad positions in a population of male, rugby union players. *Int J Sports Physical Therapy*. 2020;15(2): 210-220.

Infrared Thermal Imaging (TI) is well evidenced for the quantification of skin surface temperature (T_{sk}) and abundantly used within cryotherapeutic research [1–4]. We have published several articles recently on the effects of local cryotherapy with the physiological effects quantified through T_{sk} via TI techniques [3,4]. The remit of those studies was based on two key themes: (i) T_{sk} response to contemporary cooling modalities compared to traditional applications (ii) T_{sk} and physiological response to contemporary cryo-compressive devices with varying pressure adjuncts for the management of musculoskeletal injury or as a recovery strategy in sport. Comparison of traditional methods of cryotherapy modalities to modern alternatives in sport provided justification to progress the knowledge in theme (i). Literature to support theme (ii) was evidently lacking and developed naturally to combine multiple contemporary cooling modalities that operate cooling and compression simultaneously. All of which quantified T_{sk} through infrared TI and followed guidance by Moreira et al. [2], for the setup of thermology capture.

Several investigations utilize infrared TI as an objective measure to quantify the efficiency of common cooling modalities used in sport by way of T_{sk}. Preferences on the choice of cooling modality often amount to whether optimal temperatures can be achieved in the target tissues and are quantified via T_{sk}. In our recently published manuscript in the *International Journal of Sports Physical Therapy* [3], we aimed to determine differences in the cooling ability of three different cryotherapy modalities (Wetted Ice, Crushed Ice and CryoCuff®), in a specific sports population through physiological measures of T_{sk} using TI. Physical characteristics vary between playing positions in rugby union due to the demands of the game, and in consideration of this, levels of adipose tissue vary and influence interference on the efficacy of local cooling applications. To date, although studies consider a comparison of multiple cooling modalities, typically methods fail to report heterogeneities of participants or properties of the modality. A therapeutic temperature range for target T_{sk} following local cooling applications of 10–15°C has previously been proposed [1]. This typically represents a T_{sk} range whereby physiological responses occur and are often referred to in publications related to cooling parameters achieved by cryotherapeutic modalities [1]. Results from our study [3] demonstrated differences in T_{sk} response to cooling with wetted ice displaying the greatest reductions. The main findings however highlighted not only the significant differences between T_{sk} when comparing between the three different modalities (Wetted Ice; Crushed Ice and CryoCuff®) but also across playing positions (forward and backs). Results suggest using TI, to determine the effects of such variable (physical characteristics) is useful to consider in relation to the efficacy of cryotherapeutic applications in the assumption that adipose tissue levels vary between these positional characteristics. This may appear obvious, and cooling applications in terms of duration should be altered to account for the insulating effects of adipose tissue. That said, no evidence was available that compared contemporary cooling to traditional methods, nor contemplated the physical characteristic differences in playing position in specific sports populations at the time. Evidently, analysis using infrared TI results indicates that potential phase change differences alongside characteristic variables may both be responsible for variance in target T_{sk} responses [3]. In terms of an applied practical impact, individualization of local cooling applications and choice of modality is imperative for optimal response. From

Figure 15. Abstract taken from, Alexander and Rhodes, (2020). Editorial Commentary - Thermography for defining efficiency of cryotherapy modalities in sport.

3.3.3 Publication 8 Critical Account

Publication 8 is an editorial commentary which critiques the use of thermal imaging (thermology) for defining the efficiency of cryotherapy modalities in sport. The context of the publication refers specifically to a previous publication in the thesis **(Alexander, J., *et al;* The effects of three different cryotherapy modalities on skin surface temperature across squad positions in a population of male, rugby union players. *Int J Sports Phys Ther.* 2020;15(2): 210-220).** Publication 8 corresponds with Theme 3 (Table 1, pg. 26-28) and Research Question; *How does the use of thermology for challenge the preferences and define efficiencies of cryotherapy applications in sport?* (Table 2, pg. 42-52) identified for exploration.

Publication 8 Study Rationale

Several articles presented in the thesis investigate the effects of local cryotherapy with the physiological effects quantified through T_{sk} via TI techniques (Alexander *et al,* 2018; 2019; Rhodes and Alexander, 2018; Alexander and Rhodes, 2020; Alexander *et al,* 2020a; 2020c; 2021a; 2021d; 2021e and 2021f; Selfe *et al,* 2014). All those studies quantified T_{sk} through infrared TI and followed guidance by Moreira *et al,* (2017) (for studies 2017 onwards) for the setup of thermology capture. It seemed logical to produce a commentary on this topic as a transient measure noted throughout all themes in the thesis. Recent literature had debated the accuracy of infrared thermal imaging, challenged by Maley *et al,* (2020) followed by a counterpoint argument for its use by Havenith and Lloyd (2020) published in the same journal (Journal of Thermal Biology). Neither however contemplated the practical applications of thermal imaging in an applied nature in terms of its benefit to practitioners in the field of sports medicine and performance.

Publication 8 Results and Conclusion

From an evidenced-based perspective, findings from published work in the thesis, support the use of TI. Therefore, in consideration of the implications on the development of what may be ‘optimal protocols’ of cooling in sport, thermology measures of T_{sk} were important to define. Subsequently, and with these collective findings considered, the editorial commentary publication proposed that infrared

TI provides an objective measure to quantify T_{sk} differences between various cryotherapy modalities and those with adjunct pressure options offered by contemporary pneumatic cooling modalities, as a safe non-invasive method.

Publication 8 Practical Implications

Infrared TI is beneficial in challenging preferences of contemporary cooling applications in sport through thermography for decision-making, however further validation of methods is welcomed to provide accurate measurement of T_{sk} in the lower limb. Practically the editorial highlights to readers the importance of thermology and presents contemporary arguments for its accuracy to develop optimal research study design through gold-standard equipment to quantify appropriate physiological measures to determine optimal cryotherapy applications in sport.

Publication 8 Research Implications

With the perspective that thermology is useful in quantifying the physiological effects of cooling modalities on T_{sk}, individual measures of TI may provide useful data challenging future study design to consider multiple metrics that represent relevant parameters of investigation in sports-related cryotherapy investigations, beneficial simultaneously to infrared TI measures. Many studies do represent this in the thesis and therefore continue to provide data with translational outcomes when investigating cooling protocols in sport. Implications on further research therefore consider individual response analysis rather than group average data as important and may eliminate positional differences in team sport investigations (as one example). This editorial publication highlights those future studies could achieve these investigations through the utilisation of multiple metrics combining physiological, such as TI, biomechanical and psychological measures and individual data analysis, with the aim of greater impact to practice through optimal individualised approaches for contemporary cryotherapeutic applications. Publication 8 acknowledges the many approaches in which accuracy of thermographic cameras can be improved for their use in cryotherapeutic studies including camera configuration, utilisation of reference values, greater number of temperature pixels or advanced camera technology, (Havenith and Lloyd, 2020). That said, the comparison to other methods of thermology may be justified in future research too.

3.4 THEME 4: CONTEMPORARY CRYOTHERAPY APPLICATIONS AND RESPONSES (PUBLICATIONS 9-11)

3.4.1 Publication 9.

Alexander, J., *et al,* (2021). Cryotherapy in Sport: A Warm Reception for the Translation of Evidence into Applied Practice. *Research in Sports Medicine.* 10: 1-4. *(*Appendix 4a).

RESEARCH IN SPORTS MEDICINE
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Cryotherapy in sport: a warm reception for the translation of evidence into applied practice

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ABSTRACT

Research contributing to the understanding of the mechanisms that underpin cryotherapy application in sport are evident. The translation of impactful findings that contribute to the design and implementation of cryotherapy protocols which are advantageous to the athlete in an applied sport setting, however, are still being explored. The role of cryotherapy for acute sport injury management is challenged in recent literature and discrepancies around the periodisation of cooling to maximise injury management or recovery, contribute to the confusion around optimal applications of cryotherapy in sport. The purpose of this work was to provide a contemporary summary of current perspectives, challenges and approaches for the use, application and translation of cryotherapy evidence into applied practice in a sporting context. The intention being to stimulate further debate on the topic and highlight key considerations for future study designs that reflect current practices. For improved translation of evidence for or against the use of cryotherapy in sport, it is suggested that future study design and methodologies should reflect contemporary demands within sporting environments where cryotherapy protocols for injury, rehabilitation or recovery are a feature of athlete management through investigation of individual response, and multi-measures of well-being and performance.

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KEYWORDS
Injury; cooling; research; musculoskeletal; pain

Figure 16. Abstract taken from Alexander *et al,* (2021b). Cryotherapy in Sport: A Warm Reception for the Translation of Evidence into Applied Practice.

3.4.1 Publication 9 Critical Account

Publication 9 is an editorial commentary which critiques contemporary approaches in the application of cryotherapy for acute injury management and the developments around current perspectives which implicate practice. Considerations around translation of evidence into practice is evaluated to stimulate debate and future studies that best represent current practice and industry demand. The context of the publication refers specifically to contemporary acronyms such as POLICE (Bleakley *et al,* 2012) and PEACE and LOVE (Dubois and Esculier, 2020). Publication 9 corresponds with Theme 4 (Table 1, pg. 26-28) and Research Question; *What are the current perspectives of cooling for acute injury?* (Table 2, pg. 42-52) identified for exploration.

Publication 9 Study Rationale

As the collection of publications progressed and the themes emerged in a way to present the studies it became apparent of the contemporary debates in the literature and new concepts for and against the use of cryotherapy for acute injury management. These debates had some baring on the studies which followed in theme 4 and 5. Because the focus of many of the publications in this thesis were aimed at immediate effects of application and multifaceted responses, the development of a short editorial piece seemed fitting and a way to acknowledge that current topical debates were considered within the thesis and study designs of subsequent publications.

Publication 9 Results and Conclusion

The evaluation of current perspectives in this piece, in brief, suggested multifactorial approaches for sports injury management are ideal. Contemporary challenges to historical debates of the use of cryotherapy for acute injury management need to be investigated further.

Publication 9 Practical Implications

Deciphering optimal cooling protocols for sporting scenarios such as acute injury management or recovery were highlighted as challenging in this editorial. These are thought to be caused by confusion still evident in the literature and conflicting debates about when and if to use ice for acute injury management at all. Periodisation is a term which appears relevant for future investigations to consider when evaluating the applications of cryotherapy for both acute injury management and recovery in applied practice settings. Practically of interest to sports and exercise medicine or performance practitioners it would provide useful research that reflects current practice debates and may answer simple questions around when and how is the best way to incorporate cryotherapy into acute injury management or recovery principles. The editorial further highlights the key messages of individualisation of cooling application to an athlete's needs. Studies in theme 5 of this thesis address some of the practically relevant interests which have emerged from this editorial article with respect to the reflection of real-world research and individual responses of cryotherapy protocols in sport.

Publication 9 Research Implications

The context of the editorial presents' ideas for deliberation in future research around the translation of evidence into practice; *'discovery research'* being one through *'theory driven translational research'* (Owoeye *et al,* 2020). The implications of this being a positive approach in reducing the gap between research and practice. To do this successfully however it is important to gain a perspective on what practitioners deem important to their daily challenges in practice within elite, high-performance environments to maximise the impact of future research in this area. A recent example of this was achieved through collaboration on a project that investigated athlete, coach and practitioner knowledge and perceptions of post-exercise cold-water immersion for recovery (Allan *et al,* 2021). Findings from that study supports the suggestions made in this body of work, where CWI in this example is useful for recovery in sport and the focus of scientific research evolution should consider investigating the psychophysiological interaction through appropriate methodology (Allan *et al,* 2021). In reference to Figure 1 (pg. 41) presented in this thesis, the four categories of response (*biomechanical, biochemical, physiological, psychological)* are an important part of the development of *'theory driven translational research'*. Collectively these represent the multifactorial approaches in sport that may be appropriate to quantify the benefits or advantageous qualities that cryotherapy can offer to the individual athlete in several contexts of sport performance, such as recovery.

THEME 4: CONTEMPORARY CRYOTHERAPY APPLICATIONS AND RESPONSES

3.4.2 Publication 10.
Alexander, J., *et al,* (2021). Cryotherapy and Compression in Sports Injury Management: A Scoping Review. *International Journal of Therapy and Rehabilitation.* 28(10): 1-19. (Appendix 4b).

IJTR

REVIEW

Cryotherapy and compression in sports injury management: a scoping review

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Abstract

Background/Aims For the management of sports injury, cryotherapy is commonly applied, yet modalities differ extensively in application including levels of compression. The aim of this study was to provide a comprehensive review of the current position in the literature on contemporary cryo-compression applications for musculoskeletal sports injury management.

Methods A total of eight databases were searched: Sport Discus, Science Direct, CINHAL, Scopus, PubMed, Cochrane, ProQuest and MEDLINE. Publications were restricted to 30 years and had to be in the English language. Medical subject headings, free-text words, and limiting descriptors for concepts related to cryotherapy and compression for sports injury were applied. Inclusion criteria determined at least one modality of cryotherapy treatment applied simultaneous to compression or as a comparison, relevant to sports injury management. Modalities included cryo-compressive devices and gel/ice packs, in association with concomitant compression. Male, female, healthy and injured participants were included. Two reviewers independently selected eligible articles, resulting in 22 studies meeting the inclusion criteria following full-text appraisal.

Results Inconsistent methodologies, low sample sizes and variability in outcome measures provided uncertainty over optimum protocols. A lack of previous understanding in the protocols in the available literature for isolated cryotherapy/compression applications prevents understanding of the therapeutic benefits of combined cryo-compression. No definitive agreement behind optimal cryo-compression applications were identified collectively from studies other than the consensus that compression aids the magnitude of cooling.

Conclusions Although compression appears a useful adjunct to cooling modalities for the management of sports injury, no definitive agreement on optimum compression concurrent with cooling protocols were drawn from the studies. This was because of several methodological gaps in reporting throughout studies, highlighting a lack of studies that represent applications of compression and cryotherapy within a sporting context or applied nature within the available research.

Key words: Cooling; Cryo-compression; Modalities; Musculoskeletal; Physiological

Submitted: 23 October 2020; accepted following double-blind peer review: 2 June 2021

Figure 17. Abstract taken from Alexander *et al,* (2021c). Cryotherapy and Compression in Sports Injury Management: A Scoping Review.

3.4.2 Publication 10 Critical Account

Publication 10 was the first to purposely investigate current agreement from the evidence base on simultaneous cryotherapy and compression applications in sport. This publication corresponds with Theme 4 (Table 1, pg. 26-28) and Research Question; *What is the current opinion on contemporary cryo-compressive applications in sport for injury and recovery management?* (Table 2, pg. 42-52) identified for exploration. The effectiveness of cooling modalities is dependent on several variables acknowledged in developmental research, consequently optimal protocol or choice of modality is confusing. Study 10 became a natural extension of the investigations comparing modalities and the effects on physiological markers in the thesis (Alexander *et al,* 2016; 2018; 2018; 2019; 2020a). Prior to further intervention study designs that involved cryo-compressive devices it was felt that an understanding of agreement through a scoping review would help define subsequent approaches in the thesis publication route. Consequently, the purpose of this piece of work was to produce a synopsis that offered current debate on contemporary cryo-compression applications for musculoskeletal sports injury management.

Objectives were to:

1. *Examine current research conduct and summarise the available evidence base for the application of simultaneous cryotherapy and compression modalities typically applied in the management of musculoskeletal sports injury.*
2. *Highlight knowledge gaps in the current evidence base that may help inform future research in the topic area.*

Publication 10 Study Rationale

A scoping review study design was decided based on the opportunity to explore a broader topic area and contemplate the value, quality and type of evidence available. This would form the argument of whether a future systematic review would be beneficial to the topic area. To gain an understanding of the current agreement for simultaneous application of cryotherapy and compression provided the opportunity to highlight accurately that cryo-compressive protocols currently applied in sports settings are based on weak, diverse and difficult to compare evidence.

Publication 10 Results and Conclusion

Twenty-one full text publications made up the final scoping review. Qualitative appraisal indicated that although compression appears a useful adjunct to cooling modalities to increase the magnitude of temperature reduction, no conclusive agreement on optimum compression concurrent with cooling protocols were determined. It was considered that studies were of poor methodological quality, low sample sizes and highly variable in the outcome measures utilised. To determine 'optimal protocols of cryo-compression' was difficult based on the available evidence which provides uncertainty over the best methods of application in sport for both injury and as a recovery strategy. A lack of prior understanding around the responses to isolated cryotherapy or compression applications prevents the development of combined cryo-compression protocols. This impacts the ability to determine definitive clarity on the therapeutic benefits of cryo-compressive applications for utilisation in sport.

Publication 10 Practical Implications

Findings from the study considered the dynamic interplay taking place within the body's homeostatic mechanisms. Conclusively it was logical to highlight that research should investigate the variables in cryotherapeutic applications independently from compression and vice versa. If there is no definitive understanding around the effects of cooling or compression independently it becomes problematic to clearly assume the impact on physiological markers that may occur from simultaneous cryo-compressive applications. The inadequate available research to base best / optimal practices for cryo-compression is acknowledged. Variables not quantified or representative of markers relevant to sport throughout the studies appraised in the scoping review were evident. Clinically the implications of these findings are two-fold, defining that; 1) protocols utilised currently in sport are unlikely to be based on substantive research, and 2) research does not represent / test current processes of cryo-compressive applications or contemporary devices utilised in practice.

Anecdotally the benefits of cryotherapy are noted to be advantageous to the athlete when applied at their most optimal period within musculoskeletal injury or recovery management. Evidence to support when or through which modality this might best represent requires further investigation. The potentials of using cryo-compression as a recovery strategy are perhaps misconstrued or lost within the evidence base due to a lack of quality methodologies or critical appraisal with limited progression of recent quality systematic reviews. The lack of randomised controlled trials with methods that represent current practice of cryotherapy, compression and cryo-compression in the field of sports medicine or elite performance settings negates impact within the field. Practitioners should be mindful of the developments required in research to progress optimal protocols of cryo-compressive devices to support or refute their practices. From a purely critical standpoint, the consideration of a significant number of variables are vital to shape future study design. To achieve greater impact of findings into practice; these considerations may include and in no order, nor limited to the following.

i. *Consideration and comparison of contemporary cryo-compressive devices.*
ii. *Periodisation of cooling / cryo-compressive applications.*
iii. *Dose-response of contemporary cryo-compressive applications.*
iv. *Appropriate markers representative of multifactorial approaches in elite sport for athlete recovery.*
v. *Individual analysis of data interpretation vs group analysis to best represent intervention response to cooling, compression or cryo-compressive applications in sport.*

Publication 10 Research Implications

Further enquiry of technological advancements that provide cryo-compression are warranted. To advance current practice of such applications commonly applied in elite sports settings, research needs to define several parameters of investigation, including optimal temperature, time, or compression in isolation ultimately leading to dose-response study designs. Aside to this, full consideration of the variables that influence interpretation of objective markers are imperative to the impact future research should have on applied practices. McCall *et al.* (2015) suggest that practices often used in sports settings are not always supported by validated recommendations from evidence and vice versa. Perhaps a different approach should be considered to prospective study designs to generate robust and beneficial data that would impact practice more effectively. To further the understanding on optimal cryo-compressive applications, the investigation of current protocols applied by sports medicine or performance practitioners in practice should utilise relevant outcome measures that would determine whether advantageous physiological effects are being achieved from current practices relevant to that sport, rather than a one-size fits all approach to study design and data interpretation. Findings from this scoping review instigate and facilitate such an approach. With thought given to comparison of contemporary technological advancements in cryo-compressive devices the opportunity to progress this topic (cryo-compression) as a recovery strategy progressed in studies 11 and 12.

THEME 4: CONTEMPORARY CRYOTHERAPY APPLICATIONS AND RESPONSES

3.4.3 Publication 11.

Alexander, J., *et al,* (2020b). Physiological Parameters in Response to Levels of Pressure during Contemporary Cryo-Compressive Applications: Implications for Protocol Development. *Journal of Athletic Enhancement.* 9(1): 1-6. (Appendix 4C).

Alexander et al., J Athl Enhanc 2020, 9:1

Journal of Athletic Enhancement

Research Article — A SCITECHNOL JOURNAL

Physiological Parameters in Response to Levels of Pressure during Contemporary Cryo-Compressive Applications Implications for Protocol Development

Alexander J[1]*, Greenhalgh O[1] and Rhodes[2]

Abstract

Background The effectiveness of simultaneous dosages of compression and cryotherapy that cryo-compressive devices can offer are of interest in the management of sports injury or post-exercise recovery. Dose-response in terms of physiological parameter is required to inform current practice in the remit of sports medicine to help define optimal protocols for application. The current study aimed to investigate the physiological effects and subjective responses of different cryo-compression dosages offered by two cryo-compressive devices over a rewarming period. Methods Twenty-nine healthy male and female participants (male n=18; female n=11) volunteered (mean ± SD: age 22 ± 3.6 years, height 168.2 ± 8.6 cm, weight 67.4 ± 11.5 kg and thigh circumference 50.7 ± 6.7 cm). Objective measures included skin surface temperature, muscle oxygenation saturation, thermal comfort and sensation. Data were collected pre, immediately post and over a 20-minute rewarming period. Participants were randomly assigned to either Group A (Game Ready); B (Squid) or C Control group. Intervention groups received different cryo-compressive protocols for testing, but all received 15-minutes of cooling. Results Significant reductions in skin surface temperature were displayed across the intervention groups for all time-points ($p \le 0.05$). Analysis of all data displayed a significant effect of time ($p \le 0.001$) on muscle oxygenation. Collapse of the data indicated significant differences in muscle oxygenation across the different modalities and pressure ($p \le 0.05$). Conclusion Muscle oxygenation saturation and skin surface temperature responses differ depending on pressure dose in conjunction with cooling. Higher initial increases of muscle oxygenation saturation immediately post intervention correlate to higher levels of compression. Greater magnitudes of cooling can be achieved through the adjunct of compression. Dose-response relationships between cooling and simultaneous compression should be considered and are dependent on the therapeutic aim of treatment. In order to develop optimum protocols for management of either injury or recovery parameters further investigation is required of contemporary cryo-compressive devices.

Keywords

Cryotherapy; Physiology; Muscle oxygenation; Skin temperature; Compression

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Introduction

Cooling for post-exercise recovery or injury management is common practice within sport, with the belief that recovery characteristics benefit from such protocols [1-3]. Symptoms of delayed onset muscle soreness (DOMS) for example reportedly reduce following cryotherapeutic interventions due to positive physiological responses [2,4]. Cryo-compressive devices aim to provide simultaneous cooling and compression for sports injury and enhance recovery benefits. With recent literature, reporting positive influences on performance recovery parameters [5]. Nevertheless, several questions remain that surround the effects of cooling and simultaneous compression on physiological parameters such as SmO_2, and optimal protocols are unsubstantiated from the variability in methodologies published. Thus providing confusing conclusions for sport medicine practitioners unsure on the differences that may exist between cryo-compressive devices, settings and outcomes for optimal applications, Previous literature reports decreases in SmO_2 following cold-water immersion [6,7] it is suggested that compression aids the magnitude of cooling [8-10]. Conversely, isolated external compression is reported to increase SmO_2 [11,12]. To what extent the physiological response of muscle oxygenation is affected by such applications that combine cooling with compression therefore is still under contention.

Measurements of muscle oxygen saturation (SmO_2) and skin surface temperature (T_{sk}) support the understanding of the potential effects local cryotherapy may have on objective markers [3]. Prominently observed in literature, a local cryotherapy application initiates the reduction of T_{sk}, skin blood flow, and muscle oxygenation [13]. The ratio of oxyhaemoglobin concentration to total haemoglobin concentration in the muscle reported as a percentage, is useful in providing real-time physiologic feedback. Indicators of muscle metabolic activity can be noninvasively monitored by collating muscle oxygenation and haemodynamic, with such devices as MOXY sensors (MOXY, Swinco, and Zurich, Switzerland). Previously studies have demonstrated decreases SmO_2 following cooling applications of cold-water immersion [3,6,7]. Simultaneous dosages of compression (mmHg) and cryotherapy that cryo-compressive devices can offer are of interest in the management of sports injury or post-exercise recovery. Consequently, the effectiveness of these devices for injury or recovery management in sport is warranted. An insight as to whether different physiological effects occur after exposures to different cryo-compression dosages is important to inform current practice in the remit of sports medicine. Over a rewarming period, the current study aimed to investigate the physiological effects and subjective responses of different cryo-compression dosages offered by two cryo-compressive devices. We hypothesised that higher compressive dosages would result in greater magnitude of cooling, demonstrating larger reductions in $T_{sk,}$ and subsequently greater reductions in $SmO_{2.}$

Materials and Methods

Participants

The host university ethics committee, in accordance with the Declaration of Helsinki, agreed approval of the study. Participants were provided with information regarding study protocol prior to

Figure 18. Abstract taken from, Alexander *et al,* (2020b). Physiological parameters in response to levels of pressure during contemporary cryo-compressive applications implications for protocol development.

3.4.3 Publication 11 Critical Account

Unequivocal use of pneumatic cryo-compressive devices in sport is known for their part in rehabilitation and recovery. Publication 10 corresponds with Theme 4 (Table 1, pg. 26-28) and Research Question; *Do physiological differences occur in response to varied cryotherapy and compression dosages in sporting populations?* (Table 2, pg. 42-52) identified for exploration.

Publication 11 Study Rationale

Despite the assumption within the available literature that the magnitude of cooling is enhanced by compression, there is a limited understanding of the multifaceted responses and consequently the rationale for its use via cryo-compressive devices. The protocol design for publication 10 emerged from the findings of the earlier scoping review (publication 10) which indicated the need for investigative studies of contemporary pneumatic cryo-compressive devices and dosages commonly utilised in sport. The review acknowledged that understanding around protocols for cryotherapy and / or compression in isolation is lacking (Alexander *et al,* 2020). Furthermore, the emerging importance of dose-response to optimise cooling protocols in sport fuelled the rationale for this study, recognised as an important variable in understanding the physiological responses to cryotherapy. Several questions remain as to the effect on physiological parameters from cryo-compressive applications in sporting populations. These critical questions are indicative of a responsibility to examine the variables that affect human response to local cryo-compression applications to develop optimal applications in sport advantageous to the athlete. Muscle oxygenation saturation is a common marker utilised to determine physiological effects of such interventions. Separately, cooling (CWI) has been reported to decrease muscle oxygenation saturation (SmO_2) (Ihsan *et al,* 2013; Yeung *et al,* 2016), however an increase in SmO_2 following compression is previously identified (Neuschwander *et al,* 2012). Simultaneous applications of cryotherapy and compression in terms of dose-response are however unavailable in the current evidence base. Indeed, methods of cooling struggle to eliminate all added concomitant compression during application (Alexander *et al,* 2020e), however minimal studies acknowledge that physiological responses may be affected by the level of compression. Often compression adjuncts are not quantified in terms of pressure in such studies (Alexander *et al,* 2020e). Typical examples are represented through traditional methods of ice and plastic wrap applications. In association, publication 10 indicated the value of progressive studies warranting development of cryo-compressive protocols based on the understanding of physiological responses to support or refute current practices.

Publication 11 Results and Conclusion

Significant physiological changes in SmO_2 were noted following simultaneous cooling and compression protocols. Significantly greater reductions in T_{sk} occurred from the addition of compression. For both cryo-compressive devices SmO_2 demonstrated an increase from baseline, immediately (0 minutes) followed by a decline. Interestingly SmO_2 demonstrated a decline immediately post exposure (0 minutes) in the group exposed to cooling and no controlled compression. Relationships between pressure (mm Hg), T_{sk} (°C) and SmO_2 (%) are observed. Furthermore, the trend in decline in SmO_2 over the 20-minute rewarming period for cryo-compressive devices regardless of compression adjunct corroborates previous data, notwithstanding varying methods of cryotherapy (Ihsan *et al,* 2015; Hohenauer *et al,* 2018). The implications of which directly impact sports medicine practitioners when considering the desired effects of pneumatic compression adjunct alongside cooling for injury or recovery management in sport. The discussions of which are pertinent to the discrepancies identified in the literature base around cryotherapy and compression with results presented in publication 10.

Publication 11 Practical Implications

Agreement of sports medicine practitioners in practice regarding optimal cryo-compressive protocols applicable for use within an elite sports performance setting are often based on anecdotal or traditional protocols. These protocols are often unquestioned due to poor translational evidence from research into practice to challenge their effectiveness. Given the practical constraints and ambiguity of measures relating to performance or recovery, practitioners rely on contemporary research to impact practice, however this is often difficult due to irrelevant markers applied in studies. To ensure ecologically sound testing, study design should replicate measures repeatable or relevant practically identified in performance settings for recovery and injury management. It was considered that T_{sk}, SmO_2 and perceptual measures of thermal comfort and sensation measures in this study was the first step to develop this approach. Evidently the findings indicated physiological responses differ and are contingent on pressure dosage. Although it was clear great magnitudes of cooling result from larger dosage of pressure, it does not concurrently support greater changes in SmO_2 reductions. The impact of temperature appears to have a greater effect on SmO_2. This should be considered by sports medicine and performance practitioners when applying cooling and compression simultaneously, as it is dependent of the therapeutic nature or aim of treatment / application. Consensus between researchers and practitioners in the field is required to define common protocols utilised in current practice which would provide contemporary protocols to test, with the aim to provide merited evidence for research informed practice.

Publication 11 Research Implications

The combination of T_{sk} and SmO_2 measures supports the approach of multiple markers to determine response in relevant physiological parameters following interventions such as cryotherapy. Future studies, however, should consider quantifying actual pressure measures from cryo-compressive devices to determine accuracy of pressure settings advertised by the manufacturers. This would demonstrate potential reliability and validity pertinent to each device to achieve said pressures and subsequently identify discrepancies in consistency of applications between device settings and the ability to achieve optimal response based on the aim of application.

3.5 THEME 5: MULTIFACETED RESPONSES TO CRYOTHERAPY AS A RECOVERY STRATEGY IN ELITE SPORT (PUBLICATIONS 12-15)

3.5.1 Publication 12.

Alexander, J., *et al,* (2021). Recovery Profiles of Eccentric Hamstring Strength in Response to Cooling and Compression. *Journal of Bodywork and Movement Therapies*. 27: 9-15. (Appendix 5a).

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Prevention and Rehabilitation

Recovery profiles of eccentric hamstring strength in response to cooling and compression

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ABSTRACT

Introduction: The effectiveness of different forms of cryotherapy and combined compression (cryo-compression) commonly used in sport to enhance recovery following exercise are not fully understood. Therefore, the exploration of protocols that use contemporary cryo-compression is warranted. The purpose of the study was to investigate the effectiveness of using a cryo-compression device to recover hamstrings eccentric strength following a fatiguing exercise.

Methods: Eighteen healthy male adult footballers were randomly allocated to receive cryo-compression or rest following a lower limb fatiguing protocol. Cryo-compression was applied for 15-min, target temperature of 10 °C, and high intermittent pressure (5–75 mm Hg) using the Game Ready® device. Rest consisted of 15-min in a prone position on a plinth. To induce hamstring fatigue, participants performed the Yo-Yo intermittent fatigue test (IFT). Skin surface temperature (T_{sk}) and hamstring eccentric strength measures were taken at three time points; pre-IFT, immediately post-fatigue test (IPFT), and immediately post-intervention (IPI) (rest or Game Ready®). Participants returned one week later and performed the Yo-Yo IFT again and were exposed to the opposite intervention and data collection.

Results: Significant decreases in T_{sk} over the posterior thigh were reported for all timepoints compared to pre cryo-compression temperatures (*p=<0.05*). Overall data displayed no significant main effects for timepoint or condition for PT or AvT (*p=<0.05*). There was no timepoint × condition interaction for PT or AvT (*p=<0.05*). Collapse of the data by condition (CC/R) demonstrated no significant effect for time for PT or AvT (*p=>0.05*).

Conclusions: No significant changes in HES occurred after exposure to cryo-compression or rest applied immediately following the Yo-Yo IFT. Further investigations to maximise beneficial application of contemporary cryo-compression applications in sport are required. Multiple measures of performance over rewarming periods, within competitive training schedules after sport-specific training are required to develop optimal cooling protocols for recovery.

Figure 19. Abstract taken from Alexander *et al,* (2021d). Recovery Profiles of Eccentric Hamstring Strength in Response to Cooling and Compression.

3.5.1 Publication 12 Critical Account

Publication 12 was the first to purposely explore eccentric strength of the hamstrings measured via the Nordbord®, following a fatiguing protocol and the effects of cooling using the Game Ready® device as a recovery strategy. Methods of cryotherapy and combined compression (cryo-compression) are thought to enhance recovery following damaging exercise in sport, although responses and the mechanisms behind how and to what extent are debated. Inconclusive agreement on the measurable benefits of cryotherapy and compression separately are noted however the exploration of optimum recovery protocols is warranted of which the Game Ready® device is commonly utilised for. This publication corresponds with Theme 5 (Table 1, pg. 26-28), and Research Question; *Are cryo-compressive modalities advantageous to the athlete in terms of recovery of eccentric strength profiles following fatiguing exercise?* (Table 2, pg. 42-52) identified for exploration.

Publication 12 Study Rationale

The rationale for the study was initiated from the need to explore common applications of such devices to determine how to optimise the value of this commodity for the athlete from a recovery perspective. The design of the study evolved naturally from the work established and published in Theme 4, around contemporary practices and the use of cryo-compressive devices and their rationale for use in a sport environment (publications 10 and 11). Often the comparison or investigation for cooling in a recovery sense has focussed on CWI rather than pneumatic cryo-compressive devices, despite their known use in industry.

Publication 12 Results and Conclusion

T_{sk} measures demonstrated significant reductions in the group exposed to cooling, following immediate removal of the Game Ready® device as anticipated. Yet, despite the reduction in T_{sk} no significant changes were found for hamstring eccentric strength measures at the same time point. The same was reported for the group receiving the rest intervention. It was concluded that significant strength differences following cooling did not occur because of several factors influencing the expectations of the application. Longer dose durations of cooling were hence recommended to potentially alleviate muscular fatigue.

Publication 12 Practical Implications

The shorter cooling application time of 15-minutes chosen in this protocol reflected time conscious demands or scenarios in sport for injury and recovery strategies. Practically this method of cooling at the dose applied did not actively induce ideal temperature ranges targeted at 10-15°C on immediate removal (Kennet *et al,* 2007). It is questionable what affect this had on deeper structures, although those measures were outside the scope of this study. That said, for recovery purposes warmer temperatures via CWI have been reported to provide positive responses in performance recovery (Vieira *et al,* 2016). This suggests that the mode of cooling and phase change ability of the application requires adaptation of dose and pressure to reflect similar responses. From a practitioner perspective this opens a myriad of questions rather than answers in terms of what the optimal recovery strategy may be when implementing cryotherapy in a team sport environment. Furthermore, this highlights the limited impact of the translation of evidence into practice in this topic. So many variations in fatigue protocols combined with interventions of recovery are alluded to in the literature it is difficult to forge a consensus that applies to multiple sporting demands. It does however acknowledge the need for more studies to consider individual and perceptual responses rather than group data alone. With so many variables (Figure 1, pg. 41) to contend with in terms of creating the perfect cooling recovery strategy, one measure of performance as represented in this study, barely reflects the interests of the practitioner working in a high-performance environment. In such environments multi-measures of performance to identify whether a recovery strategy such as cooling and, in this example, the Game Ready®, would better represent current practice.

Publication 12 Research Implications

Future study designs for subsequent publications in the thesis (theme 5) that considered using a protocol designed to initiate fatigue in the lower limb instead collected data mid-competitive season, following a normal scheduled fatiguing training session. Consequently, sprinting and high-speed multidirectional movements were included and ensured high-velocity and high-load exposures that were unachievable in this study through the YoYo Test. On reflection a better test to induce fatigue would have been the Soccer-Specific Aerobic Fatigue Test (SAFT^{90}) (Small *et al,* 2009) or the Technical Soccer-Specific Aerobic Fatigue Test (T-SAFT^{90}) (da Silva and Lovell, 2020).

A variation in cooling dosage and compression levels should be considered in future study methodologies to help determine the level of influence over performance and readiness to train / play perspectives. This would provide useful comparison of multiple protocols utilising the same device for practitioners in the field to refer to and guide practice. Further the observation of recovery in subsequent days post intervention would be beneficial to track any long-term effects. Future studies should consider examining the responses of female athletes in similar scenarios to reduce the scarcity of available evidence on optimal cooling protocols in women. More investigations in the remit of cryo-compression would be beneficial to the applied nature of the topic and studies should consider real-world application and quantification of data mid-competitive season in a variety of sports to be able to demonstrate current application. Consequently, this would enhance the ability to transfer knowledge into practice more readily that may arise through the distancing of laboratory-based protocols that may not best represent the physical, psychological, functional or environmental demands of high-performance sport.

THEME 5: MULTIFACETED RESPONSES TO CRYOTHERAPY AS A RECOVERY STRATEGY IN ELITE SPORT

3.5.2 Publication 13.

Alexander, J., *et al,* (2021). Effects of contemporary cryo-compression on post-training performance in elite academy footballers. *Biol Sport.* 39(1): 11-17. (Appendix 5b).

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Effects of contemporary cryo-compression on post-training performance in elite academy footballers

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ABSTRACT: Fatigue is a predisposing risk factor for injury commonly investigated in elite football populations. Little evidence advocates the most beneficial recovery strategies including contemporary cooling applications. The aim of the study was to examine immediate effects of the Game Ready® on physiological and biomechanical measures in a population of elite male academy footballers, following a fatiguing training session mid-competitive season. Twenty, elite male footballers took part (180.2 ± 8.7cm, 75.0 ± 11.4kg, 18 ± 0.5years). Following a normal fatiguing training session, players were randomly assigned to receive either cryotherapy (Game Ready®) (20-minutes at medium compression (5–55 mm Hg)) or passive recovery (PAS). Data was collected at match-day+1, immediately post-training and immediately post-intervention. Performance measures included countermovement jump (CMJ), isometric adductor strength (IAS), hamstring flexibility (HF), and skin surface temperature (T_{sk}). Significant main effects for group for CMJ data following exposure to cooling were displayed ($p = < 0.05$). Individual group analysis displayed a significant reduction in CMJ performance in the group exposed to cryotherapy ($p = < 0.05$) immediately post, but not for PAS. No main effects were identified for cryotherapy or PAS group for IAS or HF ($p = > 0.05$). T_{sk} reduced significantly ($p = < 0.05$) in the cryotherapy group, meeting therapeutic T_{sk} range. Reductions in performance immediately following exposure to pneumatic cryo-compressive devices may negate the justification of this recovery strategy if neuromuscular mechanisms are required in immediate short term. Application of such recovery strategies however are dependent on the type of recovery demand and should be adapted individually to suit the needs of the athlete to optimise readiness to train/play.

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Figure 20. Abstract taken from Alexander *et al,* (2021e). Effects of contemporary cryo-compression on post-training performance in elite academy footballers.

3.5.2 Publication 13 Critical Account

Publication 13 corresponds with Research Question; *How do therapeutic cooling devices affect recovery profiles in elite sport populations?* (Table 1, pg. 26-28) identified for exploration. The continuation of the recovery theme stemmed into two routes in terms of population, that being elite academy age and elite senior. The study considered previous findings and study designs in the thesis to establish a protocol that would capture multiple measures of data relevant to the environment of which the population was based (elite academy football).

Publication 13 Study Rationale

Little has been investigated on this age group in terms of cryotherapy for recovery and it was acknowledged that prior to this study no other had explored the Game Ready® cryo-compression device in this format. The underpinning consideration of this research was to translate into and impact practice through the purposeful study design that considered multi-measures of performance. The intention of this approach was to help guide sports medicine and performance practitioners in terms of decision making for the use of cryo-compressive applications in this elite age-group of footballers. Measures representing both biomechanical and physiological outcomes included Isometric adductor strength, hamstring flexibility, countermovement jump height (CMJ) and T_{sk}.

Publication 13 Results and Conclusion

Significant reductions in CMJ performance following cooling (Game Ready®) applied after a normal scheduled training session were reported ($p<0.05$). In the PAS group the same was not identified. No significant main effects were identified for isometric adductor strength or hamstring flexibility in either group (cooling / PAS) ($p>0.05$). Significant reductions in T_{sk} were reported in the group exposed to cooling over the hamstring and quadriceps regions quantified. Results provide insight into the importance of individualisation, markers of performance and justification of various recovery strategies in elite academy age footballers. The application of pneumatic cryo-compression may negate the immediate recovery of neuromuscular response in comparison to passive recovery approaches.

Publication 13 Practical Implications

This study was innovative in its approach to explore the effects of recovery strategies typical of elite football in a youth population during a competitive season. The differences in response from cooling utilising a Game Ready® to PAS identify the importance of individualisation of recovery strategy implementation in sport. Safe rewarming periods following cooling prior to performing exercises which require effective neuromuscular response were acknowledged by the findings in this study and require further investigation. More applicable to the aim of this study however was the consideration of optimal periodisation of cryotherapy as a recovery strategy and is therefore a significant implication of this publication. Practitioners working in elite sport environments should consider that recovery is influenced by training load, adaptation interactions and fatigue (Roberts *et al,* 2015), resulting in a complex approach to maximising the benefit of cryo-compressive recovery strategies in terms of when to apply such modality. Although significant changes in CMJ performance and differences in output compared to PAS were noted in this study, it was the non-significant findings which have greater interest as to the practical implications on athlete response to recovery and consequently readiness to train / play status. It was considered that player well-being in terms of perceptual response may have a significant baring on the conscious ability to perform isometric (isometric adductor strength) vs eccentric (CMJ) contractions. Practical implications of this suggest that players' perceptual responses to fatigue and recovery strategies should be considered simultaneous to indices of physical markers. Practically findings support multifaceted approaches of athlete monitoring, representative of the demand of the sport, which are required to fully elucidate the impact of recovery modalities used in practice such as the Game Ready®. Findings here align to the suggestion recently made by Altarriba-Bartes *et al,* (2020) whereby significant variability of response and perceptions to several recovery strategies exist, noted in an elite football population. The beneficial impacts of recovery strategies in sport are however dependent on measured responses in addition to player demand, preferences and individual performance requirements. It is essential that these are considered in future methodological study design where cooling may be applied as a strategy to improve readiness to train / play in consideration of the neuromuscular responses to cooling found in this study.

Publication 13 Research Implications

The impact of the study findings when considering future research study design inevitably stimulated debate and multiple recommendations. This study should be reported as a randomised control trial yet was published in line with the journal recommendations. The methodology in the current publication did not consider data capture at further points throughout the weekly micro-cycle of training to determine lasting effects of the specific recovery approaches. Observations of performance markers up to 72 hours post-match will provide temporal patterns of response noted in terms of recovery periods typical of elite football environments. This would be interesting to observe in this youth population too.

Given that perceptual responses were not considered in this study, it only highlighted an important consideration for future research study design. The study emphasises the need for multi-measures of performance which include subjective athlete wellbeing to fully comprehend the responses to cooling. To develop an understanding on how to maximise cryotherapy as a recovery strategy in elite sport the examination of individual athlete or player response which is reflected in the methodological and statistical considerations of future studies is important. Publication 13 which follows acknowledges the research implications of these findings and implements such approaches both methodologically and statistically to explore individual athlete response to cooling in an elite environment expanding on the findings of publication 12.

THEME 5: MULTIFACETED RESPONSES TO CRYOTHERAPY AS A RECOVERY STRATEGY IN ELITE SPORT

3.5.3 Publication 14.

Alexander, J., *et al,* (2021). Utilisation of performance markers to establish the effectiveness of cold-water immersion as a recovery modality in elite football. *Biol Sport.* 39(1): 19-29. (Appendix 5c).

Utilisation of performance markers to establish the effectiveness of cold-water immersion as a recovery modality in elite football

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ABSTRACT: Optimal strategies for recovery following training and competition in elite athletes presents ongoing debate. The effects of cold-water immersion (CWI) compared to passive recovery (PR) though a triad of performance measures after fatiguing exercise within a normal micro-cycle, during mid-competitive training cycle, in elite male footballers were investigated. Twenty-four elite footballers (age 20.58 ± 2.55 years; height 179.9 ± 5.6 cm; weight 75.7 ± 7.5 kg; body fat 6.2 ± 1.7%) were randomly assigned to CWI or PR following a fatiguing training session. Objective measures included eccentric hamstring strength, isometric adductor strength, hamstring flexibility and skin surface temperature (T_{sk}). Subjective measures included overall wellbeing. Data were collected at match day+3, immediately post-training, immediately post-intervention and 24 hrs post-intervention. Physiological, biomechanical and psychological measures displayed significant main effects for timepoint for eccentric hamstring strength, T_{sk}, overall wellbeing, sleep, fatigue, stress and group for eccentric hamstring strength, T_{sk} and sleep (groups combined). Group responses identified significant effects for timepoint for CWI and PR, for eccentric hamstring strength peak force, sleep, fatigue, and muscle soreness for CWI. Significant differences were displayed for eccentric hamstring strength (immediately post-intervention and immediately post-training) for peak force and between CWI and PR eccentric hamstring strength immediately post-intervention. Linear regression for individual analysis demonstrated greater recovery in peak torque and force for CWI. CWI may be useful to ameliorate potential deficits in eccentric hamstring strength that optimise readiness to train/play in elite football settings. Multiple measures and individual analysis of recovery responses provides sports medicine and performance practitioners with direction on the application of modified approaches to recovery strategies, within mid-competitive season training cycles.

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Elite Football
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Figure 21. Abstract taken from Alexander *et al,* (2021f). Utilisation of performance markers to establish the effectiveness of cold-water immersion as a recovery modality in elite football.

3.5.3 Publication 14 Critical Account

Publication 14 presented within Theme 5 (Figure 1, pg. 41) corresponds to the Research Question; *How does consideration of periodisation around training demand impact application of cold-water immersion exposures compared to passive recovery in elite football?* (Table 1, pg. 26-28), identified for exploration. The effectiveness of cooling for recovery, particularly around CWI has been explored exponentially in sporting populations, yet many investigations lack consideration around objective markers of performance or acknowledge the several impacting variables that may affect choice and periodisation of CWI for recovery in elite sport. Study 14 became a logical and natural extension of publications 12 and 13 encapsulating the progression of research design into an elite sport environment representing senior professionals, with multiple quantifiable parameters that appropriately represented performance markers normally utilised within the setting of which the participants were recruited from.

Publication 14 Study Rationale

To draw a conclusion around periodisation of CWI in an elite sport setting from current literature is difficult because of limited considerations around the demands of the elite training environment. In addition, individual athlete response to CWI captured in-situ is not represented in the available evidence base for any sporting population, yet important to identify to be able to implement recovery strategies which are advantageous to the athlete. This study addresses this approach within its study design and statistical representation of data, to provide significant practical impact through its attempt to investigate this. Physiological responses to CWI are reported, and these can be affected by several variables which are acknowledged in literature. Thus far, studies that have investigated the use of CWI generally do not consider typical performance measures or the influences of training load and fatigue response monitored within elite sport environments which inform the decision-making around a player's readiness to train or play. This provided the rationale to combine such markers of performance and add to the scarce body of evidence for recovery strategy implementation and assessment of its efficiency within professional team sport. Only recently Altarriba *et al,* (2020), highlighted the need for further studies that investigate recovery strategies, and which represent professional teams. Further to this the authors encourage more research that includes the observation of multiple parameters, and state within their conclusion, *'physical, physiological and wellness parameters'* should be considered to understand the interactions around such markers of recovery.

Publication 14 Results and Conclusion

Results indicated significant main effects for timepoint (eccentric hamstring strength, T_{sk}, overall wellbeing scores and individual subjective responses for sleep, fatigue and stress) and group (eccentric hamstring strength, $T_{sk,}$ and sleep). When collapsing data by group (CWI vs passive recovery (PR)), both groups demonstrated significant effects for timepoint for PkF, sleep and fatigue with CWI displaying main effects for subjective muscle soreness scores. Immediately-post intervention significant differences were reported between CWI and PR for PkF and important to note these were based on group averages. Linear regression modelling reported the percentage change to baseline data across all markers for individual players. Greater recovery was demonstrated for CWI in eccentric hamstring strength metrics (PkT, PkF) and for PR, isometric adductor strength and hamstring flexibility measures demonstrated greater recovery responses, between immediately-post training to 24hrs post intervention timepoints. Conclusively this study provides the addition of impactful information on the effects of different recovery strategies representative of an elite football population through the utilisation of multiple performance measures which monitor the recovery response of elite footballers. Results suggest the CWI may be useful to ameliorate deficits in hamstring eccentric strength and consequently optimise readiness to train / play status.

Publication 14 Practical Implications

The approach of this study consequently provides significant impact to applied practices of CWI within elite football environments. Further, the findings demonstrate the importance of the multifaceted considerations central to the premise of this thesis, those being the multifaceted responses to cryotherapy (*biomechanical, physiological and psychological*) that play a part in decision-making around optimisation of cooling applications. From the perspective of the practitioner, this study demonstrates the integral importance of individualisation of recovery strategies at an elite level when basing athlete monitoring on multiple performance markers of recovery. In addition to this, applied practitioners need to be mindful that without the consideration of perceptual response, physical markers of performance may not provide a complete player profile to be able to determine ideal recovery strategies or protocols to maximise player readiness to train / play. Ultimately, each response plays a part in determining optimal recovery strategies. Categories of response such as those outlined in Figure 1. (pg. 41) need to be emphasised however in the initial decisions made around which performance markers best represent the demands of the sport. If inadequate measures, or the infrequency of measures are not fully considered by the medical or performance team, exploration around the effects of recovery modalities such as cryotherapy in its various forms, in-situ, may not provide usable data to best inform individual or team approaches in this domain to improve readiness to train / play in the first place. Although most professional environments will consider those factors, each club will differ in their approach to task-specific performance as measurable variables, and the frequency of screening and monitoring. Further investigations using a multitude of performance measures, over longer periods that capture multiple micro- and macro- training cycles and across different demands of the season where fixture congestion is evident would be beneficial to maximise recovery strategy implementation. This would benefit the goal of achieving maximal levels of performance, minimal injury and days lost to injury through improving players individual response to training and playing demands.

Publication 14 Research Implications

Consideration of multiple external and internal load variables, along with markers that suitably measure athlete recovery and consequently the impact of the efficiency of cryotherapy applications should be considered in future methodological study designs that aim to represent elite environments and demands of the sport. One of the most important considerations taken from the outcomes of this study are the individual analysis of response. Future work is required in this area to explore individual response to recovery strategies such as cryotherapy with a focus in team-based sports and that consider positional, formation and tactical demands and characteristics to move away from simple group analysis data. With the assumption that 'one size fits all' in terms of recovery strategies already known to be an outdated approach in contemporary sports settings (Minett and Costello, 2015), the indication to support study design with appropriate statistical analysis is evident. This would benefit optimal periodisation of recovery strategies such as CWI in response to fatigue taking the approach of individualisation even further when considering positional factions and team ethos.

Future studies should consider how data (individual) is presented when considering that contemporary research in elite medicine and performance should be impactful on the practices of current practitioners in the field. Generic barriers to the translation of research into practice are identified in the literature, yet those which impact into elite sport performance settings are often not described. This may include presentation of data, or the access and dissemination of research findings in a contemporary manner which reaches the practitioners within these environments. Research should consider evidencing current practices which may be anecdotal in their success, investigate the effects of multiple recovery strategies at once, or multiple exposures of cryotherapy to demonstrate contemporary practices.

THEME 5: MULTIFACETED RESPONSES TO CRYOTHERAPY AS A RECOVERY STRATEGY IN ELITE SPORT

3.5.4 Publication 15.

Selfe, J., *et al*, (2014). The Effect of Three Different (-135°C) Whole Body Cryotherapy Exposure Durations on Elite Rugby League Players. *PLoS ONE,* 9(1); 1-9. (Appendix 5d).

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The Effect of Three Different (-135°C) Whole Body Cryotherapy Exposure Durations on Elite Rugby League Players

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Abstract

Background: Whole body cryotherapy (WBC) is the therapeutic application of extreme cold air for a short duration. Minimal evidence is available for determining optimal exposure time.

Purpose: To explore whether the length of WBC exposure induces differential changes in inflammatory markers, tissue oxygenation, skin and core temperature, thermal sensation and comfort.

Method: This study was a randomised cross over design with participants acting as their own control. Fourteen male professional first team super league rugby players were exposed to 1, 2, and 3 minutes of WBC at −135°C. Testing took place the day after a competitive league fixture, each exposure separated by seven days.

Results: No significant changes were found in the inflammatory cytokine interleukin six. Significant reductions ($p<0.05$) in deoxyhaemoglobin for gastrocnemius and vastus lateralis were found. In vastus lateralis significant reductions ($p<0.05$) in oxyhaemoglobin and tissue oxygenation index ($p<0.05$) were demonstrated. Significant reductions ($p<0.05$) in skin temperature were recorded. No significant changes were recorded in core temperature. Significant reductions ($p<0.05$) in thermal sensation and comfort were recorded.

Conclusion: Three brief exposures to WBC separated by 1 week are not sufficient to induce physiological changes in IL-6 or core temperature. There are however significant changes in tissue oxyhaemoglobin, deoxyhaemoglobin, tissue oxygenation index, skin temperature and thermal sensation. We conclude that a 2 minute WBC exposure was the optimum exposure length at temperatures of −135°C and could be applied as the basis for future studies.

Citation: Selfe J, Alexander J, Costello JT, May K, Garratt N, et al. (2014) The Effect of Three Different (-135°C) Whole Body Cryotherapy Exposure Durations on Elite Rugby League Players. PLoS ONE 9(1): e86420. doi:10.1371/journal.pone.0086420

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Introduction

Whole body cryotherapy (WBC) is the therapeutic application of extremely cold dry air, usually between −110°C and −140°C [1,2]. WBC is becoming popular amongst athletes, coaches and clinicians across a variety of sports in order to prevent injury and promote recovery. Typically the timescale of exposure is reported as between 2 3 minutes [2]. Although a number of studies [1,3 8] have investigated the physiological effects of WBC, the optimal WBC protocol required to initiate beneficial physiological responses is unknown [2,9]. This is due to the lack of randomised controlled clinical studies investigating either exposure duration or number of treatment cycles [2,9]. One of the more commonly reported beneficial changes following WBC is a reduction in inflammatory markers [2,10,11,12]. Recently the acceleration of recovery from exercise induced muscle damage (EIMD) was reported after three WBC exposures [13]. However Costello and colleagues [1] reported ineffective results of WBC when administered 24 hours following eccentric exercises in order to help alleviate muscle soreness. Furthermore the enhancement of muscle force recovery was demonstrated to be ineffective in this study [1,3]. One previous study has evaluated various physiological changes in professional rugby players, demonstrating changes in haematological profiles, following a protocol of 5 WBC exposures over 5 consecutive days [14]. However this study lacked a control group, therefore it is difficult to discriminate WBC effects

Figure 22. Abstract taken from, Selfe, *et al,* (2014). The Effect of Three Different (-135°C) Whole Body Cryotherapy Exposure Durations on Elite Rugby League Players.

3.6.1 Publication 15 Critical Account

The premise of WBC particularly in elite sport populations concentrates predominantly on the implementation of this modality with the aim of applying augmented recovery or its use within rehabilitation protocols. This study is the only publication in Theme 5 (Table 1, pg. 26-28) that responds to the following research question; *Is there an optimal exposure duration for whole-body cryotherapy and what are the effects on physiological markers in elite sport populations?* (Table 2, pg. 42-52). Although presented last in the critical evaluation and theme sequence, this study was one of the earlier publications developed in the thesis. This publication presents a multifactorial approach in terms of the objective measures chosen to investigate dose-response of WBC when investigating different lengths of exposure in a population of elite rugby union players.

Publication 15 Study Rationale

The use of WBC is increasingly introduced into elite sports performance settings as a means of recovery strategies to subsequently maintain optimal performance. Studies promote therapeutic applications of cold air ranging from -110°C to -140°C with typical exposures reported in the region of 1-5 minutes (Banfi *et al,* 2010; Costello *et al,* 2012b; Bleakley *et al,* 2014), yet literature failed at the time of this publication to present optimal protocols specifically around exposure duration. Changes in inflammatory markers following WBC exposures (Pournot *et al,* 2011; Ziemann *et al,* 2012), tissue temperature reductions (Costello *et al,* 2012; 2014), and discrepancies in symptom response to exercise induced muscle damage (EIMD) compared to control groups were reported (Costello *et al,* 2012b; Fonda and Sarabon, 2013). Despite investigation around physiological, biomechanical, biochemical and perceptual markers post WBC exposures, the ability to draw agreement from the available literature in terms of optimal protocol application was not entirely convincing. This may be due to the vast number of variables relevant to consider, consequently impacting methodological study design. With no clear protocols established and discrepancies noted across available literature, the premise was to investigate initial exposure durations of WBC to determine and help develop optimal WBC protocol applications. Inevitably, many approaches to study design were considered, for example, number of exposures, time of exposure, or exposure duration. It seemed logical to understand firstly the impacts of length of WBC dose exposure. This is highlighted in Figure 1 (pg. 41) and Table 3 (pg. 59) as one of the key variables to determine what may influence optimal applications of cryotherapy in sport.

Publication 15 Results and Conclusion

At the time of publication, no other study had investigated length of WBC exposure and responses relevant to multiple recovery markers in an elite sports population. Findings indicate that a 30-second at –60°C, followed by 2-minutes at –135°C exposure, appeared to be the optimum dose for physiological changes to occur that may be beneficial for recovery. It is important to continually develop or advance existing findings to expand or reinforce scientific knowledge but in a design that impacts practice in an applied nature. Consequently, the choice to investigate optimal dose provided a significant contribution to knowledge with practical implications for those using WBC as a recovery modality in elite sport performance settings. That said, the study emphasised the need for larger investigations over longer periods to commence due to the limited understanding of multiple exposures in elite populations.

Publication 15 Practical Implications

Findings from this study advised that sports medicine practitioners working in the field of elite sport should consider that a 2-minute WBC exposure at -135°C induces physiological changes, when compared to a 1- or 3-minute exposure at the same temperature setting. These changes may be beneficial but are dependent on the aim and target of WBC exposure, for recovery / performance / injury management. The argument for not exposing elite rugby league players to a 3-minute exposure was an important finding in the study not published previously, suggestive of negative physiological responses causing peripheral ‘shut down’ of the vasculature, particularly to the median veins of the antecubital fossa causing issues when trying to collect physical blood samples. An appropriate level of peripheral venous blood flow was often compromised due to what was thought to be caused by vascular shunting to lower from upper limbs following exposure. Lubkowska *et al,* (2012) however reported successful blood samples taken at 30 minutes post a 3-minute WBC exposure. In conclusion, it may have been too premature to collect venous blood samples at 20-minutes post exposure. Consequently, this was identified in analyses of the blood sample, whereby no differences in IL-6 levels were displayed. Moreover, large standard deviations noted in IL-6 levels demonstrated the possibility of discrepancies between positions and should be considered as a variable in future cryotherapy research whose aim is to develop optimal WBC protocols. Positional differences may therefore influence the need for individualisation of optimal protocols for any type of cryotherapy application in sport. This was recently reported in the Alexander *et al,* (2020) study in relation to local cooling applications in a rugby union population, whereby positional groups in a rugby union squad respond differently physiologically, as demonstrated in tissue-temperature reductions.

The basis of these findings suggested that future work should use this dose (2-minutes) to determine the number of sessions of WBC exposures required to aid recovery or performance parameters during the sporting season. Unlike previous research in the remit of WBC, multiple physiological parameters were observed together. Since its publication in 2014, the publication has achieved 42 citations, which demonstrates the valuable contribution to knowledge in the development of optimal protocols of WBC in sport. The study also emphasises the need for further empirical evidence to progress our understanding of this modality to gain significant advances in its application. In 2016 a review of current technologies and practical applications of WBC and PBC identified approximately fifteen producers worldwide (Bouzigon *et al,* 2016). The authors continue by highlighting the lack of validity of assessments in scientific research in the remit of WBC/PBC with many poor methodologies and lack of information provided in studies. To date literature still fails to demonstrate a consensus on its optimum application especially in elite populations, due to the differences in variables explored across studies.

Publication 15 Research Implications

A noteworthy tenet not discussed in the publication was the impact on sleep and wellbeing parameters. Although wellbeing and sleep data were collected, it was felt at the time the physiological changes noted across the investigation between exposure durations were more appropriate to present in consideration of the target journal and audience to influence practice. Since publication however a larger emphasis on wellbeing, perceptual recovery and sleep parameters in relation to recovery strategies employed in elite sport settings are acknowledged in current literature surrounding the use of WBC (Douzi *et al,* 2018; Partridge *et al,* 2019). Detailed effects on psychological wellbeing parameters however lack thorough investigation. Sleep, for example being an important factor for recovery and performance in elite sporting populations (Charest and Gardener, 2020). In hindsight, it may have been beneficial to present this data; however, subjective sleep data was only recorded +1day following exposure. Given the hesitation to explore the effects of WBC on sleep at the time consideration of what the optimal window is for WBC applications requires further investigation and is of interest; in respect to periodisation of recovery strategies in sports where fixture congestion and training schedules are constantly adapted for the demands of the sport.

Chapter 4

~ Critical Synopsis ~

CHAPTER 4 – CRITICAL SYNOPSIS

4.0 Overview

This chapter firstly presents key findings of the fifteen studies by theme and category of response (Table 9) respectively, with the intention to reduce the confusion or ambiguous perceptions behind optimising cryotherapy applications in sport. The practical influences of the studies and their significance and contribution to the field, critiqued against current literature follow and address the aim of the body of work. Consequently, practitioner considerations for the potential optimisation of cryotherapy applications in sport, based upon and cross-referenced to the fifteen publications, are introduced in Table 10. The overarching findings significantly contribute to reducing the discordance between scientific study and translation of evidence into contemporary practice. As such the synopsis concludes with an infographic (Figure 23) that illustrates considerations for optimising applied research study designs of cryotherapy protocols aimed at practitioner-researchers. Current publication metrics for all studies are presented in Table 11 and limitations by theme in Table 12. Finally, the evaluation of impact and future research developments are outlined.

4.1 Key Findings by Theme

The five themes were initiated from personal experience working in sport, gaps highlighted in the literature base, and relevant topics considered with a practical nature and impact. Each publication aligned to one of the five themes and the four categories of response (*biomechanical, biochemical, physiological and psychological*) of which performance is often determined by in sporting environments. These themes and responses are acknowledged, overlapped and varied between the fifteen studies, with the intention to align to practice. The overarching impact, significance and contribution to practice are critiqued in section 4.3 from a practical perspective, however a summary of key messages from each theme are presented here:

THEME 1: KINEMATIC RESPONSES TO CRYOTHERAPY (Publications 1 and 2):

- The ability to replicate knee joint positioning is negatively affected following local cryotherapy application, observed through multiple planes of movement.
- Based on the reductions observed in the ability to replicate knee joint positioning following local cryotherapy, rewarming periods longer than 20-minutes should be considered as part of the decision making of when to return an athlete to functional activity safely.
- Considering the multidirectional demands of many sports, heightened risk of non-contact injury is evident due to reductions in joint range noted over a rewarming period following local cooling at the knee.
- Further exploration of biomechanical responses to cooling in a field-based capacity and comparison to other cooling modalities is recommended.
- Quantification of surrounding structures which contribute to lower limb stability such as muscle strength should be considered simultaneous to kinematic assessment to provide practitioners with a comprehensive understanding around the effects of cooling.[1]

[1] *This approach is demonstrated in Theme 2.*

THEME 2: MUSCLE STRENGTH RESPONSES TO CRYOTHERAPY (Publications 3-5):

- Biomechanical responses to cryotherapy demonstrate reductions in muscle strength parameters following local cooling directly and adjacent to the muscle belly in the lower limb.
- Detrimental effects on stabilising structures at the knee caused by local applications of cryotherapy pose several implications to current practice for safe return to functional activity in sport following exposure to cooling.
- Modes of cryotherapy such as targeted and circumferential differ in their effects on muscle strength responses with circumferential application demonstrating greater effects on muscle strength parameters.
- Practitioners might consider using a targeted treatment approach compared to circumferential cooling of the lower limb structures to mitigate such responses however rationale for treatment may override this, and in that circumstance rewarming periods should be considered prior to returning an athlete to functional exercise required for performance.
- The tools considered to determine the efficacy of and between typical cryotherapeutic modalities applied in sport are important to consider in future research study design to optimise impact of findings that reflect real-world practices.[2]

THEME 3: THERMOGRAPHY AND SKIN SURFACE RESPONSES TO CRYOTHERAPY (Publications 6-8):

- The ability to reduce T_{sk} for optimal physiological response differs between cryotherapy modalities and positional factions in team sport.
- Perception of cooling varies between cryotherapy modalities typically utilised in sport.
- Differences in tactile response at the knee following local cooling suggest proprioceptive feedback mechanisms via cutaneous receptors in the skin may contribute to changes in dynamic control responses providing physiological reasoning behind the findings in theme 1.
- Practically these results influence the understanding of injury risk factor for when performing functional tasks post cooling, consequently affecting the decision making of the practitioner on the choice and application of cooling applications in sporting contexts.
- Practically differences in tactile responses may influence choice of cooling applications typical in sport and the importance of individualisation of cooling protocols for athletes in terms of different physiological responses.

[2] *This is demonstrated in Theme 3 using thermology; Theme 4 explores muscle oxygenation response and publications in Theme 5 utilise metrics of performance in elite sport.*

- Psychological (perceptual) responses to cooling comfort or sensation that align to T_{sk} may have implications when implementing cooling protocols.
- The use of thermal imaging to quantify efficacy of cryotherapeutic applications in a sport medicine context is supported through publications in this theme.[3]

THEME 4: CONTEMPORARY CRYOTHERAPY APPLICATIONS AND RESPONSES (Publications 9-11):

- Compression adjunct to cryotherapy affects magnitude of cooling as well as differences in physiological and psychological responses between modes of cryo-compressive devices.
- The physiological responses of SmO_2 and T_{sk} suggests that the adaptation of dose when using cryo-compressive devices affects response and therefore may be manipulated to optimise protocols in sport environments.
- Scarcity of agreement in advantageous protocols for pneumatic cryo-compressive devices in sport and the need for further investigation of protocols currently utilised in elite sport settings is evident from the scoping review produced in this theme.
- Ongoing debates around contemporary approaches for the use of cryotherapy in acute injury management are confusing for practitioners to determine optimal use.
- To impact real-world applications of contemporary cooling approaches, modes and devices, study design should reflect cooling protocols and measures to quantify effectiveness utilised in high-performance environments.[4]

THEME 5: MULTIFACETED RESPONSES TO CRYOTHERAPY AS A RECOVERY STRATEGY IN ELITE SPORT

(Publications 12-15):

- Sports medicine and performance practitioners working in the field of elite sport should consider that a 2-minute WBC exposure at 135°C induces physiological changes. Dose-response is influential in the development of optimal protocols in whole-body cryotherapy.
- Cold-water immersion may be useful to ameliorate potential deficits in eccentric hamstring strength that optimise readiness to train/play in elite male footballers.
- In elite academy-age footballers the application of circumferential pneumatic cooling applied bilaterally over the lower limbs immediately following a fatiguing training session observed

[3] *Theme 4 builds on this metric to determine efficiency of contemporary cryo-compressive devices in sport.*
[4] *Theme 5 presents several studies which utilise this approach.*

reductions in neuromuscular performance immediately-post cooling, compared to passive recovery. Practitioners working in this environment should adapt the periodisation of cryotherapy recovery strategies to maximise the potential benefits and negate any responses that may inhibit readiness to train / play if neuromuscular responses are required in the short-term.

- Multiple performance measures are required to establish simultaneous biomechanical, physiological, biochemical and psychological responses to contemporary cryotherapy protocols applicable to elite sports settings.
- Individual analysis of athlete response and perceptual / psychological responses to cooling interventions are important to maximise recovery strategies that incorporate cryotherapy for athlete readiness to train / compete and individualisation of protocols.
- Practically multi-measures to quantify the effects of cooling on performance are not always feasible, therefore, to develop optimal protocols of cooling beneficial to an athlete, practitioners should consider which measures best represent performance of their athlete or demands of the sport, aligning this with the aim of the cooling application and intended benefits.

4.2 Key Findings by Response

The four underpinning categories of response introduced in Figure 1 (pg. 41) in chapter 1 of the thesis were interwoven throughout each theme. Although articles considered various research questions, when synthesising the findings from each of the themes, key messages were identified for each response category (*biomechanical, biochemical, physiological, psychological*) (Table 9). Results presented by response were considered as important factors that may influence the development of cryotherapy protocols, benefiting a practitioners' understanding as to the most effective and efficient use of cryotherapy in sporting contexts. It is evident however, from the findings in this body of work, that as practitioners we cannot consider the impact of cryotherapy on one response without another. Moreover, in the studies where multiple responses were quantified, variance in outcomes across the four categories may have been associated with the athletes' perception of their current physical status (i.e., psychological response), influencing strategies behind the optimisation of cryotherapy application for recovery in sport.

Table 9. Key findings for each of the four categories of responses that underpin cryotherapy applications in sporting contexts, prevalent throughout each of the five themes and fifteen publications.

CATEGORY OF RESPONSE	KEY FINDINGS AND PRACTICAL CONSIDERATIONS
BIOMECHANICAL	- Reductions in knee JPS, dynamic stability and muscle strength occur following local knee joint or associated musculature cooling. - Potential detrimental risk of injury may be caused by negative effects on stabilising structures required during multidirectional functional movements following local cooling at the knee or associated lower limb musculature. - For biomechanical responses to return to pre-cooling measures, length of rewarming periods can be influenced by cooling dose, mode, circumferential / targeted approach, and compression adjunct. - Deleterious responses in muscle strength parameters may be negated through a targeted approach. - Reductions in neuromuscular function following pneumatic cryo-compression may negate this as a recovery strategy if neuromuscular responses are required in the short-term. - Periodisation of cooling for recovery using CWI or pneumatic cryo-compression may be useful to ameliorate deficits in eccentric hamstring strength to optimise readiness to perform.
BIOCHEMICAL	- A single exposure of WBC, irrespective of duration did not significantly alter IL-6 levels. - Individual variation in IL-6 levels between players is evident and respective of individual demands in competition. - Periodisation of WBC exposure and collection of blood markers in respect to recovery interventions such as cryotherapy is warranted to determine optimal effectiveness.
PHYSIOLOGICAL	- Significant changes in SmO_2, T_{sk}, SSS, core temperature is influenced by dose (duration), mode, compression adjunct / pressure levels, positional characteristics. - Physiological responses underpin and may rationalise biomechanical responses.
PSYCHOLOGICAL	- Perceptual response of thermal comfort and sensation post-local cooling corresponds to levels of T_{sk} reduction and differ between positional characteristics and mode of cryotherapy. - Thermal comfort measured during cryotherapy application indicates differences in comfort scores between modalities regardless of compression level. - Lower levels of comfort are associate to higher levels of compression during pneumatic cryo-compressive applications. - 1~ WBC exposure is not long enough to initiate perceptual changes in temperature sensation, although longer exposure to WBC >1~ is associated to cooler temperature perception scores. - Self-reported increases in recovery scores in response to CWI were observed immediately following exposure. - Self-reported increases in recovery scores in response to CWI vs PR at 24hrs post exposure suggest greater scores for PR than CWI, although scores were maintained for players exposed to CWI. - Positive psychological responses >24hrs post-CWI may be dependent on dose or cumulative exposure.

$Sm0^2$ = muscle oxygenation; T_{sk} = skin surface temperature; SSS = skin surface sensitivity; WBC = whole-body cryotherapy; CWI = cold-water immersion; JPS = joint position sense; IL-6 = interleukin 6 inflammatory marker; PR = Passive Recovery.

4.3 Practical Impact of the Research

4.3.1 Significance and contribution to the field

Cryotherapy is a principal injury and recovery method and despite its universal acceptance in the sports environment and plethora of research available (Kwiecien and McHugh, 2021), evidence to support or optimise its application remains limited. Confusion around contemporary cryotherapy applications from a sports medicine or performance practitioner perspective continues as consequently no evidence exists as to the optimal cryotherapy protocol or indeed how to best optimise its application through its various modes for sport injury, rehabilitation, recovery or performance. Limited understanding of the multifaceted responses (Figure 1. pg. 41) relevant to those underpinning the use of cryotherapy in sport are apparent. Further, a lack of applied research that reflects contemporary use of cryotherapy in sport has resulted in controversy over the efficacy of both traditional and modern cryotherapy modes. The principal aim of this body of work was to examine the effects of cryotherapy across several categories of response that underpin the optimisation of its application in sport from an applied, multiple study design and methodological approach. As a collective the objectives were to critically determine the influence of variables and moderating factors across four categories of response (*biomechanical, biochemical, physiological, psychological*) considering rewarming periods and multi-measures of performance. This was achieved though the development of contemporary methodologies that addressed problems reflective of applied practice in sport from a medical and performance practitioner perspective. With the intention of reducing the disconnect between research and practice, these approaches would rely on the consideration of contemporary topics surrounding cryotherapy in practice and adapting the methodologies to real-world demands throughout each of the studies that contributed to this body of work. Progression through the five themes notes the importance of the applied context for study design which evolved from laboratory-based studies to the latter studies that reflect the demands of elite or high-performance environments maximising the opportunity for impact into current practice.

Findings from the fifteen publications offer sports medicine and performance practitioners several considerations that influence the optimisation of cryotherapy applications in sport, largely advancing the evidence base in cryotherapy from an applied perspective. Findings from the studies presented in this body of work contribute to a larger scope of research that originated in 2014 and is ongoing, although, it seems appropriate at this juncture to highlight one long-standing question pertinent throughout the work referring to the limited agreement in, '*What constitutes optimal cryotherapy protocols?'*. In response, Table 10 (pg. 227) provides applied practitioners with some considerations for optimising cryotherapy practices derived from the fifteen studies in this thesis, demonstrating the contribution to knowledge and impact of the work. The proposal presented in Table 10 (pg. 227) is not without its limitations, and it is acknowledged that studies underpinning column 1 (injury) and 2 (rehabilitation) in the table are limited in the respect that data was collected on healthy athletes. That said, the purpose of the table is to convey the originality and breadth of findings from the fifteen publications in this thesis that may influence and maximise contemporary applications of cryotherapy in applied sporting contexts and future research studies that explores the changing face of cryotherapy.

Table 10. Practitioner considerations for cryotherapy application by intention based on the thesis findings and cross referenced to the fifteen studies.

Optimising Cryotherapy Application Protocols in Sport

(Lower Limb Sport Specific Considerations for Practitioners)

1. INJURY		2. REHABILITATION		3. RECOVERY		4. PERFORMANCE		Intention of Use
Q. Is the athlete likely to return to play?		Q. Is the athlete likely to perform dynamic stability, flexibility or strength specific exercises as part of their lower limb rehabilitation?		Q. Is the athlete in a period of congested competition, training or fixtures?		Q. Is the athlete required to perform neuromuscular function (NMF) as part of multi-sessional training schedules that day?		
(a) Yes	**(b) No**	**(a) Yes**	**(b) No**	**(a) Yes**	**(b) No**	**(a) Yes**	**(b) No**	**Practitioner Considerations**
Consider:	**Consider:**	**Consider:**	**Consider:**	**Consider:**	**Consider:**	**Consider:**	**Consider:**	
-≤10' dose -Opt for targeted modality[5] -Avoid circumferential cryo-compression[5] -Strength / JPS deficits when applying wetted/crushed ice[6], circumferential cryo-compressive modalities ≥15'[7] -Appropriate rewarming period before RTP[8].	-15-20' dose -adapt to positional characteristics[9] location. -Increase magnitude of T_{sk} by compression adjunct[10]. -Use wetted ice / cryo-compressive pneumatic system where available[9]. -Avoid gel pack modalities due to uneven distribution of cooling[9]. -TC/TS differences between modalities[5,9].	**-In addition to 3(a)** -Post-session targeted cooling where strength adaptation is required[5]. -Avoid pre-session cryo-compressive circumferential joint / thigh cooling to negate reductions in flexibility / strength / JPS required[6]. -TC/TS differences between modalities / athlete preferences[5,9].	**1(b) in addition to:** -Cryo-compressive pneumatic circumferential[10] -Psychological influence on recovery measure[11] -Periodise cryotherapy application to individual rehabilitation schedule and response[11].	-CWI (ameliorate HAM_{ecc} deficits)[11] -Periodise protocols[11], adapt mode[5,9], compression[10] dose, CWI temperature to individual training demands and desired response / performance[11]. -Psychological influence on recovery measures[11]. -For lasting wellbeing perception multiple CWI + windows of PR[11]. -WBC 2-minute -135°C induces physiological changes without peripheral vascular shutdown[12].	**3(a) in addition to:** -Avoid standardised approach of recovery strategies across a squad[11]. -Choice of performance tests most beneficial to provide useful data to support adaptability of recovery strategies in high-performance settings[11,13]. -Lower levels of fatigue demonstrate less recovery benefits from cryo-compressive circumferential applications – consider rationale[14].	-Psychological influence on recovery measure[11]. -Avoid cryo-compressive pneumatic circumferential applications or provide appropriate rewarming period prior to NMF[13] -Periodise cryo-compressive circumferential[13], CWI modalities within micro-cycles and training schedules[11]	-Desired performance outcomes[11]. -Periodise cryo-compressive circumferential, CWI modalities within micro-cycles and training schedules. -Choice of performance tests most beneficial to provide useful data to support adaptability of cryotherapy protocols. -Psychological influence[11]	**Application Considerations**
HAM_{ecc} = *Eccentric Hamstring Strength; CWI = Cold-water immersion; TC = Thermal Comfort; TS = Thermal Sensation; JPS = Joint Position Sense; RTP = Return to Play; PR = Passive Recovery; NMF = neuromuscular function.*								

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[5] Alexander *et al,* (2021a).
[6] Alexander *et al,* (2016; 2018); Rhodes & Alexander (2018); Alexander & Rhodes, (2019); Alexander *et al,* (2019).
[7] Rhodes & Alexander, (2018).
[8] Alexander *et al,* (2018); Alexander & Rhodes, (2019).
[9] Alexander *et al,* (2020a).
[10] Alexander *et al,* (2020b).
[11] Alexander *et al,* (2021f).
[12] Selfe *et al,* (2014).
[13] Alexander *et al,* (2021e).
[14] Alexander *et al,* (2021d)

Recently it was suggested that the efficacy of cryotherapy applications is dependent on the timing and duration of the intervention (Kwiecien and McHugh, 2021). Although the findings in the current thesis do not disagree with this, it is considered that several other components may equally influence the optimisation of cooling protocols in sporting contexts. These include considerations such as periodisation of application within congested periods, the use of contemporary modes of pneumatic cryo-compressive or targeted cooling devices, compression adjuncts, positional characteristics in team sport, perceptual and performance measures, and demands of the athlete in addition to those variables presented earlier in Figure 1 (pg. 41), specific to the context of cooling. Similarly, from a recovery strategy perspective, findings from this thesis highlight other moderating factors that may influence the optimisation of cryotherapy application on *biomechanical, biochemical, physiological, and psychological* responses. For example, performance and perceptual effects, frequency, periodisation, timing specificity, dose, intensity, duration and temperature as emphasised previously by Peake, (2019) for other recovery interventions in sport. This only highlights the balance of enquiry between the control of characteristics and exploration of multiple comparisons of applications to determine differences attributable to potentially small differences in the characteristics between modes. In the context of recovery, Thorpe (2021) recently critiques the importance of periodised approaches to cooling (and heating) with the aim of providing evidenced based reasoning for the application of periodising recovery strategies through a practical framework. Studies in THEME 5 of this thesis support the approach by Thorpe (2021) although provide further contemporary evidence reflective of applied practice and not limited to one measure of physiological outcome as is defined within the framework offered (Thorpe, 2021). Rather, the approach of periodisation (of cooling) in this thesis considers four categories of response (*biomechanical, biochemical, physiological, psychological*), individually and collectively. This adds clarity and directional influence for applied practitioners through contextual performance investigations. This was highlighted by Thorpe (2021) as lacking in the current evidence base.

The illustration of Figure 1 (pg. 41) presents the complex interpretation of multi-factorial components deemed to potentially influence the optimisation of cryotherapy protocols, many of which are not investigated previously from an applied perspective. To optimise an athlete's response to cryotherapy for injury, rehabilitation, recovery or performance reasons, collective findings from the thesis suggest protocols should adapt in consideration of those influencing variables. This approach may be obvious although solutions have not been presented in previous literature. Although limited to the lower limb, the impact collectively illustrated in Table 10 (pg. 227) from a practical perspective evidenced through the fifteen studies. As noted from the findings in the thesis, some variables may be more influential on the intended application which then dictates the responses(s) most likely to be affected. Therefore, the practitioner should consider their choice of application and protocol based on the known effects and effectiveness of the cryotherapy modality after the variables and moderating factors are taken into consideration. Collectively, this would maximise the use of cryotherapy by optimising the measurable outcomes pertaining to the context of the situation where cryotherapy is being applied (*i.e., sports injury, rehabilitation, recovery, readiness to perform*) and the demands of the individual athlete.

In critique of figure 1 (pg. 41), from the twenty-one variables, seventeen were investigated across the fifteen publications. Variables that were not investigated in this thesis were considered although it was concluded that such variables had been explored elsewhere and were of little impact to the specific research question being explored at the time. Examples include adipose tissue (Otte *et al,* 2002; Selkow, 2019) or volume / weight of ice bag application (Janwantanakul, 2009). It felt important however to recognise as many variables known to demonstrate the challenges faced in trying to develop or optimise protocols of cooling in sporting contexts. Many of which have not been investigated, nor in an applied environment before so prove difficult to compare findings. This lack of comparable evidence however substantiates the originality of the thesis and reduces several of the knowledge gaps recently highlighted by Kwicien and McHugh, (2021).

In addition to the suggestions made in Table 10 (pg. 227) an infographic (Figure 23, pg. 231) was produced. The purpose of which is to provide practitioner-academics with a visual reference to influential considerations that may direct future study designs that investigate protocols that best reflect applied practices of cryotherapy in sport. An optimal protocol should elicit the necessary changes across multiple categories of response (*biomechanical, biochemical, physiological and psychological*) whilst considering the influence of cooling across and between those measurable outputs. This point again emphasises the need for individualisation and periodisation of cryotherapy strategies in sport specific to the context of its use. Contrastingly, and more fitting to the overall approach of the thesis perhaps; the infographic may be of benefit to those practitioner-researcher dual roles emerging from medical or science positions within high-performance settings. Here the implementation of meaningful research alongside performance driven demands often meets challenges in design, stakeholder acceptance and ethical dilemmas. Consequently, there are often conflicting ideals between the reporting of data that benefits the organisation (club) and the academic's association (Champ *et al,* 2020), despite several benefits and value to these relationships and the impact of such applied research and transmission of evidence then into practice. In summary, the infographic provides a journey of considerations derived from the fifteen studies that brings together multiple domains identified as influential when investigating cryotherapy use in contemporary practice. Practitioner feedback on Table 10 (pg. 227) and Figure 23 (pg. 231) in the future would be beneficial to guide further investigations of cryotherapy applications in sport.

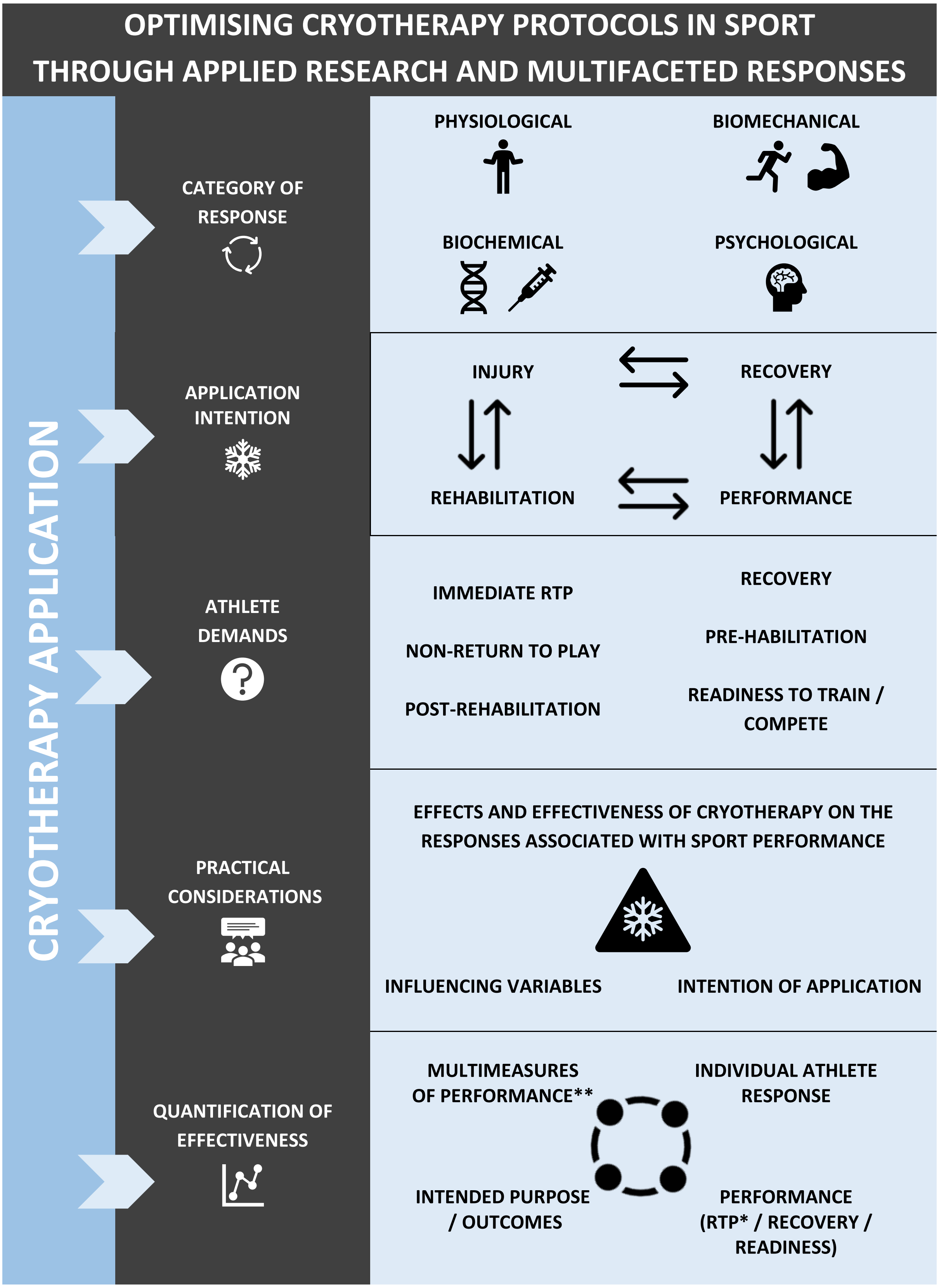

Figure 23. Practitioner-Researcher considerations for optimising applied research that investigates cryotherapy applications in sport when quantifying the effects on *biomechanical*, *biochemical, physiological* and *psychological* responses. (*RTP = return to play; ** = encompassing the four categories of response).

Results herein of the fifteen studies highlight the complex crossover of the four categories of response (*biomechanical, biochemical, physiological, psychological*) that are influenced through cryotherapy application and consequently influence the optimisation of cooling protocol development. Although there are recent debates as to the use of ice in acute injury management (Takagi *et al,* 2011; White and Wells, 2013; Dubois and Esquilier, 2020), the intention from the studies in theme 1 was not to challenge whether ice should or should not be used and the physiological influences in such context. The rationale for its exclusion in acute injury management is based on limited evidence and potential misconstrued understanding of its intention by practitioners. This is most likely due to the poor translation of evidence or relevance of the study for practice. Currently, the overarching fact is that cryotherapy is used widely in current sports injury management, practitioners apply it pitch side, and commonly athletes return to the field following exposure. What practitioners may be unaware of are the potential biomechanical changes in JPS and structures that stabilise the knee following local cooling applications of crushed ice, key impacts resulting from the earlier studies in theme 1 (Alexander *et al,* 2016; 2018). Practitioners and athletes alike should recognise the possible implications of this, which have informed the considerations in column (A) in Table 10 (pg. 227) and subsequent publications in the body of work particularly into theme 2 for example. Consequently, applications can be adapted safely and effectively as those demonstrated in Table 10 (pg. 227). In consideration of the optimal cryotherapy modality, this is dependent on several factors outlined in the thesis and represented practically again in Table 10 (pg. 227) from those modalities investigated throughout the publications. It is known that different thermodynamic properties exist between modes of cooling and influences the magnitude of T_{sk} and T_{im} (Merrick *et al,* 2002; Vieira *et al*, 2003). Pneumatic cryo-compressive devices and Peltier cell technology for targeted applications however have not previously been considered in the evidence base in this context owing to a lack of contemporary approaches that several of the publications address in this body of work.

From a recovery perspective, previously Peake (2019), acknowledges the effects of intense sport exercise on *physiological* and *biochemical* changes in athletes and provides an overview of common recovery strategies, cryotherapy being one. Considering the overarching findings in the thesis, it is suggested that biomechanical and psychological responses should also be acknowledged from the perspectives across all intended purposes of cryotherapy application (*sports injury, rehabilitation, recovery and performance*). To support this point, the effects of cryotherapy on perceptual and wellbeing responses was demonstrated in papers within theme 5, acknowledged as a key strand to understanding the mechanistic effects of cooling for recovery to enhance or optimise applications. Previously, the influence of ice as a single application has shown to have no influence on perceptual levels of soreness following exercise (Gulick *et al,* 1996; Nogueira *et al,* 2019). In agreement with Kwiecien and McHugh (2021) it is unlikely that a localised application of ice, short in duration would beneficially impact such responses. Findings from the current thesis suggest however that pneumatic circumferential or CWI cooling exposures during periods of congested fixtures offer a more optimised application, quantified by simultaneous psychological, biomechanical and physiological responses. Alternatively, WBC has been well received in terms of perceptual benefits in the literature (Hausswirth *et al*, 2011; Pournot *et al*, 2011; Ziemann *et al,* 2012; Costello *et al,* 2015; Rose *et al,* 2017), although not reported in study 15, despite considering multiple measures of performance recovery at the time. Overall, the approach and results from the studies in the thesis suggest that to best develop and implement 'optimal' cooling protocols, all four categories of response should be considered by the practitioner or applied researcher. That said, the context in which cryotherapy is intended is important. Although recovery benefits following cryotherapy are previously reported, it is acknowledged that the variation in how performance is assessed may preclude any definitive conclusions as to its actual effectiveness (Peake, 2019). The journey through the thesis reflects this position. Publication 14 addresses those considerations highlighted by Peake (2019), and earlier studies in the thesis, through the implementation of multi-measures of performance that reflected all four categories of response (*biomechanical, biochemical, physiological, psychological*). Yet, it is important to note that how much these elements can be quantified may differ between standards of sporting environments and is something which medical and performance teams need to consider in respect to their own methods of athlete monitoring. This is often dependent on infrastructure, staffing, access, costs and maintenance of cryotherapeutic modalities. Furthermore, significant variability across staff and teams in response to individualised perceptions of recovery strategies are noted in elite football (Altarriba-Bartes *et al,* 2021).

All publications in this programme of work were developed with contemporary practices in mind, therefore performance indicators were determined initially rather than trying to force the design of testing protocols into separate categories of *biomechanical*, *biochemical, physiological* or *psychological* responses. On reflection this strengthened the approaches taken in the studies to answer questions underpinning the development of optimal cryotherapy protocols for use in sport. Further to this, often methodological issues are faced when obtaining intervention data within these populations and settings to provide objective evidence and subsequent impact into the field. For example, complex study protocols with unnecessary metrics of measures that fail to reflect performance or intended outcomes of the intervention. To partly counter these problems across publications 13-15 methodology and study designs were built pragmatically around normal practices of the clubs. This approach complemented earlier considerations of appropriate performance indicators for recovery and the typical micro- and macro- cycles of training and recovery scheduled within elite rugby league and football settings utilised across some studies, whilst taking into consideration multiple responses to cryotherapy through various quantification methods typically used within the performance setting of where the study took place. This demonstrated an intention of the infographic put into practice before its inception (Figure 23, pg. 231).

It is acknowledged however that data collected within single club settings as many of the studies represented, can be affected by sample size, influenced by player rotation, time-loss injuries, or suspensions for example (Carling *et al,* 2015). Frequently current form or injury status of players may dictate inclusion into intervention studies with strict inclusion / exclusion criteria by the performance team. That said, despite some data collection methods being invasive (such as core temperature pills) and applied mid-competitive season, the success of the testing protocols using multiple measures in publication 15 was also evident via subsequent citations and successful applied methodologies designed for papers 13 and 14. As such the findings of these studies demonstrate quantifiable impact both academically and practically. At different operational levels the results have impacted club considerations around individual adaptations of cooling protocols. Indeed, several findings such as periodisation of CWI or the implementation of 2-minute WBC protocol for example, have been adopted by the medical and performance teams in which the studies were aimed for including adaptation of dose, pressure, periodisation, mode and individualisation of cryotherapy applications for injury and recovery strategies. Furthermore, the protocol of 2-minute WBC exposure taken from publication 15 has been the basis of succeeding WBC testing in recent literature (Hohenauer *et al,* 2020). Notably, the translation of evidence into practice was a key focus of the short communication (publication 9), and although the successful impact of several studies is critiqued here it would be beneficial to determine the impact in practice further through practitioner and athlete feedback in the future.

One important critique to note in this body of work is the quantification of T_{sk} repeatably through thermal imaging techniques to establish differences or effectiveness of cryotherapy applications. The effectiveness of cryotherapy modalities has been investigated through several parameters in previous literature (Bleakley and Davison, 2010; Ishan *et al,* 2016; Mawhinney *et al,* 2013; 2020), and T_{sk} is a common physiological measure often used to understand changes in T_{im} (Janwantanakul 2004; 2009; Kennet *et al,* 2007; Ihsan *et al,* 2013; Estefani *et al,* 2019) when invasive measures are not applicable or appropriate. It is appreciated that T_{sk} may be a poor predictor of T_{im} (Bleakley and Hopkins, 2010; Kwiecien and McHugh, 2021) and it is the magnitude of temperature change in deeper tissues not skin surface that is the target for effective recovery (Bleakley and Hopkins, 2010). Several of the studies in the thesis used T_{sk} to demonstrate the effectiveness of cooling observed between contemporary modalities, pneumatic compressive adjuncts, simultaneous measures of psychological wellbeing, physical outcome measures, such as SmO_2, and as a measure of determining consistency of achieving therapeutic range (Kennet *et al,* 2007), not to determine intramuscular temperature per se. What was key and influential from the design of those studies was the impact of cooling on performance measures when considering multiple categories of response (*biomechanical, biochemical, physiological, psychological*) across the five themes and T_{sk} as a consistent measure of defining efficacy between cooling protocols. This was important to determine effective applications and reflective of contemporary practices not established previously. In addition, it is known that an inverse correlation exists between magnitude of muscle temperature change and subcutaneous adipose tissue (Otte *et al,* 2002), although this has never been applied to positional factions in a team sport, which publication 7 alludes to and publication 8 critiques.

Findings in publication 14, from a statistical analysis and presentation of data perspective, possess merit to challenge earlier studies in the thesis, around group average vs individual analysis of data. The favouring of mean over individual responses has some limitations to the impact of translation of findings to practice. This was of note in the latter studies presented in theme 5. This is a contemporary debate reflected in a recent blog (Morin *et al,* 2020) and literature (Buchheit *et al,* 2021). Because of presenting the data in mean, individual and associated individual change between the variables quantified in publication 14 clarity around what was observed in response to the cryotherapy intervention was achieved. Not to discredit the approaches of earlier work in the thesis, this approach has impactful practical and scientific standing and provides the opportunity for future research study designs to be developed. Accordingly, findings suggest that the adaptation of cryotherapy applications to the individual athlete may maximise optimal protocols for injury, rehabilitation, recovery or performance; an influential recommendation from this study, although is not a new concept in terms of a '*one size does not fit all'* approach in terms of specificity and context for recovery strategies (Minett and Costello, 2015). This is highlighted in previous work that considers cryotherapy duration (Jinnah *et al,* 2019) or in terms of adapting cooling to levels of adipose tissue (Otte *et al,* 2002). Yet, the confounding difference in the studies presented in this thesis compared to previous appraisal, reflect contemporary cryotherapy modalities, study design, methods and objective performance markers in elite sport settings within competitive seasons which, consequently, validate and reaffirm those suggestions from a practical perspective. These studies have therefore developed greater impact on modern day practices through their original contribution to knowledge, reducing the disconnect from real-world approaches of applied practices and evidenced based literature. Results from this programme of work are intended to influence positively the current practices of acute cryotherapy applications, challenge and refine debates around cryotherapy protocols through rigorous enquiry, and to optimise the use of cryotherapy in elite sport settings for recovery of performance in anticipation of readiness to train and compete demands, ultimately improving athlete management in high-performance settings where cryotherapy is a commodity of everyday athlete management.

A key ethos underpinning each publication was the applied nature of the methodologies and successful translation of evidence into practice. The outcomes of the studies as mentioned presented the investigation of current practices and in the latter studies particularly in theme 5 demonstrate high ecological validity. Several of the publications have initiated ongoing validation investigations within the elite performance settings of where data was originally collated. Notably, high-performance settings possess competitive situations and require optimal performance of their athletes, be that during a rehabilitative or recovery process. Results of studies in the programme of work that considered variables which influenced optimal applications of cryotherapy are now implemented within the recovery strategies of sports teams utilised in the publications consequently. Results from publications 13 and 14, are thought crucial to their players' readiness to train or play through adaptation of their recovery strategies that incorporate cooling protocols. In an associated publication (not part of this thesis) where acceleration and deceleration demand during the covid 2020-2021 season were captured for the same English Football League Two team where CWI data was collected, the impact of congested periods of games and frequency of high-intensity accelerations and decelerations were found to have a significant impact on performance (win / lose / draw). It was concluded that specific conditioning and recovery strategies should be considered in future studies to optimise performance during competitive games. Consequently, individualisation protocols of CWI that considers player wellbeing and demands of competitive fixtures within the micro-cycle of a specific week will be implemented this coming season (2021-2022) across several clubs with a follow up of impact next year.

The impact of publications 10-15 have led the directive for current research studies with internal (Football Performance Hub, UCLan – Recovery Research Strand) and external industry colleagues from several elite clubs (Premier League, FC Kopenhagen, Plymouth Argyle FC, Rangers FC, Blackpool FC, Everton FC, Hungarian National Football team). The first being a systematic review on *'Profiling Recovery Strategies and Response in Football Players to Increase Performance, Reduce Injury Risk and Maximise Player Availability'* with collaborative input from external colleagues named above.

In response to the findings from publication 10 which suggest an overarching agreement that advantageous protocols for cryo-compression is lacking, despite compression increasing the magnitude of cooling, the development of a longitudinal study in elite football is underway, with the aim of understanding cumulative and individualised cryo-compressive protocols over a season-long period for optimising recovery strategies. Further projects influenced by paper 5, include a commercial partner venture through a knowledge transfer partnership (KTP) that aims to further investigate the pneumatic cryo-compressive device ProMOTION EV1 (Swellaway LTD.). Publication 5 was a fundamental study in the early stages and progression of the design and promotion of its unique selling point, being of targeted application as opposed to circumferential cooling. The current product design (ProMOTION EV1) was influenced by the findings of study 5 specifically around the arrangement of the Peltier cell technology, changing from two separate Peltier cells limited to a knee brace application to a single cell configuration for improved cooling performance and application to multiple sites, maximising its application and optimising its response for sport injury and recovery use in elite athletes. Studies are ongoing today as part of the KTP initiative and have gained further investment and backing from professional footballers and stakeholders.

Finally, with the aim of reducing the gaps in knowledge, findings from the thesis identified three key areas of practical importance in how optimal applications of cryotherapy (in the broadest sense) within sporting contexts may be developed and be advantageous to the athlete. To further the understanding around determining optimal protocols of cryotherapy, researchers and practitioners might consider:

1. *What measures best represent performance and capture biomechanical, biochemical, physiological and psychological responses simultaneously for optimising cryotherapy applications through quantification of response.*
2. *Adapt cooling protocols based on the influential variables pertinent to the intention of the application (i.e., sports injury, rehabilitation, recovery, readiness to perform).*
3. *Identify individual athlete response when multiple categories of response are considered through relevant and accurate multi-measures of performance.*

4.3.2 Publication Metrics

The publication strategy aimed to influence practitioners in the field of sports medicine and performance and provide examples of contemporary research reflective of current practices in sport and elite sport environments that would support research-informed teaching which practically addresses contemporary issues relating to cryotherapy application in sport. Table 11 represents an overview for each publication with relevance to the impact factor (IF) of the journal, number of citations, source normalised impact per publication (SNIP) and Field-weighted citation impact (FWCI) (as of 2021). Journals chosen for submission of articles were not based on impact factor alone, but the target reader and whether the journal was applied in nature.

Table 11. Metrics for each publication of the thesis.

Reference	IF	Citations	SNIP	FWCI	Journal Rank
THEME 1: KINEMATIC RESPONSES TO CRYOTHERAPY					
Publication 1 (Appendix 1a) Alexander, J., *et al.* (2016). An exploratory study into the effects of a 20-minute crushed ice application on knee joint position sense during a small knee bend. *Phys Ther Sport,* 18(1); 21-26.	2.18	n=10	1.001	0.46	0.91
Publication 2 (Appendix 1b) Alexander, J., *et al.* (2018). Delayed effects of a 20-min crushed ice application on knee joint position sense assessed by a functional task during a re-warming period. *Gait and Posture,* 62: 173-178.	2.65	n=8	1.492	0.51	0.85
THEME 2 MUSCLE STRENGTH RESPONSES TO CRYOTHERAPY					
Publication 3 (Appendix 2a) Rhodes, D, and Alexander, J. (2018). The effect of knee joint cooling on isokinetic torque production of the knee extensors; considerations for application. *Int J Sports Phys Ther,* 13(6); 6-8.	2.55	n=10	0.235	-	-
Publication 4 (Appendix 2b) Alexander, J, and Rhodes, D. (2019). Temporal patterns of knee extensor isokinetic torque strength in male and female athletes following comparison of anterior thigh and knee cooling, over a rewarming period. *J Sport Rehab,* 18(29): 723-729.	1.93	n=6	0.592	0.63	0.61
Publication 5 (Appendix 2c) Alexander, J., *et al.* (2021). Evaluation of muscle strength responses to contemporary cooling modalities in sport. *Isokin Ex Sci.* Pre-Press. 1-9.	0.38	In Press	0.413	0.26	0.21
THEME 3 THERMOLOGY AND SKIN SURFACE REPONSES TO CRYOTHERAPY					
Publication 6 (Appendix 3a) Alexander, J., *et al.* (2019). Mapping of skin surface sensitivity and skin surface temperature at the knee over a re-warming period, following cryotherapy. *PRM+,* 2(1): 1-5.	n/a	n=2	-	-	-
Publication 7 (Appendix 3b) Alexander, J., *et al.* (2020a). Comparison of cryotherapy modality application over the anterior thigh across rugby union positions: A Crossover Randomized Controlled Trial. *Int J Sports Phys Ther,* 15(2): 210-220.	2.55	n=3	0.235	-	-
Publication 8 (Appendix 3c) Alexander J and Rhodes D (2020). Thermography for defining efficiency of cryotherapy modalities in sport. *Temperature,* 8(2): 105-107.	2.10	n=1	1.365	0.85	0.98

THEME 4 CONTEMPORARY CRYOTHERAPY APPLICATIONS AND RESPONSES					
Publication 9 (Appendix 4a) Alexander, J., *et al*. (2021b). Cryotherapy in Sport: A warm reception for the translation of evidence into applied practice. *Res Sports Med.* 10: 1-4.	2.55	n=0	1.117	0.88	1.4
Publication 10 (Appendix 4b) Alexander, J., *et al*. (2021c). Cryotherapy and compression in sports injury management and rehabilitation: A Scoping Review. *Int J Therapy and Rehab.* In Press.	0.4	In Press	0.384	-	0.19
Publication 11 (Appendix 4c) Alexander, J., *et al.* (2020b). Physiological parameters in response to levels of pressure during contemporary cryo-compressive applications; Implications for protocol development. *J Athl Enhancement.* 9(2): 1-6.	1.54	n=1	-	-	-
THEME 5: MULTIFACETED RESPONSES TO CRYOTHERAPY AS A RECOVERY STRATEGY IN ELITE SPORT					
Publication 12 (Appendix 5a) Alexander, J., *et al.* (2021d). Recovery Profiles of Eccentric Hamstring Strength in Response to Cooling and Compression. *J Bodywork Movement Ther,* 27(3): 9-15.	1.26	n=0	0.821	-	0.47
Publication 13 (Appendix 5b) Alexander, J., *et al.* (2021e). Immediate effects on performance following contemporary cryo-compressive application post-training in elite academy footballers. *Biology of Sport,* 39(1): 11-18.	2.78	n=0	1.268	-	0.94
Publication 14 (Appendix 5c) Alexander, J., et al. (2021f). Utilisation of performance markers to establish the effectiveness of cold-water immersion as a recovery modality in elite football. *Biology of Sport,* 39(1): 19-29.	2.78	n=0	1.268	-	0.94
Publication 15 (Appendix 6a) Selfe, J., et al. (2014). The Effect of Three Different (-135°C) Whole Body Cryotherapy Exposure Durations on Elite Rugby League Players. PLOS ONE, 9(1): 1-9	2.87	n=51	1.349	2.68	0.99

SNIP = Source normalised impact per publication; IF = Impact Factor; FWCI = Field-Weighted Citation Impact.

4.3.3 Limitations

Whilst the body of work in its entirety presents a significant contribution to the evidence base it is not without limitations. Strengths and novelty of the work are listed earlier in Table 2. (pg. 42-52). Limitations are presented in Table 12 by theme and contribute to the presentation of future research considerations.

Table 12. Limitations identified and critiqued by publication, per theme.

Theme	Limitations
Theme 1 **Publications 1 and 2**	Publication 1 (Alexander *et al,* 2016) was limited to only the immediate effects and lacked a rewarming observational period. Findings were limited to a single measure of JPS in publications 1 and 2, where consideration of multiple objective measures of functional performance may have supported further understanding of the biomechanical and physiological responses affected by local cooling. Use of a control group may have benefitted the further understanding of whether the known effects are due to cold and not compression adjunct. Consideration of a fatigue affect in publication 2 should be acknowledged and considered in future study design and interpretation of results.
Theme 2 **Publications 3-5**	A limitation of publication 3 is the use of the handheld thermometer to quantify T_{sk}. Literature recommends the use of infrared thermal imaging as gold standard technology to use in terms of quantifying T_{sk} application in cryotherapy research (Costello *et al,* 2012a). Population of athletes in similar research (being non-elite) may have implications on the eco validity of such data across levels or gender of athlete for elite sport settings. Several criticisms are levelled at the study design with regards to the functional test executed and interpretation of results for JPS or measures of proprioceptive components. Likely due to the misinterpretation of proprioceptive terminology (Hillier *et al,* 2015). Although the movement test employed in earlier studies (Alexander *et al,* 2016; 2018) were considered functional, deliberation over its ability to truly reflect the extreme movements in land-based sports may be challenged. A cutting movement for example may be more representative of function and closely related to typical non-contact mechanism of injury for the anterior cruciate ligament (David *et al,* 2017). There was however ethical hesitation around progressing investigations of local cooling and its effects on JPS or other components of proprioception such as dynamic stability or neuromuscular control, considering the negative effects on proprioceptive components following cryotherapy application. In publication 4, the decision not to collect skinfold thickness measures may be considered a limitation. The population group were of athletic slim build, and generally from sports that present minimal differences in characteristics due to positional demand as demonstrated in publication 6 (Alexander *et al,* 2020), it was considered that minimal discrepancy of adipose tissue between participants would have any effect on results. Despite this, known differences in levels of adipose tissue are reported when comparing between genders, with females typically presenting with higher levels (Change *et al,* 2018). This may have contributed to the findings of the study, limits the translation of results to a male population. Generally, a limitation of healthy and rested state participants is a consideration across several studies including study 4. A limitation to publication 5 considers the application of only one level of compression (mm Hg) despite the devices offering multiple protocols. General limitations of muscle strength parameter studies, intra-muscular temperature was not quantified and is a consideration for future studies.

Theme 3 **Publications 6-8**	In publication 6, inclusion of male and female subjects may be considered a strength and limitation of the work which presented interesting comparisons of results when considering the somatosensory influences that hair and hair follicles play in sensory feedback. Triggered by tactile stimuli (Abraira and Ginty, 2013), differences were noted in feedback that may have been attributed to the reduction of hair over the anterior knee in the female population group compared to the males. From a critical view, results suggest lower thresholds of SSS in females at baseline compared to male participants, making it difficult to compare gender groups but incidentally contributes to the understanding that differences occur in gender response to cooling (Cankar and Finderle, 2003). The addition of a control group rather than participants as their own control (i.e. compared to pre-intervention levels) may have reduced the limitations of the results and should be considered in future methodological approaches. A limitation of study 7 was the absence of T_{im} measures. Mechanisms of response in deeper structures are therefore assumed based on previous relationship theories between T_{sk} and T_{im}. Furthermore, the methodology in this study is focussed on an all-male population, differences are known to present in response to cooling between genders (Cankar and Finderle, 2003) and therefore results may not be directly apparent in the equivalent female rugby union population.
Theme 4 **Publications 9-11**	Limitations were evident in this theme through publication 11, as there was no attempt in this piece of work to quantify actual values of pressure across devices as this may have distracted away from the practical application and eco validity of the results. That said, the strengths of this work outweigh that limitation, and foster the need for further study.
Theme 5 **Publications 12-15**	The quantification of strength would have been beneficial at multiple timepoints rather than only immediately post exposure to determine whether a delayed response in muscle strength parameters occurred in publication 12. This would align with the known recovery time-course periods in football post-competitive fixtures of between 48-96 hours (Nédélec *et al,* 2012; Rhodes *et al,* 2018; Altarriba-Bartes *et al,* 2020). Results are not applicable to the female football player, nor can it be assumed the same results would have occurred from other cooling modalities. The limitations of this study posed further questions around dose-response, periodisation of cooling, optimal choice of cooling modality and insight into future study designs. The importance of 'individualisation' of recovery strategies are encouraged, yet individual response per se were not quantified in study 13. Group averages in terms of the statistical approach did not consider this although it provided a catalyst for future publications in the thesis to consider as part of future study design and analysis. The protocol of collecting baseline data at matchday +1 rather than at pre-training on the day of cooling vs PAS intervention, which was matchday +3, may have been less beneficial in terms of understanding the acute response in terms of player performance. When comparing to a baseline measure taken at matchday +1, a drop in objective performance may already have been evident and expected following a competitive fixture. Although, percentage differences were representable from specific timepoints which represented meaningful effects quantified within mid-season micro-cycle of the recovery strategies employed in the study. Further limiting factors of this study which may avert transferrable finding are due to the heterogeneity of the population (age group), location of cooling (lower limb - thigh), application of cooling (temperature, compression levels, mode of cooling, circumferential application) and choice of multi-measures to quantify effect which represented the specific approaches of the club training and ethos for recovery. The lack of

	quantifying a temporal response over a longer period inhibits understanding around the lasting effects or benefits of either intervention (cooling / PAS). It is appreciated in publication 14 that some limitations provide key considerations that should be taken forward in future studies to appraise and impact contemporary applied practices within elite sport settings. A follow up of performance markers at 48hrs post-intervention, and again at 72hrs post-intervention is necessary to appreciate the full impact of recovery strategies and time-course recovery typical of an elite football environment and not reported in this study. These timepoints further acknowledge the known deficits in fatigue following post-match competitive play. Finally, translation of current findings to female athletes or other sports and the response to other recovery methods or types of cryotherapy applications are limited due to the specific heterogeneity of the population group and other study design features. Not having a temperature-controlled room for quantifying measures post-exposure to WBC in study 15 was a limiting factor and constant monitoring of fluctuations was key. Fluctuation in the WBC chamber temperature was considered due to prolonged use (Savic *et al,* 2013). Ideally T_{sk} measured inside the chamber may have been useful to measure internal convective strength of the cooling modality. The greatest challenge was to maintain high numbers of participating, injury-free players during the testing period. Often a limitation when working with squads of elite athletes, mid-competitive season due to the prevalence of injury risk whilst playing which then precludes them from participation in such research.

4.4 Future Research Considerations

Several gaps and questions remain or indeed have emerged from this programme of work however they provide the opportunity to build upon the findings of the publications presented in this thesis. A pertinent point made at the start of work was the consideration around the application of therapeutic modalities being a fundamental element in the management of injury, rehabilitation, recovery and readiness to perform in sport, and considered to be dependent upon a practitioner's application protocol of cooling, determined by the evidence base or anecdotally informed. To explore this further, toward the end of the Ph.D. journey the opportunity to be involved in a collaborative study on this topic emerged and has since been published (Malone *et al,* 2021). The work titled *Athlete, coach and practitioner knowledge and perceptions of post-exercise cold-water immersion for recovery: a qualitative and quantitative exploration,* although not part of this Ph.D. has influenced the design of future studies that will consider psychophysiological interactions to optimise the application of CWI in elite sport environments. Findings confirmed the belief that CWI is useful for recovery in sport with respondents largely involved in elite sport having used CWI previously, yet protocols differed and failed to align to recommendations in scientific literature (Malone *et al,* 2021). This supports the earlier suggestions of publication 9 in the thesis and the importance of knowledge transfer and context applied to data. With that being one example of future research considerations, several others emerged from the thesis. In essence to maximise contemporary understanding and impact of findings into practice, future investigations should consider the following approaches to study design to understand how protocols of cryotherapy for sport injury, rehabilitation, recovery and performance can be further optimised. Listed below are considerations taken from the findings of this thesis and accompanying publications from which they emerged.

1. *Utilise multi-centre, multi-level, female, and male athletes (Publications 6, 7 and 14).*
2. *Collate season-long data and apply longitudinal studies to reflect the impact on individual response, performance and optimal periodisation of cooling (Publication 14).*
3. *Consider a battery of sport-specific multi-measures of performance to quantify the effectiveness of cryotherapy applications specific to the intention of the application (Publication 13, 14 and 15).*

4. *Investigate contemporary cryotherapy and cryo-compressive modalities reflecting current applications in sport vs traditional methods and repeated applications (Publications 7, 11, 12, 13, 15).*
5. *Quantify intramuscular response to contemporary methods of cooling and establish associations with simultaneous kinematic, muscle strength and skin parameters of response (Publications 3-5).*
6. *Quantify multiple categories of response (biomechanical, biochemical, physiological, psychological) to cryotherapy relevant to the demands and physical performance indicators for the sporting population of enquiry when designing study protocols (Publications 1-15 collectively) (Refer to Figure 23. pg.231).*
7. *Consider athlete and practitioner perceptions of cooling modalities during application of cryotherapy for injury, rehabilitation, recovery and performance.*
8. *Embed where possible the execution of cryotherapy investigations within club settings, maximising or developing the role of the practitioner-researcher to enhance the ecovalidity of the research and impact of findings.*

Further investigations around individual athlete response to periodised cooling applications in team based elite sport utilising a range of performance measures that represent the four categories of response to cryotherapy for readiness to train / compete situations are underway. The multi-site, multifaceted response study design intends to explore simultaneous perceptual and performance response to cooling across several modes for recovery in high-performance sport settings during micro and macro cycles throughout competitive seasons. To guide the methodological designs of these studies, practitioner feedback to help understand the research need and questions on cryotherapy application in sport is key and something only considered from a personal perspective in this collection of work. Since the writing of this thesis however involvement in a collaboration project, introduced earlier, that explored athlete, coach and practitioner knowledge and perceptions of post-exercise cold-water immersion for recovery (Allan *et al,* 2021) was subsequently published. The involvement and findings of that work along with those published as part of this thesis have collectively influenced future research study designs and areas of investigation influential to contemporary practices of cooling and recovery in sport.

Overall, findings have provided greater insight into current practices of cryotherapy in sport and their effects simultaneously across multiple categories of response (*biomechanical, biochemical, physiological, psychological*). Critical synopsis of the thesis has inspired the writing of an opinion piece, yet to be submitted at the time of writing. The premise of that piece hopes to capture and contribute a central perspective for the collective interpretation of findings from the body of work presented in this thesis. The narrative centralises its discussion around Figure 1 (pg. 41) through scientific discourse which challenges the evidence in this area. The ideal scenario of developing a framework of evidence that would direct a practitioner's decision making around optimal protocols of cryotherapeutic applications in sport was an underpinning consideration. Although too broad for this programme of work alone, the studies in the thesis pave the way for future research that may develop such a tool. That said, Table 10 (pg. 227) and Figure 23 (pg. 231) offer an integral part in the progression of this idea and are included in the opinion piece underway. The impact of which remains to be seen and hopes to be quantified, of which optimal cryotherapeutic protocols may be based upon in practice and scientific communities in the future.

4.5 Conclusion

Despite the extensive use of cryotherapy in sport (Kalli and Fousekis, 2020; Kwiecien and McHugh, 2021), confusion surrounding the optimisation of its application is evident. The principal aim of this thesis was to examine the effects of cryotherapy on several responses that underpin the optimisation of its application in sport from an applied approach. To influence the development of beneficial protocols of cryotherapy in practice through scientific enquiry, study designs and approaches considered the demands of sport and environments where cooling is often applied to ensure translation of evidence and impact on contemporary practices. Original investigations of contemporary cryotherapy devices were tested, and in-season methodology provided real-world data collection and analysis in elite sport building on earlier laboratory-based experimental designs.

Findings were presented by theme and category of response, signifying that individual athlete responses across concurrent *biomechanical*, *biochemical, physiological* and *psychological* categories should be considered and can influence practitioner applications of cryotherapy. Sports medicine and performance practitioners should appreciate the potentially detrimental biomechanical responses to local cooling at the lower limb when considering the multidirectional demands of function in many sports. It was noted that variables introduced in Figure 1 (pg. 41) have significant influences on *biomechanical*, *biochemical, physiological* and *psychological* responses over rewarming periods. This may present detrimental effects that may inhibit safe immediate return to play following local cooling exposures at the lower limb. Alternatively, advantageous protocols of cooling should be modified to optimise their applications dependent on the therapeutic intention or demands for readiness to perform as a recovery strategy.

With regards cooling protocols, the ability to reduce T_{sk} for optimising intended physiological response differs between dose, modality type, compression adjunct and positional characteristics in team sport. Furthermore, despite compression increasing the magnitude of cooling, there is no agreement in advantageous protocols for cryo-compressive modalities separate to isolated cooling application. Consequently, results found that muscle strength responses were influenced by these moderating factors with variances evident between circumferential and targeted applications.

Interestingly this differs to suggestions in recent literature whereby it is suggested that *''the application of different cryotherapy techniques does not appear to significantly affect (positively or negatively) the strength of athletes''* (Kalli and Fousekis, 2021). Current findings in the thesis are thought to be rationalised by the choice of quantification output and population. For example, multi-measures of performance were a key developmental study design and driver offering interesting outputs in latter publications (theme 5). Rather than presenting the impact of cooling on one output, multi-measure approaches show the complex interplay between multifaceted responses that are influential to the optimisation of cryotherapy applications. This reflects the measurable demands of the sport in the populations represented in those specific studies (i.e., elite academy / senior footballer / rugby union players). This methodological approach contributed to the originality of the work whilst addressing the need for such investigations of cryotherapy as proposed in recent review (Kalli and Fousekis, 2020; Kwiecien and McHugh, 2021). In consideration of recovery parameters and the use of cryotherapy it was found that CWI may be useful to ameliorate potential deficits in eccentric hamstring strength in elite adult footballers. In addition, when comparing circumferential cooling vs passive recovery in elite academy footballers, differences found in neuromuscular performance suggest periodisation and individualisation of cryotherapy protocols in these environments is important to negate responses that may inhibit readiness to perform.

The implications of the findings suggest that the progression of advantageous protocols for sport injury, rehabilitation, recovery and readiness to perform is inherent to the understanding of the relationships between mechanisms that underpin the effected output and response in the working context of cryotherapy. The significance of the findings builds upon previous literature in the scope of cryotherapy yet provides an original contribution to the broader fields where practitioners should consider the effects of cryotherapy upon performance response as reported in this body of work. Adaptations to cryotherapy protocols suggested through Table 10. (pg. 227) may be implemented accordingly to achieve beneficial outcomes from this modality within sport.

5.0 References

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6.0 Appendices

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6.1 Appendix 1: Theme 1 Publications: KINEMATIC RESPONSES TO CRYOTHERAPY

Appendix 1a: Copy of Publication 1.

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Original research

An exploratory study into the effects of a 20 minute crushed ice application on knee joint position sense during a small knee bend

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ABSTRACT

Objectives: The effect of cryotherapy on joint positioning presents conflicting debates as to whether individuals are at an increased risk of injury when returning to play or activity immediately following cryotherapy application at the knee. The aim of this study was to investigate whether a 20 min application of crushed ice at the knee immediately affects knee joint position sense during a small knee bend.
Design: Pre- and post-intervention.
Setting: University movement analysis laboratory.
Participants: Eleven healthy male participants.
Main outcome measures: Kinematics of the knee were measured during a weight bearing functional task pre and post cryotherapy intervention using three-dimensional motion analysis (Qualisys Medical AB Gothenburg, Sweden). Tissue cooling was measured via a digital thermometer at the knee.
Results: Results demonstrated significant reductions in the ability to accurately replicate knee joint positioning in both sagittal ($P = .035$) and coronal ($P = .011$) planes during the descent phase of a small knee bend following cryotherapy.
Conclusion: In conclusion a 20 min application of crushed ice to the knee has an adverse effect on knee joint repositioning. Team doctors, clinicians, therapists and athletes should consider these findings when deciding to return an athlete to functional weight bearing tasks immediately following ice application at the knee, due to the potential increase risk of injury.

1. Introduction

The application of ice for the treatment of soft tissue injuries is common practice within sport and clinical settings (Bleakley, Costello, & Glasgow, 2012; Bleakley, McDonough, & MacAuley, 2004; Costello & Donnelly, 2011). Cryotherapy in this instance is generally applied to provide cold induced analgesia by aiming to reduce tissue temperatures to 13.6 °C (Bleakley et al., 2012; Bugaj, 1975; Jutte, Merrick, Ingersoll, & Edwards, 2001) in order for physiological changes to occur (Algafly & George, 2007; Fishman, Ballantyne, Rathmell, & Bonica, 2010; Knight & Draper, 2013; Nadler, Weingand, & Kruse, 2004; Rice, McNair, & Dalbeth, 2009). It has been previously established that cellular metabolism is reduced by 10% when skin surface temperatures (Tsk) are between 10 and 11 °C (Bugaj, 1975). Other research suggests a reduction in nerve conduction velocity (NVC) occurs at 12.5 °C (Jutte et al., 2001), and hypometabolism onset at 15 °C (Knight & Draper, 2013). Algafly and George (2007) reported a 33% reduction in nerve conduction velocity (NCV) when Tsk was cooled to 10°, supporting earlier work by Chesterton, Foster, and Ross (2002). Kennett, Hardaker, Hobbs, and Selfe (2007) suggest Tsk between 10 °C and 15 °C can therefore define an optimum therapeutic Tsk range. It is interesting that although the effects of cryotherapy on proprioception and joint position sense (JPS) are largely unknown (Costello & Donnelly, 2010), clinicians and therapists continue to apply cold modalities such as ice in a clinical or pitch side setting (Bleakley et al., 2011). Anecdotal evidence suggests that ice is applied during rehabilitation to facilitate joint movement. Athletes therefore often perform exercises immediately after cryotherapy. There is however, little consensus in the literature on how functional performance and joint range of movement is affected by the application of cold, with recent systematic reviews (Bleakley et al., 2012; Bleakley & Costello, 2013) reporting varying conclusions.

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In sport poor JPS has been associated with functional instability and increased risk of knee injury thought to be caused by increases in postural sway, balance deterioration and disturbances to gait patterns (Kiran, Carlson, Medrano, & Smith, 2010). Although it is still undecided as to how JPS reduces due to cryotherapy applications and the implications it may have on the risk of injury, due to potential changes in functional stability. Assessment of joint position can influence clinical practice, with therapeutic interventions known to affect dynamic stability (Williams et al., 2001) it is recommended that active angle reproduction (AAR) should be used as a method of assessment for knee JPS (Selfe et al., 2006). Accuracy of the ability to reproduce a joint angle is affected by the type of test applied, during AAR quicker positional stabilisation was accomplished compared to passive angle reproduction (PAR) (Selfe et al., 2006). The application of active reproduction tests in the current study closely mimics functional performance in athletes, supporting previous research (Bennell et al., 2005; Stillman, 2002).

The reliability of previous research around JPS and cryotherapy application is debatable; Surenkok, Aytar, Tuzun, and Akman (2008) found that knee JPS was negatively affected following both the application of a cold pad and post application of a cold spray using a passive knee repositioning test. Neither Tsk nor duration of cold pad or cold spray was reported. Thieme, Ingersoll, Knight, and Ozmun (1996) reported no significant difference in active movement reproductions following a 20 min application of an ice pack to the knee compared to the control of no ice pack. The use of the most accurate trial instead of mean error in this study has been questioned as trials that produced a less accurate angle were disregarded (Costello & Donnelly, 2010). Alternatively a recent systematic review by Bleakley et al. (2012) suggested that a negative effect on functional performance occurs after 20 min cryotherapy application. In addition, Ribeiro et al. (2013) support the recommendation that cryotherapy has a damaging effect on proprioception at the knee. Functional impairments in JPS at the knee were also reported by Watanabe et al. (2013) following a cryotherapy application time of 15 min. Studies on the ankle (Hopper, Whittington, & Davis, 1997; La Riviere & Osternig, 1994) and the shoulder (Dover & Powers, 2004; Wassinger, Myers, Gatti, Conley, & Lephart, 2007) have also shown conflicting results. Reductions in JPS are commonly assessed clinically to identify proprioceptive deficits these may indicate that an individual is at risk of injury (Bleakley, McDonough, & MacAuley, 2006; Costello & Donnelly, 2010; Surenkok et al., 2008; Uchio, Ochi, Fujihara, Adichi, Iwasa, & Sakai, 2003; Wassinger et al., 2007; Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007). It is supported by Whatman, Hume, and Hing (2013) that the SKB lower extremity functional test is a useful tool in clinical decision making concerning risk of injury and dynamic alignment of the lower limb. Literature fails to agree whether it is safe to return athletes to dynamic functional tasks immediately following the application of ice to the knee. This study therefore examines the effects of crushed ice application to the knee using a small knee bend (SKB) as a functional assessment to observe knee JPS.

2. Methods

2.1. Participants

This exploratory study included eleven healthy male volunteers who regularly participate in team, land based sports took part in the study, with an average age of 21.3 ± 1.7 years, body mass of 83.5 ± 32.5 kg and height of 182 ± 12.8 cm. All participants provided written consent to take part in the study. The study was conducted according to the Declaration of Helsinki (WMA, 2008) and approved by UCLan Built, Sport and Health Ethics Committee (BuSH 128). All male participation was chosen to increase sample homogeneity due to gender differences found in response to local cooling (Cankar & Finderle, 2003). Criteria for exclusion from the study included previous knee joint surgery, lower limb injury in the last 6 months, referred pain either to or from the knee or any contraindications to cryotherapy (Kennett et al., 2007).

2.2. Intervention protocol

The study was a single group, pre-test–post-test design. The testing protocol took place in a movement analysis laboratory. Kinematic data were collected pre- and post-intervention using a ten camera infra-red Oqus motion analysis system (Qualisys medical AB, Gothenburg, Sweden) collecting at 115 Hz. Cameras were arranged in an umbrella formation (Richards, 2008). Participants acclimatised to a steady thermal state for a 15 min period, prior to intervention; during this phase passive retro-reflective markers were placed on the following anatomical landmarks (Fig. 1); posterior superior iliac spine (PSIS), anterior superior iliac spine (ASIS), greater trochanter, medial and lateral epicondyle of the femur, medial and lateral malleolus, calcaneus, dorsal aspect of first and fifth metatarsal heads and the middle cuneiform, acromion, lateral epicondyle of the humerus and radial styloids. Clusters of four markers mounted on a thin sheath of lightweight carbon fibre were applied to the anterolateral aspect of the femur and tibia. Three measures of Tsk were taken from the centre of participants' patella following the acclimatisation period, using a digital thermometer (Fora, Gallen, Switzerland IR19). The accuracy of the skin surface thermometer meets the accuracy required in ASTM E1965-98 and the EC directive 93/42/EEC.

Pre-testing, familiarisation to the SKB protocol of 45° was conducted measured by a goniometer, prior to kinematic data collection. The participant was given three attempts to replicate the 45° SKB in order to familiarise themselves with the movement pattern (Reurink et al., 2013). Following the 'practice' attempts participants then completed five SKB using three dimensional (3D) motion analyses to measure knee motion. No white noise or blindfolds were worn by the participants; it was felt that by removing sensory cues the eco-validity of the study would be inhibited, an athlete returning to sport immediately following the application of ice would not usually have sensory cues removed. The methodology in the current study uses an active target angle of 45°. This supports similar research by Olsson, Lund, Henrikson, Rogind, Biddal, and Danneskoid-Samsoe (2004) that suggests knee JPS test angles should be between 40° and 80° flexion when assessing SKB. Each repetition of the SKB was held at a target angle of 45° for 5 s. Literature supports a 5 s hold (Costello, Algar, & Donnelly, 2012; Mohammadi, Taghizadeh, Ghaffarinejad, Khorrami, & Sobhani, 2008; Olsson et al., 2004), suggesting that this allows for awareness of limb position (Costello & Donnelly, 2011). Testing was carried out on the participant's non-dominant leg, shown to be the most likely for knee injury to occur, in contact and non-contact sports (Krajnc, Vogrin, Recnik, Crnjac, Drobnic, & Antolic, 2010; Ruedl et al., 2012; Vauhnik, Morrissey, Rutherford, Turk, Pilih, & Pohar, 2008). The dominant leg was determined by which leg they would normally kick a ball with to ensure the non-dominant leg was established (Surenkok et al., 2008).

Two anatomical markers were removed from the medial and lateral epicondyles of the knee prior to 800 g of crushed ice contained in a clear plastic bag applied over the anterior aspect of the non-dominant knee. The aim of this application was to achieve a Tsk of between 10 and 15 °C. The bag of ice was covered by a damp single microfiber towel held in place by cling film wrap, for the clinically relevant time of 20 min (Janwantanakul, 2009; Kennet et al., 2007; Owens, Hart, Donofrio, Haralabous, & Miezejewski, 2004).

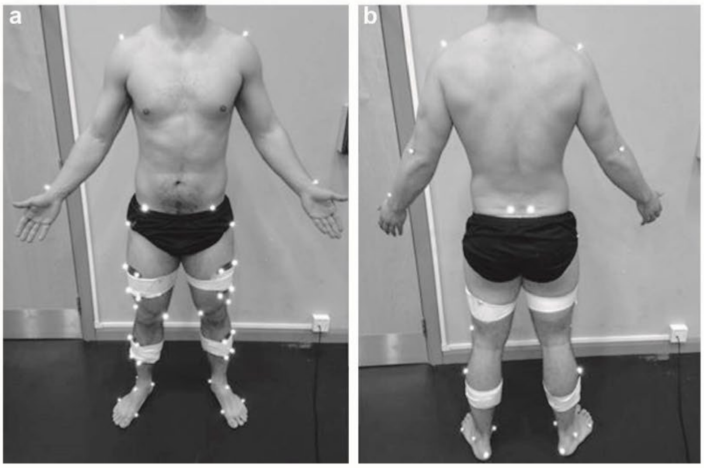

Fig. 1. Anatomical landmarks for marker placement, (a) anterior and (b) posterior.

Immediately post ice intervention three further Tsk measurements were taken, whilst the two anatomical markers on the knee were placed in the exact same position prior to the intervention. Marker points were highlighted previously on the participant's skin with washable pen pre-intervention so that marker replacement would be accurate. Collection of Tsk took approx. 8 s; participants then immediately produced the same SKB procedure, without any practice trials, followed by three further Tsk measurements.

2.3. Analysis

Maximum knee angle, minimum knee angle and knee joint range of motion (ROM) in all three planes of motion for both the loading (eccentric) phase of the movement and the entire (eccentric, hold and concentric) movement were measured. Data were processed in Qualisys Track Manager and then exported as C3D files to Visual3D (CMotion Inc., USA) software in order to quantify kinematic parameters, smoothed with a low pass Butterworth 6 Hz filter, allowing recognition of significant events within the data creating a report. All data was averaged within subjects prior to statistical analysis. The distribution of the data was assessed for normality using the Shapiro–Wilk test and found to be suitable for parametric statistical testing. A paired t-test was used to compare pre- and post-intervention data, with a Bonferroni correction applied, including data analysed using absolute error (AE) for knee flexion. Statistical significance was set at $P < .05$. All statistical analysis was conducted using SPSS version 21.0 (SPSS, Inc., Chicago, USA).

3. Results

Results demonstrated significant changes in both the sagittal and coronal planes during the descent phase of the SKB. A significant decrease ($P = .035$) in knee flexion in the sagittal plane demonstrated an angular difference of $-4.0° \pm 5.4$, 95% CI (0.3–7.6°), when comparing pre and post ROM (Fig. 2). A significant reduction in AE ($P = .002$) post cryotherapy intervention in knee flexion was found. A significant increase ($P = .011$) toward a valgus shift occurred in the coronal plane post-intervention (Table 1). No significant changes were found in knee joint velocity ($P = .579$). Tsk demonstrated a significant reduction post cryotherapy intervention ($P = .001$). Immediately post cryotherapy application average Tsk was recorded at 13.4 °C ± 2.9, reflecting a skin temperature response to within the desired therapeutic range.

4. Discussion

Many athletes are required to return to functional activities following the application of cryotherapy treatments to meet performance pressures or as part of a targeted rehabilitative setting. Despite concerns regarding neuromuscular function following cryotherapy interventions, literature is vague as to how JPS is affected, immediately post cryotherapy application. The study's findings demonstrate a significant change ($P = .035$) in the ability to reproduce knee joint flexion in the sagittal plane and a significant lack of varus control ($P = .011$) with a subsequent valgus shift in the coronal plane, during the eccentric loading phase of the SKB, in line with previous research (Ribeiro et al., 2013; Surenkok et al., 2008;

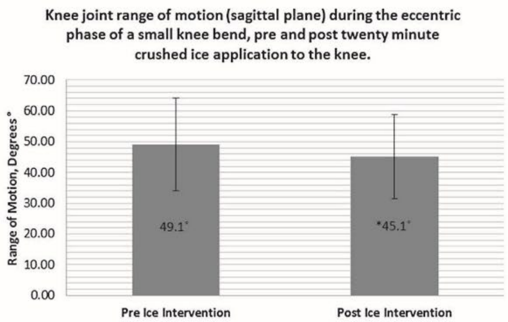

Fig. 2. Knee joint flexion during a small knee bend in the sagittal plane, pre and post 20 min crushed ice application to the anterior aspect of the knee. *Demonstrates a significant decrease in joint angular ROM post ice intervention in the sagittal plane.

Table 1
Knee joint ROM, varus–valgus during a small knee bend in the coronal plane, pre and post 20 min crushed ice application to the anterior aspect of the knee.

	Valgus position	Varus position	Valgus–varus range (ROM)	Knee flexion angle during SKB
Pre cryotherapy intervention	0.3° ± 2.4	−5.5° ± 5.7	5.8°	[a]49.1° ± 15.1
Post cryotherapy intervention	0.8° ± 2.7[a]	−4.5° ± 5.3	5.3°	[a]45.1° ± 13.7

[a] Demonstrates a significant increase in valgus shift (joint angular ROM) post ice intervention in the coronal plane.

Uchio et al., 2003; Watanabe et al., 2013). Analysis revealed no significant changes in the angular velocity of this movement. As expected, a significant decrease (P = .001) in Tsk to within the desired therapeutic range was achieved, averaging 13.4 °C immediately post crushed ice intervention, supporting previous research by Bleakley et al. (2011).

4.1. Pre/post knee joint flexion during SKB

This is the first experimental study of its kind to our knowledge that assesses knee joint motion in all three planes using 3D motion analysis during a functional closed chain weight bearing assessment following ice intervention. This study's findings suggest knee JPS and control during the eccentric phase of the SKB was significantly altered after crushed ice applied to the anterior aspect of the knee. Findings support previous methods of measuring knee JPS during a SKB by using an active target angle of 45°, thus meeting the range of ideal test angle of between 40 and 80° proposed by Olsson et al. (2004). Average pre-intervention angle for all participants during the SKB was 49.1° ± 15.0, with an average post-intervention angle of 45.1° ± 13.7. The angular decrease in the ability to accurately perform and repeat a similar knee joint flexion angle immediately following cryotherapy in this study by 4.0° ± 5.4 (Fig. 2) contradicts earlier studies by Costello and Donnelly (2011) and Hart, Leonard, and Ingersoll (2005). The current findings however support a suggestion by Uchio et al. (2003) that the knee joint may become stiffer following cryotherapy application or sensitivity of JPS may decline resulting in reductions in knee flexion angles. This may be a reason for the inability to replicate participant's pre-intervention angle of 49.1° ± 15.0 but replicated an angle closer to the target angle of 45°, in the current study. AE data in knee flexion JPS supports this reduction in knee flexion angle post cryotherapy intervention (P = .002).

Although the functional weight bearing close kinetic chain assessment used in the current study is likely to be the reason for the significant differences (P = .035); often it is the non-dominant limb used to weight bear during functional tasks in sport, such as kicking a ball for example. JPS in the current study was measured on the participant's non-dominant limb during a dynamic SKB to measure changes in functional stability, in order to replicate a functional task relevant within sport. This may be another reason for the significant results in comparison to previous research. Furthermore, methods utilised by Costello and Donnelly (2011), allowed participants to use their hand for balance on a table, providing an outlet for sensory feedback therefore reducing any variations in postural sway. In another comparative study a 30 s rest period was included between post cryotherapy trials (Hart et al., 2005), therefore allowing for increases in NCV and peripheral mechanoreceptor efficiency (Algafly & George, 2007; Schepers & Ringkamp, 2010 and Herrera, Sandoval, Camargo, & Salvini, 2011), due to the rewarming effects that may have taken place. In the current study, participants immediately post 20 min of cryotherapy intervention performed the functional SKB assessment, therefore reducing the chance of gaining greater proprioceptive feedback prior to the SKB through rewarming. In support of Schepers and Ringkamp (2010), we assume the slow adapting mechanoreceptors reduced their discharge rate under the effects of the cryotherapy intervention; therefore the disruption to the function of mechanoreceptors affected JPS in this study. Further investigation however, is still necessary to determine the actual mechanisms behind mechanoreceptor response under the conditions of cryotherapy.

Findings in the current study revealed a mean valgus shift of the knee joint of 1.0° post cryotherapy intervention (Table 1). Therefore the ability to control joint stability decreased through the medial structures of the knee. Valgus translation of 1.0° may seem minor, however as a percentage value this equates to an 18.2% valgus shift in relation to pre-loading varus movement. Consideration must be taken from this large percentile difference, which combined with flexion, excessive strain may be placed on knee structures, such as the anterior cruciate ligament (ACL), therefore the risk of sustaining an injury is potentially increased (Ford, Myer, & Hewett, 2003; Hewett et al., 2005; Malinzak, Colby, Kirkendall, Yu, & Garrett, 2001).

It is common practice within contact sports for athletes to continue competing following a short duration cryotherapy application to the lower limb. During sport, intermittent breaks in play are a common time when cryotherapy is provided to minimise pain (Bleakley et al., 2012). A systematic review by Bleakley et al. (2012), suggested an application time of <20 min to minimise the potential for reduced performance outcomes immediately following ice application. This leads to questioning however, around achieving a desired therapeutic cooling range for the rationale of applying cryotherapy in the first place. Depending on the preferred clinical therapeutic effect, duration of cryotherapy application may differ, in support of Bleakley et al. (2011) one method of icing may not be equally effective, as varied magnitudes and depths of critical cooling would occur. Findings in the current study support the recommendation by Bleakley et al. (2012) that athletes may be at a performance disadvantage but also in addition suggests a potential increase risk of injury by an athlete performing functional movements immediately after 20 min of cryotherapy application at the knee. This study investigates the changes in JPS immediately after cryotherapy; in support of recent study by Ribeiro et al. (2013) it would be useful to observe the time it takes to return to pre-intervention baseline measures in future studies following cryotherapy application using the same methods.

The specific mechanism through which cryotherapy altered knee joint control could not be determined by this study. It can be postulated however, that physiological variations occurred causing adverse adaptations to knee joint mechanics. These changes could be due to one or a combination of these factors; altered NCV as indicated by Jutte et al. (2001), where NCV is found to be reduced at 12.5 °C in line with temperatures recorded in the current study, altered spindle muscle activity, reductions in muscle strength or altered sensory information from superficial mechanoreceptors. The application of crushed ice over the lateral aspect of the knee may have affected neuromuscular control. Due to the superficial anatomical arrangement of the lateral femoral cutaneous nerve (Palastanga & Soames, 2012) it is proposed that ice application penetrated this superficial nerve more easily than the distribution of nerves over the deeper medial aspect of the knee. The current study support the concept of changes in proprioceptive feedback through altered mechanoreceptor mechanisms due to cryotherapy application, reported previously by Schepers and Ringkamp (2010). Previous studies, particularly at the knee, support the suggestion that sensory feedback via receptors in the skin have an importance in proprioceptive feedback (Richards & Selfe, 2012). Cryotherapy has been found to reduce NCV in sensory nerves greater than motor nerves (Herrera et al., 2011). It was previously thought that cutaneous receptors have not played a part in joint stability; the current study however proposes that greater consideration should be taken into the relevance of sensory feedback via the skin, and its involvement in proprioceptive feedback for JPS (Richards & Selfe, 2012). The explanation of a reduction in muscle strength due to cryotherapy application may be supported by the findings in the current study. Although muscle strength was not measured it could be assumed that alteration of Tsk and muscle temperature occurred. Original work by Sargeant (1987) noted reductions in peak force, power and maximal mean power in muscles following the reduction of muscle temperature from cold water immersion. In agreement a recent review of current evidence by Bleakley et al. (2012) suggests that cooling reduces muscle strength. A reduction in muscle strength due to cryotherapy may impact the ability of the lower limb musculature to stabilise the joint during functional tasks. This may have been a further reason behind the reductions in knee joint control reported in the current study.

5. Conclusion

The current study supports the suggestion that significant changes of JPS occur at the knee immediately following the application of crushed ice cryotherapy. Therefore team doctors, clinicians, therapists and athletes should be aware of the potential increase risk of injury to the ACL and/or medial complex during closed chain weight bearing activities immediately following 20 min of crushed ice cryotherapy application to the knee due to changes in eccentric control. Future research is needed to establish the effects of cryotherapy application alongside the specific mechanisms behind the changes in knee joint control.

Conflict of interest

None declared.

Ethical approval

The study was conducted according to the Declaration of Helsinki (WMA, 2008) and ethical approval was gained from the UCLan Built, Sport and Health Ethics Committee (BuSH 128). All participants provided written informed consent.

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Delayed effects of a 20-min crushed ice application on knee joint position sense assessed by a functional task during a re-warming period

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ABSTRACT

Delayed effects of a 20-min crushed ice application on knee joint position sense assessed by a functional task during a re-warming period.

Introduction: The effect of cryotherapy on joint positioning presents conflicting debates as to whether individuals are at an increased risk of injury when returning to play following cryotherapy application at the lower limb.

Objectives: The aim of this study was to investigate whether a 20 min application of crushed ice at the knee affects knee joint kinematics immediately post and up to 20 mins post ice removal, during a small knee bend.

Method: 17 healthy male participants took part in the study performing a functional task. Using three-dimensional motion analysis (Qualisys Medical AB Gothenburg, Sweden), kinematics of the knee were measured during a weight bearing functional task pre and immediately post, 5, 10, 15 and 20 min post cryotherapy intervention. Skin surface temperature (T_{sk}) cooling was measured via infrared non-contact thermal imaging (Flir Systems, Danderyd, Sweden) over the anterior and medial aspect of the knee.

Results: Results demonstrated significant reductions in the ability to accurately replicate knee joint positioning. A significant increase ($P \geqq 0.05$) in rotational movement in the transverse plane occurred, 20 min post ice removal.

Discussion: A 20-min application of crushed ice to the anterior aspect of the non-dominant knee has an adverse effect on knee joint repositioning and dynamic stability, 20 min after ice is removed. In consideration of returning a land-based athlete to dynamic functional activities, post cryotherapeutic intervention at the knee, clinicians should consider these findings due to the potential increase risk of injury.

1. Introduction

A common practice within clinical and sporting populations for acute injury management, cryotherapy is known to provide a multitude of physiological changes [1,2]. Reductions in oedema, nerve conduction velocity (NCV) [3], and tissue metabolism are reported [4–6] in addition to changes in joint position sense (JPS) and proprioception [7,8]. It is known that athletes commonly return to field of play following cryotherapy applications of varying exposure durations at half-time, pitch-side or during competitive play [1]. Ultimately a therapeutic analgesic affect is intended following the application of cryotherapeutic modalities and is well reported throughout literature to support early injury management [2,9]. Negative effects of cold therapy report superficial skin burns [10] and reductions in muscle strength [1]. Tissue cooling modalities used include; frozen peas, cubed ice, crushed ice, wetted ice, cold water immersion, cold packs [11,12] and whole-body cryotherapy [13]. Consensus proposes that different therapeutic effects arise across cryotherapy modalities or exposures and therefore effects may not be equitable [9]. Current literature suggests that crushed ice is a favourable method of achieving the most efficient analgesic response [11,14–16]. Recent findings however suggest that wetted ice compared to crushed ice appears to be the optimum choice for cooling the skin surface [12]. Local analgesia has been confirmed at a skin surface temperature (T_{sk}) of 13.6 °C and reductions in NCV at 12.5 °C [3,4], suggesting that a therapeutic range exists between 10 and 15 °C [11]. To observe whether therapeutic range is achieved following cryotherapeutic application, non-invasive infrared thermal imaging cameras serve as an accurate method of quantifying T_{sk} in sports medicine research [2,15,17]. In addition, a relationship has been shown between T_{sk} and intramuscular temperature (T_{im}) cooling [18], where

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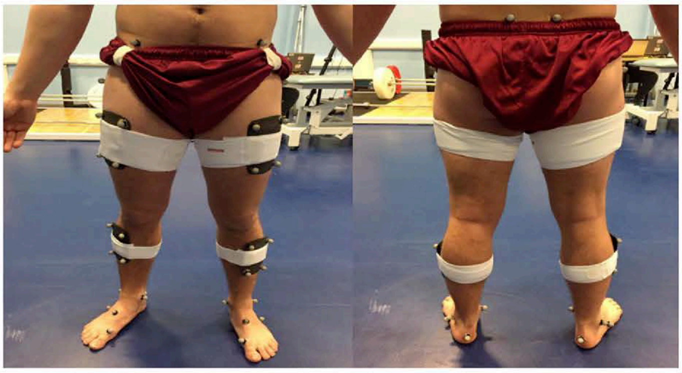

Fig. 1. Location and application of the passive retro-reflective markers on specific anatomical landmarks.

T_{im} continues to cool whilst T_{sk} rewarms and therefore showing a delayed effect. This poses consideration of the effect on muscle spindle activity and changes in neuromuscular feedback, which may also be delayed. With athletes in contact sports commonly returning to the field of play following short cryotherapy applications for the treatment of pain [1,7]. Previous work proposes a potential risk of injury in athletes commonly returning to the field of play following short cryotherapy applications for the treatment of pain [1,7], these include adverse adaptations occurring from potential physiological changes that may affect the knee joint [7]. However there is a lack of consensus in the literature as to the effect cryotherapy modalities on JPS, muscle strength and functional stability [1,19]. Awareness of joint position (joint position sense), movement and force, either consciously or unconsciously summarises clinically the term 'proprioception' [20,21], which have direct implications to functional stability. A functional way of measuring proprioceptive acuity [22,23], JPS is reported as the ability of a person to replicate a joint angle [24,25]. To observe functional movement appropriate to replicating land-based sports, weight bearing tasks are recommended [26,27]. To mimic functional performance in athletic populations, JPS may be assessed through active angle reproduction (AAR) [22,24,28]. Such proprioceptive deficits may expose athletes to reduced injury or re-injury risk, [29]. A reduction in accuracy of JPS in the sagittal plane and knee control in the coronal plane has been shown during the descent phase of a small knee bend (SKB) after the removal of crushed [7], which supports previous findings on JPS [30–32]. Conflicting discussions as to the effects of cooling on JPS and joint stability exist and literature remains scarce as to the investigation into the longevity of such effects post cooling [30]. This study therefore aimed to explore the effect of crushed ice application at the knee, pre cooling and post cooling at 5-min intervals up to 20 min on knee flexion AAR and knee joint stability. The purpose of this was to inform clinicians on appropriate local cooling protocols to reduce the risk of injury during competitive play or prior to returning to exercise.

2. Methods

2.1. Ethics

All participants provided written and verbal consent to take part in the study, and completed a Physical Activity Readiness Questionnaire (PAR-Q) prior to participation in the study. The study was conducted according to the Declaration of Helsinki [33] and approved by UCLan STEMH Ethics Committee.

2.2. Participants

The study was a single group, pre-test-post-test design. Forty potential participants were screened to participate in the study. Inclusion criteria included; aged between 18 and 40 years old, played competitive land-based sports regularly, were currently free from lower limb injury or with no history of lower limb injuries. Due to the differences in the effect of tissue cooling across genders an all-male sample was used to maintain homogeneity [34]. Exclusion criteria included; previous knee joint surgery, referred knee pain to or from the knee, contraindications to cryotherapy or lower limb injury in the previous 6 months [11]. Seventeen participants met the inclusion criteria aged 21.8 ± 3.5 years, height 177.9 ± 7.9 Cm, mass 81.1 ± 16.5 kg, and BMI 25.6 ± 2.8 kg/m^2.

2.3. Procedures

Data were collected in a movement analysis laboratory, in order to achieve a stable thermal state, participants acclimatised to the testing environment for 15 min [10,11]. Kinematic data were collected at 115 Hz using a 10 camera Oqus camera system and processed in Qualisys Track Manager (Qualisys Medical AB, Gothenburg, Sweden), data were then exported as C3D files and imported to Visual3D software (CMotion Inc., USA). T_{sk} over the anterior aspect of the non-dominant knee was measured via a non-invasive infrared thermal imaging camera (ThermoVision A40 M, Flir Systems, Danderyd, Sweden). In line with current medical standard protocols, emissivity of the thermal imaging camera was set at 0.97–0.98 [35]. Passive retro-reflective markers were applied to specific anatomical landmarks; anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), greater trochanter, medial and lateral epicondyles of the femur, calcaneus, medial and lateral malleoli, head of first and fifth metatarsals, central cuneiform. Cluster markers were applied to the anterolateral aspect of the femur and tibia (Fig. 1). Static kinematic images included; radial styloid, acromion process and lateral epicondyle of the humerus, these markers were then removed prior to the functional task.

Testing was carried out on the participant's non-dominant limb in support of earlier literature [36–38]. Previous literature suggests the non-dominant limb should be chosen in such tasks as it is commonly injured during sport compared to the contralateral limb and is commonly the weight-bearing limb during dynamic tasks on the field of play [36–38]. Participants were familiarised to the functional task of a SKB, whereby a practice attempt to replicate a 45° knee movement pattern was completed, prior to testing [39], supporting similar methodology that suggested JPS observed at the knee should commence between angles of 40° and 80° knee flexion [40]. To ensure eco-validity

Fig. 2. Small knee bend functional movement.

of the study, no blindfolds or white noise were used during testing, as it was felt that this would reduce sensory cues and would not replicate normal sporting activity [7].

To begin, the participant lay in a semi recumbent position on a plinth, and pre-intervention T_{sk} data were collected using a TI camera. Two ROIs were determined by the application of wooden markers applied to the apex and base of the patella. Five images were collected at baseline, immediately post cryotherapy removal, and at 5-min intervals, up to 20 min' post cryotherapy removal. Following T_{sk} baseline data, the participant was asked to stand centrally in the middle of the motion analysis cameras and perform five SKB for a baseline measure. Previous work suggests between 4 and 5 repetitions of a AAR allows for the stabilisation of data [22]. The target angle of 45° was held for 5 s (Fig. 2) supporting previous methodologies [2,7] and limb position awareness [8]. Participants were then removed from the motion analysis capture and taken back to the plinth via a wheelchair, and the anatomical markers on the medial and lateral epicondyles of the femur were removed. Replicating previous methodologies, a clear plastic bag containing 800 g of crushed ice (CI) was applied to the non-dominant knee over the anterior aspect for an exposure time of 20 min [7,11] covered by a damp microfiber towel and held in place by cling film wrap. On immediate removal of the CI, five TI images were taken of the anterior and medial aspects of the knee and the two reflective markers were re-applied. Participants completed five SKB and then returned to the plinth for the remainder of 5 min. At 5-min intervals this method was repeated, with five T_{sk} images and five SKB completed, up to 20-min post. The 20-min re-warming period included the time of each proprioceptive assessment at each of the 5-min time points.

2.4. Statistical analysis

Minimum and maximum knee joint ROM in all three planes for the entire SKB functional task were recorded. Prior to statistical analysis, the averaged value for each time point for each subject was found. A Shapiro-Wilk test reported that data were normally distributed and suitable for parametric testing. A repeated measures ANOVA with Least Significant Difference pairwise comparisons were used to compare differences between timepoints. Statistical significance level was set at $p = 0.05$. Statistical analysis was conducted via SPSS (Version 22, SPSS, Inc. Chicago, USA).

Table 1
Descriptive statistics of the regions of interest rewarming and main effect of the repeated measures ANOVA between regions and across time points.

Time points	Mean (sd) Patella temp	Mean (sd) Medial temp	P-value between regions	Effect size
Pre-intervention	28.7 (1.2)	29.4 (1.2)	< 0.001	0.88
0 min	14.6 (2.2)	20.3 (3.7)		
5 min	19.7 (1.7)	23.5 (2.3)		
10 min	21.7 (1.5)	25.2 (2.1)		
15 min	23.1 (1.4)	26.0 (1.5)		
20 min	24.2 (1.5)	26.8 (1.4)		
P-value between time points	< 0.001			
effect size (pη2)	0.98			

3. Results

3.1. Skin surface temperature

ROI over the anterior aspect of the knee were subdivided into ROIA (patella) and ROIB (medial knee). The repeated measures ANOVA showed significant differences between ROIA and ROIB and between all time-points ($p < 0.001$, $p\eta 2 > 0.88$), Table 1. A further pairwise revealed significant differences between all time-points indicting re-warming is occurring in both ROIs up to 20 min, at which point has not returned to the baseline temperature, Table 3. Therapeutic range was met for ROIA (14.6 ± 2.2 °C) immediately post cryotherapy removal but not for ROIB (20.3 ± 3.7 °C) at any time point.

3.2. Joint kinematics

The repeated measures ANOVA showed no significant differences in maximum and range of motion of the knee in the sagittal and coronal planes. However, a significant difference was seen in the transverse plane ROM ($p = 0.016$, $p\eta 2 = 0.31$), Table 2. Further post hoc analysis showed significant incremental differences between 20 min' post cryotherapy removal and all other time-points ($p = 0.03$ to $p = 0.004$) with the greatest change between 20 min and pre-cooling, which showed a 25% increase in transverse plane ROM. No other significant differences were recorded between time points for transverse plane ROM, Table 3.

3.3. Interaction between joint kinematics and skin and intramuscular temperature

The correlation between skin surface rewarming temperature over the two regions of interest ROIA and ROIB and transverse plane knee angle ROM were further explored using a Pearson correlation coefficient and found to be strongly positively corrected (0.82 and 0.83) respectively. In addition, the IM cooling was estimated from the equations from Hardaker et al. [18] who showed that as the surface skin temperature rewarms the IM continues to cool. Fig. 3 shows that as the surface re-warms and the IM continues to cool the transverse plane knee angle ROM, or knee instability increases.

4. Discussion

Over a 20-min re-warming period following cryotherapy intervention at the knee, it was unknown as to whether delayed effects occur in relation to joint stability, neuromuscular adaptations and JPS. This may be clinically important as in many land-based sports, athletes return to either functional activities or the field of play following cryotherapy exposures via breaks in play, or rolling substitutions with a potential increase in susceptibility for injury proposed from the present findings.

The current study reports significant changes in the rotational range in the transverse plane at 20 min' post cryotherapy removal during a

Table 2
Descriptive statistics of the regions of interest rewarming and main effect of the repeated measures ANOVA between regions and across time points.

Time points	Mean (sd) Maximum Knee Flexion	Mean (sd) ROM Knee Flexion	Mean (sd) Knee ROM Coronal plane	Mean (sd) Knee ROM Transverse plane
Pre-intervention	55.6 (8.2)	43.0 (12.0)	5.6 (1.7)	5.2 (2.1)
0 min	54.8 (8.3)	40.7 (10.4)	5.2 (1.9)	5.3 (2.3)
5 min	56.0 (9.2)	41.6 (10.9)	5.4 (2.0)	5.5 (2.4)
10 min	55.9 (9.3)	44.6 (11.0)	5.3 (1.7)	5.7 (2.7)
15 min	56.5 (8.8)	43.9 (9.8)	5.4 (2.1)	5.8 (2.7)
20 min	57.2 (9.0)	43.7 (10.9)	5.1 (2.2)	6.5 (2.6)
p–value	0.186	0.235	0.825	0.016
effect size ($p\eta^2$)	0.098	0.086	0.026	0.31

SKB ($p < 0.05$). Although the magnitude of this difference could be considered small (1.3°), this represents a 25% increase. This is similar in magnitude to the findings reported by Selfe et al. [41] when considering improvements in stability with a bracing intervention, albeit a reduction in transverse plane range of movement in this case.

Significant differences between time-point during rewarming were reported over the patella and medial aspect of the knee, with the patella reaching the therapeutic range for an analgesic response immediately post crushed ice removal [1,11]. T_{sk} did not return to baseline in either ROI at 20-min post intervention removal, which are in agreement with the findings of Kennet et al. [11] who studied a 30-min rewarming period with a variety of cooling modalities. The medial aspect of the knee (ROIB) however did not reach therapeutic range (20.3 ± 3.6 °C). Although it is suggested that the application area and modality of cryotherapy applied may have influenced this result as CI was applied directly over the anterior aspect of the knee rather than the medial or lateral regions. This may explain the non-significant results immediately post CI removal throughout all ROM. If cooling was directly applied to medial and lateral aspects of the knee immediate changes in ROM might have occurred, due to reduction in afferent information provided by muscle spindles in soft tissue structures surrounding the knee, which supports similar effects reported by Alexander et al. [7]. The application of pitch-side cryotherapy however in acute injury management is often applied for less than 10 min, and is not always packed around the entire knee joint, so further investigation is required to explore the range of common pitch-side practice. In addition, although CI is the cryotherapy modality supported in the literature [11], wetted ice may have produced a deeper and consistent cooling effect compared to CI [12].

At 20-min post cryotherapy intervention, participants were able to replicate the target angle of 45°, however a significant increase in the knee range of motion in the transverse plane at 20 min post cooling compared to all other time points were reported. Conduction and convection has been shown to influence the cooling mechanisms of superficial and deeper soft tissues [14]. Previous work showed significant negative quadratic relationship between T_{sk} and T_{im} [18], with intramuscular cooling continuing after the removal of an ice pack. We postulate that this mechanism could have a physiological influence on neuromuscular response 20-min post intervention. This is contrary to previously research, which has suggested that deeper regions of the

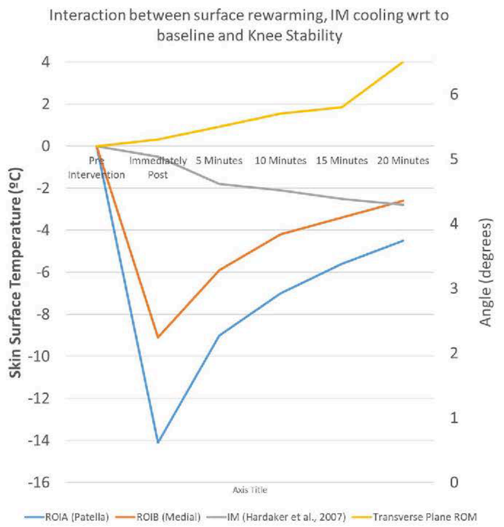

Fig. 3. Interaction between surface rewarming and IM cooing with respect to baseline (Hardaker et al. [18]) with Transverse Plane Knee Angle.

Table 3
Pairwise comparison between the time points for Knee ROM Transverse plane kinematics and regions of interest rewarming (* significant difference).

	Mean Difference Knee ROM Transverse	P-value	CI of the differences	Mean Difference Rewarming across both regions	P-value	CI of the differences
Pre to 0 min	−0.12	0.709	−0.82 to 0.57	11.5*	< 0.001	10.5 to 12.7
Pre to 5 min	−0.28	0.499	−1.15 to 0.58	7.4*	< 0.001	6.8 to 8.1
Pre to 10 min	−0.52	0.197	−1.34 to 0.30	5.6*	< 0.001	5.0 to 6.2
Pre to 15 min	−0.58	0.230	−1.56 to 0.40	4.5*	< 0.001	4.0 to 5.0
Pre to 20 min	−1.27*	0.012	−2.22 to −0.32	3.5*	< 0.001	3.0 to 4.0
0 min–5 min	−0.16	0.638	−0.85 to 0.54	−4.1*	< 0.001	−4.8 to −3.5
0 min–10 min	−0.40	0.241	−1.09 to 0.29	−6.0*	< 0.001	−6.6 to −5.3
0 min–15 min	−0.46	0.186	−1.15 to 0.24	−7.1*	< 0.001	−8.0 to −6.2
0 min–20 min	−1.15*	0.004	−1.88 to −0.41	−8.1*	< 0.001	−9.0 to −7.1
5 min–10 min	−0.24	0.566	−1.11 to 0.63	−1.8*	< 0.001	−2.1 to −1.6
5 min–15 min	−0.30	0.512	−1.23 to 0.64	−2.9*	< 0.001	−3.3 to −2.6
5 min–20 min	−0.99*	0.031	−1.87 to −0.10	−3.9*	< 0.001	−4.4 to −3.5
10 min–15 min	−0.06	0.836	−0.63 to 0.52	−1.1*	< 0.001	−1.4 to −0.8
10 min–20 min	−0.75*	0.018	−1.35 to −0.14	−2.1*	< 0.001	−2.5 to −1.7
15 min–20 min	−0.69*	0.035	−1.32 to −0.05	−1.0*	< 0.001	−1.2 to −0.8

sensorimotor system within a joint are not affected by the application of cryotherapy [42]. In addition, Wassinger et al. [43] assumed that deeper mechanoreceptors were able to compensate for receptors affected by cryotherapy at a superficial level.

The current study proposes that deeper sensorimotor mechanisms may be affected through the delayed T_{im} response over a're-warming' period, which could affect proprioceptive feedback and motor control. A concept which is supported by Uchio et al. [32], who reported a decrease in NCV and altered proprioceptive feedback caused by cryotherapy intervention. Therefore, as T_{sk} re-warms Hardaker et al. [18] suggested that T_{im} continues to cool and affecting the proprioceptive mechanisms and in turn control at the knee due to delayed intramuscular and ligamentous cooling. However to date literature has not reported the effects of re-warming on joint control and stability. This is particularly pertinent, as a decrease in rotational stability at the knee, as seen in this study, is a known injury mechanism at the knee, therefore it may be suggested there is a risk of injury at 20 min' post cryotherapy removal through altered mechanoreceptor feedback resulting in reduced proprioceptive control.

In consideration of the known T_{sk} and T_{im} relationship suggested in previous literature [18], the current study proposes that a relationship exists between skin temperature, intra muscular temperature and transverse plane knee stability over a re-warming period of 20 min. Represented in Fig. 3, post cryotherapy removal, time-points for T_{sk} and transverse ROM were combined with T_{im} data presented by Hardaker et al. [18] and compared to baseline pre cooled values. The delayed deeper tissue cooling could affect the function of muscle spindle firing via responsive afferent and efferent signals [44]. Another explanation for the increase in the transverse plane knee ROM at 20 min post cooling, may be due to the continued cooling effect on the muscular tissues structures surrounding the joint inducing a stiffening response around the joint producing a compensatory mechanism.

The implications of this study has a confounding impact on not only the management of pitch-side cryotherapy application but also the application for use in facilitating joint movement during rehabilitation. The consideration of a controlled re-warming period prior to any closed-chain functional movement of the lower limb after icing the knee is important. This may reduce the chance of injury risk, specifically considering movement patterns for non-contact ACL injury, by returning to functional activities within this 20-min window, post cryotherapy application which has yet to be addressed within the literature. Future considerations into observation of longer re-warming periods may be of interest to observe the return of baseline ROM following local joint cooling.

4.1. Limitations

In this study we chose to conduct the assessment without blindfolding the participants as this would represent how the small knee bend would be performed in clinical practice or normal sporting activities, however allowing visual input may have influenced the assessment of proprioception. Future research should consider removal of visual cues to ensure changes observed were due to proprioceptive deficits as visual feedback may have mitigated potential changes reported here. In addition, we chose to move the participants into position using a wheelchair to minimise activity and hence standardise between participants, therefore these results should be taken in context of minimal muscle activity which would influence rewarming. Another limitation to this study is the lack of control group to ensure no learning effect has taken place. The monitoring of longer rewarming periods should be considered to investigate at what point joint control returns to baseline measures.

5. Conclusion

A 20-min exposure of crushed ice to the anterior aspect of the non-dominant knee presented adverse effect on dynamic stability, post 20 min following ice removal. This may be due to delayed neuromuscular responses in deeper tissues affecting sensorimotor mechanisms and mechanoreceptor feedback through reduced proprioceptive control. When returning to dynamic functional activities, post cryotherapeutic intervention, clinicians should consider these findings with the view of potential increase risk of injury.

Conflict of interest statement

We can confirm that there is no conflict of interests for any of the authors.

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6.2 Appendix 2: Theme 2 Publications: MUSCLE STRENGTH RESPONSES TO CRYOTHERAPY

Appendix 2a: Copy of Publication 3.

Rhodes, D and Alexander J. (2018). The effect of knee joint cooling on isokinetic torque production of the knee extensors; considerations for application. *International Journal of Sports Physical Therapy,* 13(6); 6-8.

IJSPT

ORIGINAL RESEARCH

THE EFFECT OF KNEE JOINT COOLING ON ISOKINETIC TORQUE PRODUCTION OF THE KNEE EXTENSORS: CONSIDERATIONS FOR APPLICATION

David Rhodes, PhD
Jill Alexander

ABSTRACT

Background: Cryotherapy is commonly used in sport for the management of injury or during recovery, however the effects on concentric isokinetic strength appear unclear when considering the effect of joint cooling distal to the anterior thigh.

Purpose: The purpose of this study was to investigate the effect of cooling of the knee joint on quadriceps concentric isokinetic torque production. The results will inform the use of cryotherapy in practice.

Study Design: Observational cohort, Repeated Measures

Methods: Fourteen healthy male participants volunteered to take part in the study, all of whom regularly played competitive sports (mean age 20.24±1.51years; body mass 80.34±11.34Kg and height 179.45±6.59cm). 800 g of crushed ice was applied over the anterior knee joint for 20 minutes. Concentric quadriceps strength was measured using an isokinetic dynamometer (IKD) by measuring concentric peak (PkT) and average torque (AvT) outputs at pre-, immediately post and 20 minutes post cooling intervention. Additionally, skin surface temperature (T_{sk}), was measured using a hand-held thermometer at the patella at the same time intervals. Measurement was taken at the mid-point of each participant's patella, which was ascertained by measuring between the base and apex.

Results: Significant main effects reported for PkT, for time post-ice application ($p = 0.02$, $\eta^2 = 0.161$). Post-hoc analysis revealed pre-ice application PkT to be significantly higher ($p \leq 0.003$) than all other timepoints. Quadratic regression analysis revealed a strong correlation between reductions in quadriceps torque production and time post application ($r = 0.82$). The quadratic pattern of recovery displays a minima of 17.28-minutes and maxima of 34.56-minutes post ice application. AvT post-ice application demonstrated significant main effects for time post-ice application ($p = 0.03$, $\eta^2 = 0.152$). Post-hoc analysis revealed pre-ice application AvT to be significantly higher ($p \leq 0.005$) than at all other timepoints. Quadratic regression analysis revealed a strong correlation between reductions in quadriceps torque production and time post application ($r = 0.80$). The quadratic pattern of recovery displays a minima of 18.38-minutes and maxima of 36.76-minutes post ice application. T_{sk} reduced significantly, immediately post intervention ($p \leq 0.05$) without returning to baseline measures at 20-minutes post ($p \leq 0.05$).

Conclusions: Isokinetic peak torque values of the quadriceps diminish after cryotherapy application to the knee joint and are not fully recovered at 20 minutes post application on the knee. These findings could have potential implications for participation in activity immediately following ice application.

Level of Evidence: 2b

Keywords: Cryotherapy, Isokinetic Dynamometry, Knee, Quadriceps

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The authors declare no conflict of interest within or related to the present work.

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INTRODUCTION

Cryotherapy, commonly utilized within sporting populations post injury, initiates multiple physiological changes, including reductions in edema, nerve conduction velocity (NCV), and tissue metabolism,[1,2] while concurrently inducing an analgesic effect. With regard to muscle strength, changes in cold-induced NCV presents no consensus in current literature3 indicating a detriment to muscle performance through reductions in receptor firing rate and muscle spindle activity. Authors suggest that variance in myotatic stretch reflex and ion (Na^+, K^+, Ca^+) diffusion at the motor end plate causes the known reduction in enzymatic activity at lower temperatures,[4,5] with previous research suggesting that cooling impairs Ca^+ release therefore ensuing adenosine triphosphate decline altering cross bridge function. Current literature[6,7] provides evidence of increased muscle stiffness post cooling, suggesting inability to monitor stretch limit within the muscle, potentially increasing the risk of tissue injury. The emerging evidence also suggests that joint cooling also affects joint position sense (JPS).[8,9] Altered mechanoreceptor feedback caused by reductions in proprioceptive control[9] following cooling at the knee, could make a heightened risk of injury to the anterior cruciate ligament (ACL) and medial complex. The effect of cooling on muscle strength around the knee may also have implications deleterious to athletes returning to functional activities immediately following cryotherapy. Although reported widely on in current literature, there are variations across studies and conflicting magnitudes of change in muscle strength following local applications of cold.[7,12,13,24,32] This thought to be due to differences in research design, with some studies failing to analyze muscle strength in conjunction with tissue temperature.[27] Study outcomes are consequently difficult to compare.

Decreases in recorded T_{sk} following local cooling correlates to reductions in muscle function.[5] Deterioration in both extension torque and power by around 5% for every 1°C decrease in intramuscular temperature has been previously reported.[10] Colder intramuscular temperatures (~30°C) reported in research were associated with lower concentric isokinetic torque production, at varying speeds from fast to slow.[11] However, Thornley et al., describe moderate or contradictory changes such as, reporting increases in isometric quadriceps strength after 30-minutes of thigh cooling.[12] Recent suggestions imply that an increase in muscle stiffness occurs post cryotherapy application, lowering the available sustained stretch in muscle tissue therefore increasing potential injury risk.[7] Variability in duration of application of cryotherapy modalities noted in published literature recently considers realistic applications (10 minutes) of local cooling in sport, compared to traditional clinical protocols of 20-minute durations.[5] Cryotherapy modality type, duration, and method of application also vary throughout the available studies, including cold-water immersion and crushed ice via local applications, reflecting further difficulty in comparison ability and outcome implications within literature.

Isokinetic Dynamometry (IKD) commonly used in research[17] to evaluate torque production as a measurement of muscle strength, due to its high test-retest reliability.[18] Suggestions for the use of isokinetic dynamometry include measurements of both peak torque (PkT) and average peak torque (AvT) in order to describe muscle function and has been utilized to assess reductions in strength post fatigue protocols.[19] Quadriceps strength or a potential strength deficit is important to consider during the evaluation of knee joint function,[20] as this can have implications on knee function, including stability during performance.[21] When considering muscle strength deficits post cooling[11] (indicative of potential changes in quadriceps strength), awareness must be paid to of possible effects on neuromuscular parameters, which may be related to knee injury risk. Impact on joint control and stabilization may be a result of decreased capability of muscle tension regulation16 impairing knee extensor control of the quadriceps through reduced sensitivity of receptors following cooling. When considering knee injuries in sport, decreases in quadriceps function may present reductions in the ability to prevent abnormal or excessive movement when performing functional movement patterns.[22] Decreases in quadriceps function and control during performance, alongside other neuromuscular considerations, are highly relevant during acceleration and deceleration, and may increase the risk of non-contact musculoskeletal injuries.[22]

Skin surface temperature (T_{sk}) and intramuscular temperature (T_{im}) post cooling presents a highly significant quadratic association.[14] Although fluctuations in the rate of temperature change between various applications of modalities have been reported, research presents consensus on the relationship between superficial and deeper intramuscular cooling.[2] A change in temperature during post-cooling phases occurs as heat from deeper tissue structures transfers to superficial tissues.[14,15] Since muscle continues to cool following removal of cold, while skin re-warms,[14] the delayed effects this may induce in respect to muscle strength and joint control should be considered. Data appears contradictory when considering the effect of cooling distal to the anterior thigh on strength of the quadriceps.[16,23,24] The purpose of the present study was to investigate the effect of cooling of the knee joint on quadriceps concentric isokinetic torque production. The results will inform the use of cryotherapy in practice.

METHODS

Participants

A priori power calculation was conducted to determine a sample size of fourteen healthy male participants (statistical power > 0.8; $p < 0.05$). Subjects participating in the study regularly took part in competitive sports (age 20.24 ± 1.51years; body mass 80.34 ± 11.34Kg and height 179.45 ± 6.59cm). All participants provided written consent to take part in the study. The study was conducted according to the Declaration of Helsinki[25] and approved by University of Central Lancashire Ethics Committee. To increase sample homogeneity all-male participants were used due to gender differences found in response to local cooling.[26] Exclusion criteria contained; any contraindications to cryotherapy[27] previous knee joint surgery, lower limb injury in the prior six months, and/or referred pain either to or from the knee.

Intervention Protocol

Testing took place in a movement analysis laboratory. Kinematic data (PkT and AvT) was collected pre- and post- intervention using a Cybex IKD (Cybex, division of Lumex Inc., Ronkonkoma, NY, USA) chosen due to its high reliability (0.9 – 0.98).[18,19,21] Superficial skin temperature was measured using a hand-held digital thermometer (Fora, Gallen, Switzerland, IR19). The digital thermometer meets the required standard in ASTM E1965-98 and EC directive 93/42/EEC. Prior to testing participants acclimatized to a steady thermal state for 15 minutes prior to intervention. Following the acclimatization phase, three measures of T_{sk} were recorded at the center of participants' patella for average baseline data.

Concentric isokinetic torque measurements of the quadriceps were performed. Subjects performed three repetitions of knee extension to at $60^{\circ}s^{-1}$ on the dominant leg, passively moving into flexion at $10^{\circ}s^{-1}$ between repetitions. The participant's dominant leg was determined by which leg they would normally kick a ball with.[30] The researcher recorded participants' position settings, and the same settings were utilized during each measurement (pre, immediately post-, and 20-minutes post- crushed ice intervention). During isokinetic testing, participants sat in the IKD with straps applied across the chest, pelvis and mid-thigh to minimize extraneous body movements during testing. The rotational axis of the dynamometer aligned with the lateral femoral epicondyle and the tibial strap placed distally at three-quarters of the length of the tibia. Participants were instructed to position their arms across the chest to isolate the quadriceps during torque production.[28] Participants completed each repetition throughout every set to their maximum and were encouraged to do so throughout with verbal and visual feedback.[29] A total of three maximal repetitions were completed at $60^{\circ}s^{-1}$ and an average of two consistent repetitions were taken for PkT_{conc} and AvT_{conc} measures. Researchers observed each repetition completed on the IKD ensuring that smooth and consistent effort was exerted, throughout the subject's performance.

Following the collection of baseline data, the researcher applied 800g of crushed ice contained in a clear plastic bag held in place by cling film wrap, following previous protocols[31] over the anterior aspect of the knee, on the dominant leg, for a period of 20 minutes.[5] Post the 20-minute cryotherapy application, the ice was removed from the limb and concentric torque data was collected. This was then repeated at 20-minutes post removal of the ice after the subject had been exposed to a period of rewarming.

Statistical Analysis

A one-way repeated measures ANOVA was used to investigate a within factors main effect for time. The assumptions associated with the statistical model were assessed to ensure model adequacy. To assess residual normality for each dependant variable, q-q plots were generated using stacked standardized residuals. Scatterplots of the stacked unstandardized and standardized residuals were also utilized to assess the error of variance associated with the residuals. Mauchly's test of sphericity was also completed for all dependent variables, with a Greenhouse Geisser correction applied if the test was significant. Where significant main effects were observed, post hoc pairwise comparisons with a Bonferonni correction factor were applied. Measures of significance were supplemented with partial eta squared (η^2) values calculated to estimate effect sizes for each dependant variable, and provide a measure of meaningfulness. As recommended by Cohen (1988), partial eta squared was classified as small (0.01–0.059), moderate (0.06-0.137), and large (>0.138).

The temporal pattern of changes in each isokinetic variable over the time collection period was examined using regression analyses. Quadratic polynomial models were applied, with the optimum fit determined by the strength of the correlation coefficient (r). Where a quadratic regression analysis represented the best fit, the regression equation was differentiated with respect to time to elicit the time (torque values post-exercise) at which the data reached maxima (or minima). All statistical analysis was completed using PASW Statistics Editor 22.0 for windows (SPSS Inc, Chicago, USA). Statistical significance was set at $p \leq 0.05$, and all data are presented as mean $\pm$ standard deviation.

RESULTS

Peak Torque

Figure 1 displays the effects of a 20 minute ice application on PkT immediately post ice application and 20 minutes post ice application. There was a significant main effect for time post ice application (p = 0.02, η^2 = 0.161).

Post hoc testing revealed that pre ice application PkT was significantly higher ($p \leq 0.003$) than at all other time points. The quadratic regression revealed a strong correlation (r = 0.82), displaying a minima of 17.28 minutes and maxima of 34.56 minutes post ice application.

Average Peak Torque

The acute influence of ice application and the subsequent recovery of AvT post ice application are

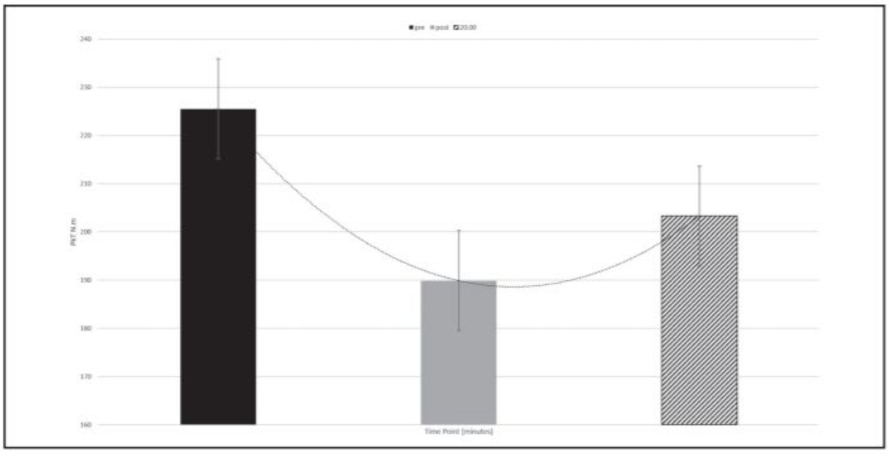

Figure 1. *Mean PkT_{concQ} (Peak Torque Concentric Quadriceps) Values for Pre, Post and 20 Minutes Post Crushed Ice Application for Isokinetic Speed of $60^{o/s-1}$.*

displayed in Figure 2. There was a significant main effect for time post ice application ($p = 0.03$, $\eta^2 = 0.152$).

Post hoc testing revealed that pre ice application PkT was significantly higher ($p \leq 0.005$) than at all other time points. The quadratic regression revealed a strong correlation ($r = 0.80$), displaying a minima of 18.38 minutes and maxima of 36.76 minutes post ice application.

Skin Surface Temperature

T_{sk} (measured at the center or the patella) demonstrated significant reductions post cryotherapy intervention ($p \leq 0.05$). Average T_{sk} immediately post cryotherapy application was 13.9±1.9°C, representing a skin surface temperature response to within therapeutic range, resulting in a percentage change reduction in T_{sk} of 51%. At 20-minutes post removal of the intervention average T_{sk} was reported to be 24.0±2.9°C, supporting the known re-warming curve for T_{sk} but not yet having returned to baseline measures (Figure 3). T_{sk} displayed a 16% reduction at 20-minutes post removal when compared to baseline.

DISCUSSION

Cryotherapy applications are common in sport for the management of injury, however the effects on strength of the thigh when cold is applied to the knee and surrounding soft tissue continues to lack consensus. Musculature at the knee provides feedback for joint stability, with reductions in quadriceps strength known to increase the risk of non-contact injury around the knee.[22] The purpose of the current study was to investigate the effect of cryotherapy on the torque production ability of the quadriceps immediately and 20-minutes post cryotherapy application at the knee. Significant reductions in strength were reported in PkT and AvT when compared to baseline to both immediately post and 20-minutes post. Large effect sizes ($\eta^2 = 0.161$ and $\eta^2 = 0.152$) were reported for both PkT and AvT, indicating that cryotherapy application had a large immediate effect on strength following removal of the ice and up to 20 minutes post application. Quadratic regression analysis indicated that isokinetic strength measures reached a minima at 18.38 minutes post ice application and returned at a predicted 36.76 minutes post icing. These findings support the findings of previous research describing reductions in muscle strength following cryotherapeutic applications[5,7] but differ in the conclusion that even when the quadriceps are not directly cooled, and cooling occurred distal to the muscle belly at the knee joint, reductions in quadriceps strength still occurs. These findings suggest a need for awareness of the effects on surrounding soft tissue structures that may be affected post cooling of

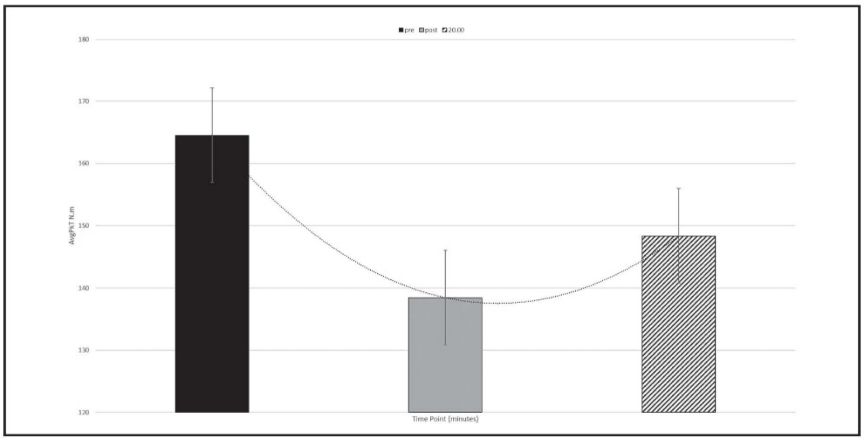

Figure 2. *Mean AvT$_{concQ}$ (Average Torque Concentric Quadriceps) Values for Pre, Post and 20 Minutes Post Crushed Ice Application for Isokinetic Speed of 60$^{o/s-1}$.*

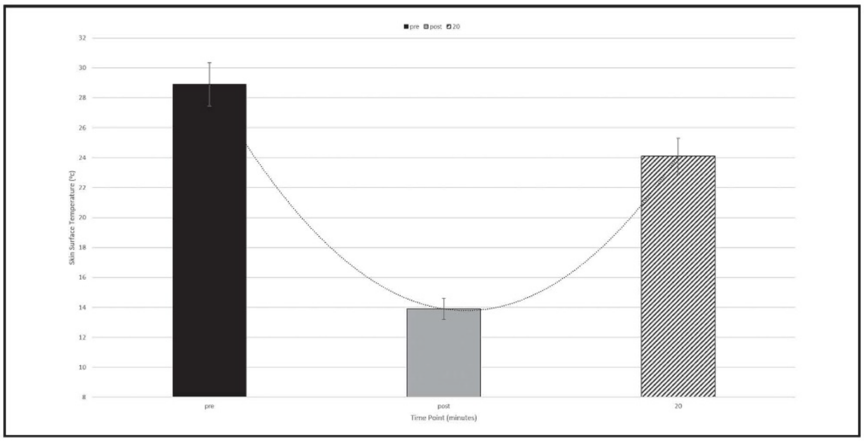

Figure 3. *Mean Skin Surface Temperature (T_{sk}) for baseline, Immediately Post and 20 Minutes Post Crushed Ice Cryotherapy Intervention.*

Table 1. *Average + SD data for all measures of PkT, AvT and T_{sk}.*

	Time Point		
Measure	**Pre**	**Post**	**20 Minutes Post**
T_{sk} (°C)	28.9±2.5	13.9±1.9	24.0±2.9
PkT	225.51±30.99	189.90±36.20	203.29±38.30
AvT	164.51±26.73	138.45±25.33	148.36±26.54

the knee joint, as an important consideration regarding performance of functional tasks.

The implications of reduced muscle strength of the quadriceps may include increased risk of non-contact injury at the knee complex.[22] Strength reductions in the current study were still evident at 20-minutes post removal of the intervention displaying a 16% reduction in PkT and AvT respectively. Although perhaps a poor comparison due to a difference in location of cryotherapy application and protocol, these findings contrast with an earlier study that observed no delayed reductions in isokinetic concentric strength at 20-minutes post ice application.[32] The amount of ice and location of application differs between studies, with 5lb directly over the quadriceps[33] compared to 800g in the current study. Both studies tested concentric isokinetic strength at $60° \cdot s^{-1}$. It may be postulated that cooling at the knee joint disrupted feedback mechanisms affecting strength capability more than cooling directly over the muscle belly alone. This is only an assumption in consideration of previous research as the current study only had a single placement of cooling. Current literature highlights increases in muscle stiffness post ice application attributing the increases in stiffness to alterations to the mechanical properties of the tissue and desensitization of the mechanoreceptors in the tissue. This may lead to reduced PkT due to alterations in the ability to sense tissue stretch to the point of sustainability prior to consequent injury, postulating a guarding mechanism resulting in reduced strength output on concentric quad activation.

T_{sk} met therapeutic range, therefore thought to induce an analgesic effect and did not return to baseline measures at 20-minutes post. A quadratic relationship exists between T_{sk} and T_{im} suggesting as T_{sk} re-warms, T_{im} continues to cool.[14] This may be the reason as to why PkT and AvT values did not return to baseline concentric strength at 20-minutes post removal of the intervention. It would however have been useful to measure T_{sk} over the quadriceps as well as over the patella in order to investigate potential distribution of cooling dispersed away from the site of application. Although the cryotherapy modality was placed over the anterior aspect of the knee, it is suggested that involvement of the quadriceps tendon insertion as a feedback mechanism for knee stability may be affected by cold application, although not quantified in the current study. Accurate indication of the required force the muscle needs to exert to stabilize the knee may not have occurred resulting in a decrease in PkT and AvT output compared to baseline following cooling. In consideration of the decreases in NCV[1] following cryotherapy, it is thought that the combination of physiological change occurring within soft tissue muscle structures and desensitization of superficial mechanoreceptors disrupting neuromuscular response may be also responsible for the reported reduction in muscle strength occurring at the quadriceps. Although contradictory to these considerations, a review on the effects of joint cryotherapy on muscle function reports increases in muscle activation (Electromyography) and strength (isokinetic), but decreases in reflexive reactions in patients with joint effusion.[33] In consideration of the contribution to the role reflexive behaviour on motoneuron recruitment and force production this may provide implications following joint cooling on proximal muscle concentric strength, as noted in the current study.

Specific mechanisms through which cryotherapy altered quadriceps strength in this study may include the additional involvement of deeper joint structures. It is suggested that structures within the joint continued to remain cool after removal of the crushed ice intervention, although this outcome was not measured in the current study. Desensitization of deep joint mechanoreceptors may have affected neuromuscular response; supporting earlier literature proposing a change in proprioceptive feedback following cooling occurs.[34] This however may not be isolated to the effects on JPS but also could affect the muscular strength of associated musculature proximal or distal to the cooling site.

LIMITATIONS

The current results cannot be generalized to other peripheral joints and muscles, weight-bearing joints in the lower limb, or females. Other limitations include variations in cryotherapy durations and modalities applied in the current study that may not be comparable to other cryotherapeutic modalities used in sport. Eccentric muscle strength was not considered in the current study however should be examined in future protocols.

Future studies should investigate combined dynamic stability following similar protocols and involve myoelectrical activity and JPS assessment to support the proposed physiological mechanisms in the current study. It would be useful to observe a longer period of delayed response to determine a suggested timescale for when muscle strength actually returns post removal of the intervention. This may help establish boundaries regarding safe return to functional activity following cooling exposures of the lower limb, and consideration by sports medicine practitioners regarding the possible strength changes following cryotherapy.

CONCLUSIONS

A 20-minute cryotherapy application at the knee induces immediate and longer-term reductions in concentric quadriceps strength. Concentric isokinetic torque production of the quadriceps does not fully recover 20-minutes post ice application to the knee. This is in support of previous findings.[32] Current findings have potential implications for injury management and athlete participation in activity immediately following and up to 20- minutes post cryotherapy application at the knee.

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Human Kinetics
ORIGINAL RESEARCH REPORT

Temporal Patterns of Knee-Extensor Isokinetic Torque Strength in Male and Female Athletes Following Comparison of Anterior Thigh and Knee Cooling Over a Rewarming Period

Jill Alexander and David Rhodes

Context: The effect of local cooling on muscle strength presents conflicting debates, with literature undecided as to the potential implications for injury, when returning to play following cryotherapy application. ***Objective:*** To investigate concentric muscle strength following local cooling over the anterior thigh compared with the knee joint in males and females and the temporal pattern over a 30-minute rewarming period. ***Design:*** Repeated-measures crossover design. ***Method:*** Twelve healthy participants randomly assigned to receive cooling intervention on one location, directly over either the anterior thigh or the knee, returning 1 week later to receive the cooling intervention on opposite location. Muscle strength measured via an isokinetic dynamometer at multiple time points (immediately post, 10-, 20-, and 30-min post) coincided with measurement of skin surface temperature (T_{sk}) using a noninvasive infrared camera. ***Results:*** Significant main effects for time ($P \leq .001$, $\eta^2 = .126$) with preice application higher than all other time points ($P \leq .05$) were demonstrated for both peak torque and average torque. There were also significant main effects for isokinetic testing speed, sex of the participant, and position of the ice application for both peak torque and average torque ($P \leq .05$). Statistically significant decreases in T_{sk} were reported in both gender groups across all time points compared with preintervention T_{sk} for the anterior thigh and knee ($P < .05$). ***Conclusions:*** Reductions reported for concentric peak torque and average torque knee-extensor strength in males and females did not fully recover to baseline measures at 30-minute postcryotherapy interventions. Sports medicine practitioners should consider strength deficits of the quadriceps after wetted ice applications, regardless of cooling location (joint/muscle) or gender.

Keywords: isokinetic dynamometry, cryotherapy, quadriceps, thermal imaging

The therapeutic technique of cooling commonly used for the treatment of musculoskeletal conditions and recovery in sport is widely debated.[1–3] Deliberation around when athletes may return to activity safely following local cooling applications is recognized,[1,2] in consideration of potential neuromuscular deficits.[4] However, methodological differences reduce the strength of consensus across current studies in this area. Within sporting situations, cryotherapeutic application is often associated with pitch-side or half-time management of injuries to induce analgesic responses.[2] Other known physiologic effects include reduced cellular metabolism,[5] receptor firing rate,[6] nerve conduction velocity,[7] and inhibition of muscle spindles[8,9] are well reported.[2,3] Reduction of tissue temperatures through local cryotherapy applications occurs through contact of cryotherapeutic modalities via skin surface initially to achieve physiological responses.[10] A therapeutic skin surface temperature (T_{sk}) target range of between 10°C and 15°C is essential to initiate those essential responses to aid acute injury management.[11] Modalities of cooling differ in thermodynamic properties and therefore cooling efficiency.[10] Efficient in phase change modalities such as crushed or wetted ice noted numerously throughout cryotherapy literature as the most efficient for inducing physiological changes.[12–14] The known effects of cryotherapy on performance and reinjury/further injury risk lack consensus with methodology difficult to compare outcome measures across studies. Previous studies discuss changes in muscle force depending on cryotherapy location and report increases, decreases, or no change.[8,15,16,17] Emerging literature[1] recognized the importance of further study in muscle strength response postlocal cooling application, applicable to sporting situations.

Although rate of temperature change between modalities presents fluctuations, the consensus agrees on a relationship existing[12] that being a highly significant quadratic association between T_{sk} and intramuscular temperatures postlocal cooling applications.[12] The gold-standard protocol to measure T_{sk} is through infrared thermal imaging.[18,19] Due to the multifactorial considerations that can affect deeper soft tissues, such as duration,[20] gender,[21] adipose tissue levels,[22] and location of cryotherapy applications, knowing the optimum protocol for reduction in muscle temperature to induce physiological changes can be challenging. Furthermore, inconsistencies in methods across studies consequently implicate the ability to compare outcomes or effects accurately. This said literature clearly displays physiological changes as a result of various cryotherapy applications[20–22] and has indicated the importance of exploration of cryotherapy on neuromuscular function.[23]

Literature indicates performance deficits as a result of cooling,[2] and these have been attributed with decreases in dynamic contractile force.[1] These conclusions were drawn based on measures of ultrasound shear wave elastography and myoelectrical activity; no output measures of strength were ascertained. It is important to note that the changes in dynamic contractile force were strongly related to muscle stiffness, which resulted in acute change in muscle mechanical properties after air-pulsed cryotherapy intervention.[1] The authors propose this may reduce the amount of stretch available to sustain by the muscle without resulting in injury. The evaluation of muscle strength with isokinetic

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dynamometry data is commonly used in research due to its high test–retest reliability.[24] Measurements of peak torque (PT) and average torque (AvT) to establish muscle function can determine reductions postfatigue protocols.[25] Strength deficits can have implications on knee stability during performance.[26]

Significant reductions in PT and AvT quadriceps strength compared with baseline measurements following a 20-minute crushed ice application to the knee did not fully recover at 20-minute postcooling intervention in a recent study.[27] The authors suggest reductions in concentric strength can still occur even when indirectly cooled distal to the muscle belly.[27] Due to no anterior thigh cooling in the previous study, we cannot allude as to whether differences occur regarding cooling location and severity of effects on muscle concentric strength in the lower limb.[27]

In consideration of the available literature, a comparison between joint and direct muscle cooling over the anterior thigh may further develop the evidence base in the understanding of the effects of cooling on muscle strength and subsequent implications on lower-limb injury risk in sporting populations. Physiological differences in gender response to cooling due to levels of adipose tissue, with females generally recording higher levels, cause variables in the efficiency of heat withdrawal from deeper tissues.[21] Therefore, the aim of the current study is to compare superficial anterior thigh versus knee cooling on concentric quadriceps muscle strength in male and female athletes over a rewarming period of 30 minutes.

Methods

Approved by the Science, Technology, Engineering, Medicine and Health Ethical Committee, the process of this study commenced according to the Declaration of Helsinki.[28] All participants provided written informed consent to take part in the study. Physiological gender differences reported in the literature[21] detail that females have larger adipose tissue; however, the effects of cooling on biomechanical function between males and females are limited. Twelve participants (6 males: height 179.0 [4.4] cm, weight 65.4 [6.4] kg, age 19.2 [1.3] y, and body mass index 20.4 [1.3] kg/m^2 and 6 females: height 163.1 [8.7] cm, weight 59.7 [6.0] kg, age 19.2 [0.9] y, and body mass index 22.4 [1.4] kg/m^2) volunteered to take part in the study based on an a priori power calculation to determine optimum sample size (statistical power >0.7; $P < .05$). Participants adhered to the following inclusion criteria: healthy; aged between 18 and 40 years; no history of lower-limb musculoskeletal injury in the past 6 months; no neurological disease; and no known contraindications to cryotherapy or cold, such as Raynaud.[13] Advice against the consumption of caffeine/alcohol or partake in physical activity[11] minimized external factors that may affect local cooling intervention and standardized protocol prior to data collection. All data collection took place in a movement analysis laboratory.

Participants were randomly allocated (randomisation.com) to receive either anterior thigh or knee cooling, returning 1 week later for exposure to the intervention on opposite location. Both groups followed a clinically relevant cooling dosage of 10-minute wetted ice, supporting earlier suggestions for investigation into dosages of cooling in line with pitch-side or half-time applications of cryotherapy in sport.[2] Upon arrival, participants underwent a 15-minute acclimatization period, supporting previous study methods,[27] to ensure a steady thermal state. Room temperature recorded at hourly intervals throughout the testing monitored fluctuations as closely as possible. During the acclimatization period, anthropometric measurements and dominant leg were established. The dominant limb for testing chosen due to regularly being the limb used to kick in land-based sports and determined by which leg the participant naturally chose to kick a football with.[29]

Following gold-standard recommendations in current literature,[18,19] T_{sk} data using an infrared thermal imaging camera (ThermoVision A40M; Flir Systems, Danderyd, Sweden) gathered at baseline, immediately post, and at 10-minute intervals up to 30 minutes after for either the anterior thigh or the knee, dependent on group allocation, was facilitated by determining a region of interest (ROI). To create an anatomical ROI over the anterior thigh, application of thermally inert skin surface markers formed a framework.[12] Location of markers consisted of superior marker placement (one-third way between ASIS and base of patella) and inferior marker placement (two-thirds way between anterior superior iliac spine [ASIS] and base of patella). Central thigh was determined by the measure of thigh circumference at center of thigh, located at 50% between ASIS and base of patella. Markers were then placed at 10% of this distance in medial and lateral directions from the center of the thigh to complete the ROI for the anterior thigh.[12] Markers were also placed at the base of patella and medial and lateral borders of patella tendon margin at tibiofemoral joint line level, and tibial tubercle determined a ROI for local knee cooling.[30] The thermal imaging camera placed at a height of 134 cm from the ground, positioned perpendicular to the anterior lower limb, with participants laying supine on a plinth followed standard clinical setup with an emissivity setting of 0.97 to 0.98.

Following baseline T_{sk} data collection, a measure of concentric quadriceps muscle strength determined baseline strength data using an isokinetic dynamometer (Cybex, Division of Lumex Inc, Ronkonkoma, NY) chosen due to high reliability assessments of the musculoskeletal system.[24] A 10-minute wetted ice application either to the anterior thigh or to the knee region followed,[2] depending on allocation of group. Previous research surrounding cooling techniques recommends use of wetted ice.[12] [14] Therefore, the protocol for wetted ice intervention consisted of 800 mL of cubed ice and 800 mL of room temperature water, then placed into a clear polythene bag size of 22 × 40 cm, with the excess air removed and secured with a knot.[13] A thin, damp microfiber towel placed between skin and the wetted ice bag was held in place securely to the limb with a cling film wrap, and application dose consistent of a 10-minute application to either the knee or anterior thigh.[11,30]

In the same format at T_{sk}, isokinetic dynamometry data were collected immediately postintervention and at 10-minute intervals up to 30 minutes after for each group as recommended in a previous study.[27] Between isokinetic measures, participants were asked to long sit on a plinth. Previous research within isokinetic testing advocates the use of a range of testing speeds.[25] The gravity-corrected torque–angle curve was analyzed for each testing speed, with analysis restricted to the isokinetic phase. PT, the corresponding angle (θ), and AvT across the isokinetic phase were identified for each player at each testing speed.[25] Concentric isokinetic torque measurements for the quadriceps were performed at 3 repetitions per time point into knee extension at 60°/s and at 150°/s, with passive movement into flexion at 10°/s between repetitions.[27] The two repetitions eliciting the highest PT value were identified for each time point and utilized for subsequent analysis. Observation of each repetition completed by the same researcher ensured consistent and smooth effort exerted by each participant throughout testing.[27] To minimize participants' extraneous body movements, standard positional setup using chest, pelvis, and midthigh straps was applied[27] with the tibial strap placed 3 quarters distally on the tibia and rotational axis of the dynamometer aligned to the lateral femoral epicondyle. To isolate torque production at the quadriceps, participants crossed their upper limbs across the chest.[27]

Statistical Analysis

A univariate, repeated-measures general linear model quantified main effects for recovery duration postice application and isokinetic testing speed. Significant main effects in recovery duration were explored using post hoc pairwise comparisons with a Bonferroni correction factor. The assumptions associated with the statistical model were assessed and met to ensure model adequacy. To assess residual normality for each dependent variable, Q–Q plots were generated using stacked standardized residuals. Scatterplots of the stacked unstandardized and standardized residuals were also utilized to assess the error of variance associated with the residuals. Mauchly test of sphericity was also completed for all dependent variables, with a Greenhouse–Geisser correction applied if the test was significant. Partial eta-squared (η_p^2) values were calculated to estimate effect sizes for all significant main effects[31] and classified as small (.01–.059), moderate (.06–.137), and large (>.138). Interactions within the general linear model were also identified within the analysis of data. All statistical analysis was completed using PASW Statistics Editor 24.0 for Windows (SPSS Inc, Chicago, IL). Statistical significance was set at $P \leq .05$, and all data are presented as mean (SD).

Results

Skin Surface Temperature (°C)

Whole-group T_{sk} data demonstrated statistical significant decreases at the knee for all time points compared with preapplication temperatures, immediately post (IP) ($P \leq .001$), 10-minute ($P \leq .001$), 20-minute ($P \leq .001$), and 30-minute postintervention ($P = .03$) (Figure 1). Postcryotherapy application to the quadriceps noted statistically significant decreases in T_{sk} at IP ($P \leq .001$), 10- ($P \leq .001$), and 20-minute postintervention ($P = .04$). No statistically significant changes in T_{sk} were reported at 30-minute postintervention for the anterior thigh ($P = .11$); however, T_{sk} did not return to baseline temperatures for whole group (Figure 1).

Statistically significant decreases in T_{sk} were also noted when comparing male and female groups separately across all time points for the knee ($P \leq .05$; Table 1). Comparatively, statistically significant decreases for quadriceps T_{sk} were noted in males at each time point up to 20-minute postintervention ($P \leq .05$); however, no significant decreases in T_{sk} were noted for males ($P = .41$) or females ($P = .19$) at the anterior thigh at 30-minute postintervention (Table 1). Throughout the entire investigation, ambient room temperature was constant (21.1°C [0.5°C]).

Peak Torque

Table 1 summarizes the effects of wetted ice application and the temporal pattern recovery on PT. There was a significant main effect for time ($P \leq .001$, $\eta^2 = .126$), with preice application higher than all other time points ($P \leq .05$). With the data set collapsed to consider each speed in isolation, PT displayed a significant main effect for time at all speeds (PT_{60}: $P = .03$, $\eta^2 = .98$; PT_{150}: $P = .001$, $\eta^2 = .177$) (Table 1). There was also significant main effects for isokinetic testing speed ($P \leq .001$, $\eta^2 = .264$), sex of the participant ($P \leq .001$, $\eta^2 = .269$), and position of the ice application ($P \leq .001$, $\eta^2 = .151$) (Table 1). There were no significant interactions found between speed, time, position, and gender for PT ($P \geq .05$).

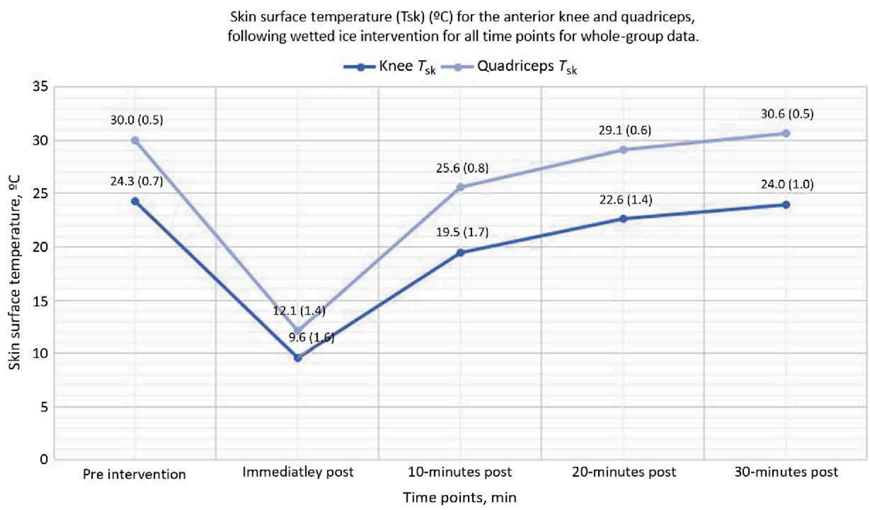

Figure 1 — Skin surface temperature profile for the knee and anterior thigh following wetted ice over a rewarming period.

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Table 1 Summary of the Effects of Wetted Ice Application on T_{sk} and the Temporal Pattern Recovery on PT and AvT

Time point, min	PRE	IP	10	20	30	PRE	IP	10	20	30
Group	Anterior thigh cooling males					Anterior thigh cooling females				
T_{sk} (°C)	31.6 (0.5)	13.9 (1.3)*	27.0 (0.9)*	26.3 (0.7*	32.1 (0.5)	28.4 (1.5)	10.4 (1.5)*	24.1 (0.8)*	27.5 (0.6)*	29.1 (0.5)
Speed (°/s)										
60°/s PT	132.9 (29.9)	116.6 (32.3)	114.0 (25.4)	105.9 (16.0)[a]	108.0 (23.1)[a]	92.4 (21.1)	75.7 (18.0)[a]	67.6 (11.6)[a]	73.4 (14.0)[a]	73.9 (14.7)[a]
60°/s AvT	113.2 (24.2)	88.1 (18.5)	90.4 (23.0)[a]	102.4 (24.1)	109.2 (25.5)	79.6 (16.9)	70.5 (11.5)	63.0 (8.4)[a]	68.9 (11.3)	72.8 (11.5)[a]
60°/s PT	67.3 (16.5)	71.3 (7.6)[a]	65.1 (8.4)	74.8 (6.5)[a]	70.9 (8.4)[a]	72.2 (10.4)	69.3 (6.3)[a]	65.5 (10.0)[a]	65.0 (8.4)	70.8 (7.3)
150°/s PT	104.0 (31.0)	89.4 (20.8)	69.6 (22.3)[a]	79.9 (19.1)[a]	80.6 (17.2)[a]	70.7 (14.4)	55.4 (13.6)[a]	53.6 (19.7)[a]	55.4 (14.7)[a]	59.2 (15.3)[a]
150°/s AvT	81.0 (22.2)	64.3 (18.9)	60.0 (11.4)[a]	61.8 (12.4)	71.4 (19.2)[a]	54.3 (12.5)	40.7 (13.6)[a]	41.8 (12.5)[a]	46.4 (12.6)	49.4 (14.6)[a]
150°/s PT	58.2 (13.0)	48.7 (10.7)[a]	42.1 (8.3)[a]	47.2 (10.8)[a]	46.0 (10.0)[a]	36.4 (9.8)	40.1 (7.2)[a]	45.4 (4.9)[a]	43.3 (6.6)[a]	45.1 (8.2)[a]
Group	Knee cooling males					Knee cooling females				
T_{sk}, °C	26.8 (0.8)	8.6 (1.7)*	16.6 (2.0)*	22.8 (1.5)*	23.9 (1.1)*	25.8 (0.8)	9.1 (1.5)*	19.6 (1.3)*	21.4 (1.2)*	24.0 (1.0)*
Speed, °/s										
60°/s PT	149.8 (34.1)	109.1 (26.0)[a]	117.2 (34.5)[a]	131.3 (31.7)	137.8 (32.1)	113.4 (25.6)	98.1 (1.2)	102.3 (26.9)	96.8 (19.4)	108.1 (27.4)
60°/s AvT	115.7 (26.3)	81.3 (20.1)[a]	95.0 (23.9)	103.5 (22.4)[a]	104.7 (26.0)[a]	92.2 (31.6)	76.1 (18.1)[a]	75.9 (15.5)	74.6 (13.0)[a]	85.8 (19.1)
60°/s PT	56.9 (9.5)	55.2 (8.9)[a]	52.0 (7.8)[a]	54.1 (10.9)	58.8 (13.4)	61.6 (8.8)	59.3 (6.8)	56.8 (9.5)	54.3 (10.2)[a]	60.0 (8.6)[a]
150°/s PT	115.1 (17.2)	72.7 (17.2)[a]	89.6 (16.3)	96.0 (13.6)	108.4 (17.7)	90.6 (22.4)	78.0 (16.9)	76.9 (11.0)	73.9 (11.5)	82.3 (13.7)
150°/s AvT	92.0 (11.8)	69.4 (9.6)[a]	72.6 (9.9)	67.8 (13.2)[a]	89.6 (9.6)	81.0 (14.8)	61.4 (9.7)	62.1 (9.6)	65.2 (11.1)[a]	75.3 (13.0)
150°/s PT	44.1 (15.7)	37.7 (15.3)	45.9 (4.3)	48.5 (8.3)	52.8 (8.9)	54.7 (10.6)	51.0 (7.4)	51.0 (8.4)	49.7 (11.5)	49.2 (9.4)

Abbreviations: AvT, average torque; IP, immediately post intervention; PRE, pre or before intervention/baseline data; PT, peak torque; T_{sk}, skin surface temperature.
[a]Greater percentage reduction in strength when comparing between cooling locations against preintervention data and within gender group.*Significant reduction in T_{sk} reported postcooling.

Average Peak Torque

Table 1 further summarizes the effects of wetted ice application and the temporal pattern recovery on AvT. There was a significant main effect for time ($P \leq .001$, $\eta^2 = .159$), with preice application higher than all other time points ($P \leq .02$) except at 30-minute postintervention ($P \geq .05$). With the data set collapsed to consider each speed in isolation, AvT displayed a significant main effect for time at all speeds (AvT_{60}: $P = .01$, $\eta^2 = .126$; average torque $[AvT]_{150}$: $P < .001$, $\eta^2 = .234$) (Table 1). There was also significant main effects for isokinetic testing speed ($P \leq .001$, $\eta^2 = .301$), sex of the participant ($P \leq .001$, $\eta^2 = .246$), and position of the ice application ($P \leq .001$, $\eta^2 = .085$) (Table 1). Apart from speed × position interaction ($P = .02$, $\eta^2 = .028$), no other significant interactions were found ($P \geq .05$).

Discussion

The current study reports the effects of anterior thigh and knee cooling on PT and AvT isotonic strength of the quadriceps in males and females over a rewarming period. Previous studies have traditionally cooled over the exercising muscle[13] and others only the distal joint[32] or simultaneously[4]; to our knowledge, no study compares both. However, it is unclear as to the extent of positive or deleterious effects of local cooling at different locations over the peripheral lower limb on the mechanical properties of muscle strength, with literature failing to reach a strong consensus. Results demonstrate reductions in PT and AvT concentric quadriceps strength in males and females, which did not fully recover to baseline at 30-minute postcryotherapy intervention. Findings from the current study not only agree with,[1,2,27] but also refute[16,17] some evidence. It is problematic, however, to copiously compare results directly because of the variability in testing protocols across available literature. Notably, current findings report the need for further enquiry into the immediate and latent effects of common cryotherapeutic applications used pitch side in sport with varied dosage applications on muscle strength.

To mimic closely common applications of cold-applied pitch side or at half-time during competitive sport, duration of wetted ice followed a 10-minute dosage in the current study.[33] Although contrasting to longer dosage protocols,[3,8,9] the decision supports the recommendation for investigations in cryotherapy to replicate simulated play and helps understand the extent of effects induced by cryotherapy applications in sporting scenarios.[2] A 10-minute wetted ice exposure initiated whole-group average T_{sk} recorded at 9.6°C (1.6°C for knee) and 12.1°C (1.4°C for anterior thigh), immediately postintervention in the current study. These results establish a T_{sk} response to within the desired therapeutic range of cooling (10°C–15°C),[11] expected for physiological response occurred after a 10-minute application (Figure 1). Whole-group T_{sk} did not return to baseline levels at 30 minutes over the knee (24.0°C [1.0°C]) or at 20 minutes after over the anterior thigh (29.1°C [0.6°C]) for whole-group data (Figure 1), supporting previous literature.[27] In addition, regardless of cooling location, reductions in strength were reported in both male and female groups, for both speeds ($PT_{60/150}$ and $AvT_{60/150}$) (Table 1). The noted reductions in strength coincide with reductions in T_{sk} over the rewarming period and demonstrated a relative incline over 30-minutes postremoval (Table 1). Observation of percentage difference in concentric quadriceps strength data between cooling locations noted no definitive pattern when comparing all postdata with baseline. However, a trend is suggestive that concentric strength data immediately post demonstrate greater reductions noted subsequently following knee joint cooling than the anterior thigh in males for both speeds (PT/AvT: 60°/s /150°/s), but not in females. Accordingly, at all other time points (10, 20, and 30 min), data recorded greater reductions for anterior thigh cooling compared with knee for both gender groups and speeds. Unsurprisingly, this supports previously reported quadratic relationship mechanisms between T_{sk} and deeper musculature response to cooling following removal of local cooling[12]; that being as skin rewarms, muscle continues to cool pertinent to cooling ability of the cryotherapy modality applied. This also supports the findings that strength following cooling at either locations, across both gender groups and speeds, does not return to preintervention levels at 30 minutes. Although data largely report different percentages of strength deficit noted following anterior thigh compared with knee cooling, both cooling locations demonstrated statistically significant reductions in concentric strength over the rewarming period (Table 1) regardless of gender or speed compared with baseline measures. Due to the relatively small sample size utilized in the current study, caution when comparing findings between genders may be noted. This may also contribute to the interactions between variables highlighted in the complex study design. Significant interactions were highlighted for speed × position in AvT, with a small effect size reported. Consideration must be given to this in future work.

Local cryotherapy in athletic practice, particularly prior to returning to activities that expose muscle tissue to exercise-induced damage should consider the findings from the current investigation. Results agree with those conclusions of previous authors that a ≥10 minute cooling reduces muscle contractility and subsequently, performance.[8] Furthermore, the authors agree that desensitization of deep joint mechanoreceptors following knee joint cooling may affect neuromuscular response, proposing a change in proprioceptive feedback,[34] but importantly reaffirm the detrimental effects distal cooling has on the strength of musculature as much as that of direct cooling over the anterior thigh. Reductions in torque production ability of the quadriceps are formerly reported immediately following a 20-minute cooling application over the anterior knee joint and highlighted the importance of investigating rewarming periods prior to returning to sport.[27] The implications of reduced muscle strength of the quadriceps or surrounding musculature may predispose an increased risk of noncontact injury at the knee complex.[35] Investigations report that acute changes in the mechanical properties of muscle following cryotherapy consequently lower the amount of stretch that muscle tissue is able to sustain without subsequent injury.[1] Cooling over regions susceptible to strain injury, such as myotendinous junction, may present an increased risk of injury by returning to activity soon after cryotherapy applications. Point et al[1] considers this increased risk is due to the reduced capacity of the muscle tendon unit to sustain external strain following cooling caused by increased stiffness in the cooled tissues.[36] Muscle fibers, therefore, are more prone to damage[1] due to known mechanisms predisposing to soft-tissue injury, such as reductions in available range of motion[37] and increases in contractile tissue stiffness.[37] Assumed putative changes in global viscoelastic and myoelectrical activity initiated by lower temperatures may be factors that contribute to the reduction noted in isotonic PT and AvT in the current study, supporting previous suggestions.[1,7] Reduced muscle deformation, passively, has been reported in cold muscles, prior to rupture, following exposure to cold-water immersion.[38,39] It may be considered, however, that cold-water immersion is more likely to affect multiple structures concurrently following exposure to the lower limb, including structures that crossover joints such as agonist and antagonistic muscles, tendons, and articular structures, suggesting potential detrimental changes to multiple stabilizing and force-producing structures.[1] Therefore, it is difficult to compare directly current results with cold-water immersion or air-pulsed cryotherapy modalities, on that basis.

Conclusions

Local cooling over superficial joint or muscles in males and females may result in performance deficits due to reductions in concentric muscle strength. Future studies are essential to establish margins whereby safe return to sport following cooling exposures to the lower limb. Sports medicine practitioners should consider reductions in strength ability of the quadriceps even after shorter application durations (<20 minutes) of wetted ice, regardless of cooling location (joint/muscle) or gender. To advance safe rationale for pitch-side cryotherapy applications, comparison of other commonly applied cryotherapy modalities are necessary, and observation of multiple variables may affect the development of optimum dose duration and return to activity panaceas.

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Exploratory evaluation of muscle strength and skin surface temperature responses to contemporary cryotherapy modalities in sport

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Abstract.

BACKGROUND: The effects of contemporary cryo-compression devices on function are limited compared to traditional applications of cooling. Development of cooling protocols are warranted.

OBJECTIVE: To investigate the effects of three different cryo-compressive modalities applied at the knee on the isokinetic strength of the quadriceps over a re-warming period.

METHODS: Eleven healthy male participants took part (23 ± 14 years; 78.3 ± 14.5 Kg; 180 ± 9.5 cm) randomly assigned to receive all modalities (Game Ready® (GR), Swellaway® (SA), Wetted Ice (WI)) applied for 15-min, separated by 1-week. Skin surface temperature (T_{sk}) via thermography and the concentric peak moment (PM) of the quadriceps at 60 and 180°/s were collected pre-, immediately-post and at 20-min post-intervention.

RESULTS: Significant reductions occurred in T_{sk} across all timepoints for all modalities ($p = \leqslant 0.05$). Significant reductions in PM for WI were noted across all timepoints and PM for GR and SA immediately-post ($p = \leqslant 0.05$) only.

CONCLUSION: Precaution for immediately returning to sport following cryotherapy is required and influenced by type of cooling on muscle strength responses. Alternate targeted treatment modalities to minimise deferred deleterious effects on muscle strength may be considered. Research into length of application, periodisation and location is warranted for the development of such contemporary cryo-compressive modalities in applied practice.

Keywords: Cooling, knee, isokinetic dynamometry, performance, sport injury

1. Introduction

It is commonplace within sport to see ice being applied at varying times throughout competition to enable the continuation of competitive play. Aetiological risk factors strongly associated with non-contact musculoskeletal injury at the knee include reductions in strength [1–3]. Research has detailed the immediate detrimental effect icing protocols may have on muscle strength [4,5] and knee joint kinematics [6,7]. These detrimental effects being shown to exist for > 20-min post application [5,6]. Evidencing that during competition, such as half-time, consideration needs to be given to the potential injury risk exposure an athlete may be subjected to post ice application. This provides sports

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medicine practitioners with the dilemma of immediate therapeutic advantages, against potential increased or further injury risk. Contemporary pneumatic cryo-compression devices aim to replicate similar reduced skin surface temperatures (T_{sk}) of between 10–15°C, such as those induced by wetted ice (WI) [8], and although investigations into technological advances in cooling devices are acknowledged [9], the effects of such modalities on biomechanical function are limited within the available literature.

Historically, literature compares traditional cooling modalities such as gel packs, cold spray, crushed ice, frozen peas and WI [10–12]. Although, modern devices that combine cooling capabilities in conjunction with compression, such as the GameReady® (GR), Squid Go® and AIRCAST® Cryo/Cuff have gained prominence in the literature [8,13–15]. Evidence considers the addition of compression alongside cooling more effective at reducing T_{sk} [13,16], increasing oxygenation within tendons [17] and muscle [13], and the magnitude of cooling [13,18], compared to the application of cooling alone. The comparison of contemporary cryo-compressive modalilties with intermittent vs consistent pressure demonstrated equivalent intramuscular temperatures decreases during applications [15], interestingly differences in T_{sk} were reported between modalities [15]. Similar findings are recently reported [13] for T_{sk} following varying levels of pressure and considered to be a key mechanism response for physiological processes to occur. Despite the known impact on physiological measures that additional compression influences, studies are still negligible that compare contemporary cooling devices with compression capabilities on strength parameters. This is most likely due to the lack of consensus individually for optimal cryotherapy or compression, including the length of application (minutes), which informs the rationale for the combined therapeutic use of cryo-compressive devices. Consequently, agreement as to what may be the 'optimum' application of such cryo-compressive devices are not yet determined. Contemporary developments in electronic pneumatic cryo-compressive devices include Swellaway® (SA) (Swellaway.com), claimed to be a targeted local cooling device, and the GR (GameReady.co.uk), which provides intermittent compression with circumferential cooling.

Physiological measures of T_{sk} through infrared thermography (IRT) and functional strength quantifications of the lower limb musculature, via isokinetic dynamometry (IKD) support the understanding of potential effects local cryotherapy may have on objective markers of function [5,18,19]. The relationship between reduction of T_{sk} and intramuscular temperature (T_{im}) is previously reported [11], with a suggested quadratic relationship aiding to the understanding of the potential strength changes as reported in some studies following local cryotherapy applications [5,10,19,20]. Varying metrics have been utilised within literature to quantify muscle strength, including peak moment (PM) [1,3,5]. Utilisation of PM metrics provides practitioners with an overview of the athletes peak strength within one degree of movement. The effects of icing on biomechanical function are evident, yet not fully understood in relation to PM when comparing multiple cooling modalities. Methodologies differ however in the location of cooling application on mechanical properties of muscle and strength responses, with some studies applying only distal joint cooling [21,22], and others directly over soft tissue structures [23]. Recent literature reported that regardless of cooling location (quadriceps vs knee joint cooling) concentric muscle strength of the quadriceps decreased after exposure to WI application [5]. Further understanding however of contemporary cryo-compressive devices such as the SA and GR and their effects on biomechanical mechanisms, may support the progression of evidence necessary in helping to define optimum cryotherapy protocols for sports injury rehabilitation and recovery. Therefore, the aim of the present study is to compare the effect of cooling through the applications of WI, SA and GR on T_{sk} and the PM.

2. Methods

2.1. Participants

A *priori* power calculation was conducted using familiarisation trials and a minimum sample size of ⩾ 10 participants was required to evaluate the interactions associated with all independent variables (for statistical power ⩾ 0.8; P =< 0.05). The study was advertised through the University of Central Lancashire, and those volunteers that met the inclusion criteria of playing semi-professional rugby (classified as National 1 or 2 for the purpose of this study) with weekly training and competitive fixtures, alongside their university sports commitments were recruited. Consequently eleven healthy male participants met the criterion and volunteered to take part in the study (age: 23 ± 14 years; weight: 78.3 ± 14.5 Kg; height: 180 ± 9.5 cm; body fat: 22.1 ± 4.7%). All experiments were undertaken with

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Table 1
Descriptive data for T_{sk} and PM for both speeds (60°.s^{-1}; 180°.s^{-1}) and across all timepoints

		Time point		
		Pre-intervention	Immediately post intervention	20 minutes post intervention
Wetted Ice				
	T_{sk} (°C)	28.6 ± 0.66°C	6.9 ± 2.67°C*	19.7 ± 1.24°C*
Speed (°s^{-1})	60°.s^{-1} PM	241.2 ± 54.5	181.9 ± 54.2†	203.2 ± 67.6†
	180°.s^{-1} PM	123.9 ± 39.7	77.8 ± 21.9†	110.7 ± 33.8†
Game ready®				
	T_{sk} (°C)	28.6 ± 0.66°C	18.4 ± 2.14°C*	24.7 ± 1.46°C*
Speed (°s^{-1})	60°.s^{-1} PM	199.5 ± 54.5	175.4 ± 69.3†	216.5 ± 53.9
	180°.s^{-1} PM	147.5 ± 26.8	112.4 ± 35.1†	147.7 ± 29.5
Swellaway®				
	T_{sk} (°C) (Medial knee)	28.6 ± 0.66°C	13.4 ± 1.61°C*	24.9 ± 1.78°C*
	T_{sk} (°C) (Lateral knee)	28.6 ± 0.66°C	15.0 ± 2.13°C*	26.7 ± 1.69°C*
Speed (°s^{-1})	60°.s^{-1} PM	204.2 ± 51.1	148.4 ± 35.6†	224.9 ± 54.7
	180°.s^{-1} PM	141.0 ± 31.9	103.9 ± 34.4†	126.2 ± 39.5

*Statistically significant reduction in T_{sk} post intervention. †Statistically significant reduction in concentric strength post intervention.

the understanding and written consent of each subject, and the study conformed with The Code of Ethics of the World Medical Association (Declaration of Helsinki, 2013), approved by the host university ethics committee (STEMH: approval date: September 2019). All male participation increased sample homogeneity due to gender differences found in response to local cooling [24]. Criteria for exclusion from this study included; females; any male under 18 years, history of musculoskeletal or neuromuscular lower limb injury in previous 6 months, any contraindications to cryotherapy [7,25]. All data was collected at pre-intervention, immediately post-intervention and at 20-min post-intervention.

Participants were randomly assigned (randomization.com) to a sequence of cryotherapy modalities, separated by 1 week, which included the GR (GameReady®, Global, UK), which provides cyclical pneumatic cooling through water and ice with simultaneous compression through manual protocol combinations; SA (Swellaway Ltd, UK) a pneumatic portable device providing simulataneous targeted cooling through Peltier cell technology and compression through pre-set protocol combinations; and WI made up from comprised of 800 g of crushed ice mixed with 800 ml of water. Each modality followed a typical clinical application times of 15-min dosage [26], standardising common practices of cryotherapy applications in sport. Anthropometric data, including skin fold measurements (Harpenden Skinfold Callipers, HSB-BI; Baty International, Burgess Hill, West Sussex, UK), to estimate the percentage body fat based on the sum of skin fold thickness for adipose tissue measurements and were taken from the following sites: abdomen, medial calf, thigh, biceps, triceps, iliac crest, supraspinatus and subscapularis [27]. Records of dominant limb was quantified following previous published methods to determine favoured kicking foot [28] and ambient room temperature established during a 15-min acclimatisation period ensured continuity between baseline data protocols and participants prior to cooling intervention following previous methods [29]. Room temperature measured every 30-min throughout testing noted any fluctuations in environmental temperature.

2.2. *Testing protocol*

Skin surface temperature via a non-invasive thermal imaging camera (FLIR C3, FLIR® Systems, Inc.) and concentric isokinetic quadriceps strength (Cybex, Division of Lumex Inc., Ronkonkoma, NY, USA) established relevant objective biomechanical and physiological markers for the study. An accurate and reliable measure of T_{sk} can be quantified through thermal imaging [20,29], and in the current study this provided the opportunity to determine whether differences in T_{sk} exist between the three modalities when applying the same length of exposure (15-min) (Table 1). A ThermoVision A40M Thermal Imaging Camera (Flir systems, Danderyd, Sweden) with emissivity set at 0.97–0.98 was used according to standard medical protocols for the use of Thermographic Imaging in Sport and Exercise Medicine (TISEM) [29]. Mounted perpendicular to the defined region of interest (ROI) over the anterior, medial and lateral aspects of the knee, on a tripod at height 53 cm; the TI camera connected to a laptop running Thermacam Researcher Pro 2.8 software (Flir systems, Danderyd, Sweden). To define the ROI over the knee, thermally inert markers developed a suitable framework for each modality application. Markers to define a ROI for WI and GR applications were placed at the tibial tuberosity, lateral and medial border of patella at the same level with the tibiofemoral joint line, middle of the base of the patella [12]. Markers to define a ROI for SA were placed at tibial tuberosity, lateral and medial border of patella at the same level with the tibiofemoral joint line, medial and lateral epicondyles of the femur, and the medial and lateral condyles of the tibia. Three images were taken at each timepoint (Pre; Immediately post intervention; 20-min post intervention) for each modality, with mean ± SD T_{sk} established during analysis.

The dynamometer was calibrated prior to each testing session. The data was collected at the same timepoints of baseline, immediately post intervention and 20-min post intervention and achieved by subjects performing five repetitions of knee extension at 60 and 180°/s on the dominant leg [22]. For each testing speed the gravity-corrected moment angle curve was analysed. Analysis was restricted to the isokinetic phase with angular sectors of 100° of knee flexion and 0° to extension and for each phase the PM was identified. Highest PM values from repetitions for each timepoint were utilised for analysis. The limb was passively moved into flexion at 10°/s between repetitions with 60 second rest between the two sets. Participants received verbal encouragement during the strength assessments. Participant position was supported at the distal thigh, distal tibia and across the chest when seated on the IKD follows standard protocol for this measurement [30]. A 90° hip and knee flexion position prior to the commencement of movement permitted the input axis of the dynamometer to align with the lateral femoral condyle of the testing limb. Positional settings were recorded for each participant to ensure standardisation between each timepoint of data capture and between the different modality exposures. Throughout testing each repetition was observed by the same researcher to ensure smooth effort was exerted by each participant [22].

Interventions were allocated to participants in a random order of exposure comprised of either the GR; applied over the knee via the anatomical lower limb wrap, set at intermittent high compression (5–75 mm Hg) of 3-minute inflation compression cycles followed by 1-minute recovery deflation, with a target temperature manually set to 10°C target temperature on the device (Fig. 1); WI comprised of 800 g of crushed ice mixed with 800 ml of water in a sealed bag, held in

Fig. 1. Contemporary cryotherapy cooling modalities used in the study; the Game Ready® and the Swellaway® device.

place using standard cling wrap [10] over the anterior aspect of the knee; or the SA knee unit with × 2 modular Peltier cells arranged medially and laterally over the knee joint line, held in place by a custom knee brace, with consistent pressure set at 35 mm Hg and target temperature manually set to 10°C (Fig. 1). All cooling applications were applied with a standardised duration of 15-min [26]. Participants remained in a long sitting position on a medical plinth for the application of each cryotherapy modality. Following immediate removal of the intervention, thermographic images of the anterior knee and concentric quadriceps strength measures were taken following the same protocol as pre-intervention. The participant then returned to a long sitting position for a re-warming period of 20-min before further T_{sk} and the isokinetic moment measurements of the quadriceps were repeated. The choice to test at 0 and 20-min post-intervention was thought to replicate shorter time periods where athletes may return to functional competitive activity after exposure to cooling and timepoints representing previously published methodologies [5,7]. During the rewarming period, participants were encouraged to remain as still in the same position throughout this time. Participants returned at 1 and 2 weeks via randomisation for exposure to all modalities in the study.

2.3. Analysis

Statistical analysis was completed using PASW Statistics Editor 26.0 for Windows (SPSS Inc, Chicago, IL). A univariate, repeated-measures general linear model quantified the main effects for recovery duration following cooling interventions and for all isokinetic testing speeds. Significant main effects in recovery duration were explored using post-hoc pairwise comparisons with a Bonferroni correction applied. To ensure model adequacy the assumptions associated with the statistical model were assessed and met. Mauchly test of sphericity was also completed for all dependent variables, with a Greenhouse-Geisser correction applied if the test was signficant. To estimate effect sizes for all signficant main effects partial eta-squared (η^2p) values were calculated and classified as small (0.01–0.059), moderate (0.06–0.137), and large (> 0.138) [31]. Interactions within the general linear model were identified within the analysis of data. Statistical significance was set at $P \leqslant 0.05$, and all data are presented as mean (SD).

3. Results

3.1. Skin surface temperature (T_{sk})

Skin surface temperature demonstrated statistically significant reductions immediately post cooling ($P < 0.05$) and at 20-min post cooling for all three modalities ($P < 0.05$) compared to pre-application temperatures (Table 1). It did not return to baseline temperatures at 20-min post intervention for any of the three modalities (Table 1).

3.2. Peak moment

Table 1 summarises the effects of all cryotherapy modalities and the temporal pattern of recovery on PM. There was a significant main effect for speed post-intervention ($P \leqslant 0.001$, $\eta^2 = 0.47$) and time ($P \leqslant 0.001$, $\eta^2 = 0.21$), with no significant effect of modality found ($P > 0.05$, $\eta^2 = 0.02$). No significant 2-way or 3-way interactions between the variables speed, time and modality were observed ($P > 0.05$) and therefore led to the examination of modalities separately for further exploration.

With the data set separated to consider effects of speed and time for each modality, significant main effects for time and speed for PM were identified for all three modalities (WI: time: $P = 0.007$, $\eta^2 = 0.17$, speed: $P \leqslant 0.001$, $\eta^2 = 0.546$; GR: time: $P \leqslant 0.001$, $\eta^2 = 0.17$, speed: $P \leqslant 0.001$, $\eta^2 = 0.39$; SA: time: $P \leqslant 0.001$, $\eta^2 = 0.30$, speed: $P \leqslant 0.001$, $\eta^2 = 0.47$). No significant speed x time interaction were found ($P > 0.05$) for PM. All modalities identified a significant reduction in strength immediately post intervention ($P < 0.05$), with only WI however demonstrating a significant reduction in strength 20-min post intervention ($P < 0.05$) for PM.

3.3. Collapse of test speeds

Analysis of the different speeds identified significant main effects for time ($P < 0.001$), but not for modality ($P > 0.05$) for 60°/s and both time and modality for 180°/s ($P < 0.001$) for PM. Observation of time points for PM for both speeds identified significant differences between time points pre and immediately post intervention ($P < 0.001$) and immediately post intervention and 20-min post intervention ($P < 0.001$). Further analysis identified no significant differences in strength at 60°/s between modalities for PM. Strength at 180°/s however identified significant differences between WI and GR ($P < 0.001$); WI and SA ($P < 0.001$); but not between GR and SA ($P > 0.05$).

4. Discussion

The purpose of the study was to investigate the effects of three different cryotherapy modalities on concentric knee extensor strength over a re-warming period. Findings report significant differences in the amount of PM output between GR, SA and WI modalities when applied to the knee for the same exposure period of 15-min. With WI having the greatest effect on strength reduction across multiple time points. Optimal cryotherapy protocols in sporting contexts are yet to be established. In consideration of the known immediate and latent effects on strength, a key aetiological risk factor associated with non-contact musculoskeletal injury [1–3], it is important to investigate and compare the biomechanical responses across different cryotherapy modalities to help best inform practical application in sport. This is the first study to the authors knowledge that compares contemporary cryo-compressive devices offering circumferential or targeted applications to traditional WI methods. Results within the present study are largely consistent with previous work, displaying reductions within strength parameters immediately [5] and up to 20-min post cooling [22]. Yet, findings suggest the effects may be influenced through choice of cooling modality.

It was found that WI had the greatest effect on strength and for a longer period compared to the GR or SA devices, with significant reductions identified immediately and at 20-min post-intervention. Interestingly, when observing the two contemporary cryo-compressive modalities utilised in this study (GR/SA) they were both associated with significant knee extension strength reductions immediately, but not at 20-min, post-intervention. It is evidenced that intramuscular temperatures continue to decrease after removal of cooling [10,11]. We might assume therefore that due to the efficacy of WI to conduct thermal energy this resulted in the significant reduction of strength at 20-min in the current study. A disruption to neuromuscular response through joint cooling previously suggests this may be a contributing factor to muscle strength loss in surrounding tissues such as the quadriceps [22]. Current data is representative of these presumptions and suggests that different neuromuscular responses occurred between modalities. Known physiological changes that ensue when therapeutic range is met, such as a reduction in nerve conduction velocity which influences joint receptor feedback [32] may not have been affected at 20-min post GR or SA applications. It is thought that this may be due to a) inadequate length of application exposure (time) to initiate response, and b) smaller, targeted region of joint cooling of the SA device compared to WI. The authors acknowledge literature that suggests exposure (time) should be ideally altered in consideration of adipose tissue levels [8] or target tissue [33] to induce physiological responses. In the current study however the same length of exposure (15-min) was applied across all particiants and between modalities to ensure standardisation of that particular variable, and was not the main focus of investigation in this study. Contrasting characteristics between modalities and the phase-change capability of material may advocate the results reported and contribute to the differences in strength output. Consequently this has implications on modality choice in terms of therapeutic treatment target.

Significant effects were observed in the current study for the speed of test, challenging findings in previous work questioning the use of a variety of speeds within research [34,35]. It is considered that higher velocity speeds more closely reflect the functional demands of multidirectional movements which require increased control at the knee to perform. Furthermore, injury risk is heighted through functional movements performed at higher velocity speeds. In the current study, at speeds of 180°/s, significant effects on PM for time and modality compared to only time for the lower speed of 60°/s were reported. Reductions of strength noted at higher speeds compared to lower speed following the application of local knee joint cooling may suggest greater implications on functional control exist when observing PM parameters, and be influenced by modality choice. This requires further investigation, however practitioners might consider choice of cooling modality and length of rewarming periods to help mitigate the effects on functional control at the knee following local cooling applications.

Across all three modalities a typical re-warming curve in T_{sk} was noted, replicating earlier literature [25], with T_{sk} having not returned to baseline measures at 20-min post-intervention. When comparing devices on their ability to reduce T_{sk} differences were noted, and may therefore rationalise the differences in muscle strength changes observed in the current study. Notably T_{sk} reductions were significantly greater for WI compared to the GR or SA devices. In line with previous research, it is assumed from the reduction in strength at 20-min post removal of WI, intramuscular temperatures were more adversely affected compared to the GR or SA applications, of the same length of exposure (15-min). Current findings are representative of previous work that suggests that a quadratic relationship may exist between T_{sk} and T_{im} post cooling [10] and that reductions in intra-articular temperatures may continue after the removal of cooling [36]. Although this is only an assumption as intra-articular temperature measures were not in the current study. Considering the continuing reductions possible in the intra-articular knee joint following removel of such cooling devices and applications; with therapeutic advantages of maintaining tissue temperature reductions, comes the increased potential for risk of further injury through reduced joint control, due to detrimental responses in surrounding muscle strength and neuromuscular responses to cooling [5,22]. WI cooled T_{sk} to a lower temperature, over a larger area compared to the SA device and as a result unsurprisingly negatively affected strength for a prolonged period post removal. The targeted cooling application of the SA device demonstrated the ability to reduce a local region of T_{sk} that was in direct contact with the Peltier cell, to within the therapeutic range (10–15°C) [25] without diminishing PM 20-min post-application removal. It is important to note that a much smaller targeted area of cooling via the SA device may only be achieved without any indication of cooling spread in the adjacent skin away from the Peltier cell contact, in comparison to the other modalities, with cooling targeted over medial and lateral knee joint lines in the current study protocol. Although T_{sk} varied between medial and lateral locations (Table 1)

T_{sk} reduced to within therapeutic range (10–15°C) over both contact areas (medial and lateral knee joint lines) via Peltier cells, the cooling mechanism behind the SA device. This may be beneficial for targeted intervention applications, as no spread of cooling outside Peltier cell skin contact occurs, however as a result circumferential cooling cannot be achieved in comparison to the other modalities such as the GR or WI bags. Therefore the aim of treatment is important to identify prior to application of cooling modality choice. The rapid re-warming of T_{sk} observed by the SA modality may be advantageous in the development of identifying parameters of safer return to activity post cooling, as no detrimental muscle strength losses were reported at 20-min post. It may be beneficial however to determine the effects of such device on joint kinematics, perception of pain and other physiological mechanisms to strengthen or dispute these findings further.

The 15-min exposure time application and target temperature setting of 10°C applied in the current study, reflecting pitch side or recovery applications of cooling appeared inadequate for the GR device to achieve a typical T_{sk} range of between 10–15°C immediately post removal (Table 1). Previous evidence demonstrates the ability of this device to cool to within therapeutic range [20] yet methodological differences in target temperature between studies as a rationale for the duifferences, appear to differentiate between agreement in results, which is unsurprising.

Despite similar presentations in strength responses for GR and SA devices at 20-min post it is assumed unlikely that detrimental changes in muscle strength would be reported for the GR. Previous literature applied an exposure time of 30-min for the GR device [14], but the authors felt this was not representative of shorter exposures of cryotherapy utilised in sport pitch-side, at half-time or intermittent stoppages in play, hoped to be investigated in the current study. The shorter application time for the GR device in the current study, reduced the capability of comparison to previous methodologies limiting evaluation of outcomes measured in the current study to others. Future investigations might observe longer periods of applications or cooler target temperatures for the GR (∼ 30 min) as represented in manufacturers' protocol options. This would aid as a dosage comparison and to ensure physiological changes, notably in analgesia are sufficiently induced. That said, the current findings highlight important differences in strength responses that therefore occur between cooling modalities of the same length of exposure (time). Current results suggest that both beneficial and disadvantageous differences arise between modalities, however as to which modality represents best practice is determined upon the aim of treatment and justification of use within the applied sport setting.

One application difference between the modalities in the current study was the adjunct of compression, that being manual-consistent pressure offered with WI (via plastic wrap), pneumatic-consistent pressure for the SA device, and pneumatic-intermittent pressure of the GR. Furthermore, the level of compression was not quantified and may be a limitation in the ability to justify the outcomes of the findings. It may be possible that the results of the GR were in fact due to the differences in compression adjunct (in term of intermittent vs consistent pressure) given that previous literature suggests it can produce similar levels of cooling compared to other cooling modalities [14,20]. Direct comparison to earlier studies is difficult due to differences in the modalities investigated. Further exploration of different methods of compression adjuncts offered by contemporary cooling modalities is warranted to understand the full extent of the impact it may have on physiological and biomechanical responses.

Choice of cryotherapy modality is an important part of clinical decision making. The phase-change capability of modalities is of note when comparing the efficacy of cryotherapeutic modalities, a panacea of variables influences this, including metabolic changes associated with injury, modality temperature and compressive adjunct, alongside length of exposure (time). Future research should consider the differences in material properties and length of exposure (time) of contemporary cooling applications on biomechanical functions. Subsequently the addition of eccentric muscle strength and joint position sense measures may be beneficial to develop a body of evidence around optimal protocols of contemporary cooling applications in sport. Sports medicine and performance practitioners should however continue to consider the differences and deleterious effects some applications of cooling may have on strength following lower limb cooling. A reduction in muscle strength and consequently performance suggests joint stability feedback mechanisms could also be compromised, as reported in previous literature [5,6]. Therefore, contemporary cooling devices that offer targeted local cooling, such as the SA device may be useful in comparison to circumferential joint cooling (GR) and vice versa, dependent on injury presentation, rehabilitation or recovery aim. The findings of the study are qualified by the homogeneous sample which limit the transferability of findings to female or injured populations.

Further research is required to address this issue and to provide sports medicine practitioners with evidenced based rationale for application of such modalities.

4.1. Conclusion and practical implications

Thermal imaging assessment for T_{sk} aided by isokinetic dynamometry continues to advance the development of applied guidelines for cryotherapy. Overall results are an important indication of the variation in effects on muscle strength response for several contemporary and traditional cryotherapeutic modalities. The results highlight the importance of acknowledging strength loss differences that occur between modalities following lower limb knee joint cooling. Precaution for athletes returning to functional activity following cryotherapy is required, and the extent of which is dependent on several biomechanical factors in need of further investigation simultaneously. Therapists may consider the following points when applying this modality:

- The effects of GameReady®, Swellaway® and wetted ice on muscle strength measures and skin surface temperature observed over a rewarming period differ despite consistent length of exposure (time) applied (15-min).
- Contemporary cooling devices offering circumferential joint cooling (GameReady®) may be useful in comparison to targeted local cooling (Swellaway®) and vice versa, dependent on the aim of treatment.
- Targeted treatment using the Swellaway® device may minimise any deferred deleterious effects of cooling on specific muscle strength parameters.
- Further investigation is required to optimise application protocols using contemporary cooling devices compared to traditional methods for sport injury and recovery strategies.

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Author contributions

CONCEPTION: Jill Alexander, James Selfe, Olivia Greenhalgh and David Rhodes
PERFORMANCE OF WORK: Jill Alexander, Olivia Greenhalgh and David Rhodes
INTERPRETATION OR ANALYSIS OF DATA: Jill Alexander, James Selfe, Olivia Greenhalgh and David Rhodes
PREPARATION OF THE MANUSCRIPT: Jill Alexander, James Selfe, Olivia Greenhalgh and David Rhodes
REVISION FOR IMPORTANT INTELLECTUAL CONTENT: Jill Alexander, James Selfe, Olivia Greenhalgh and David Rhodes
SUPERVISION: James Selfe and David Rhodes

Ethical considerations

All experiments were undertaken with the understanding and written consent of each subject, and the study conformed with The Code of Ethics of the World Medical Association (Declaration of Helsinki, 2013), approved by the University of Central Lancashire ethics committee (STEMH: approval date: September 2019).

Conflict of interest

The authors have no conflict of interest to report.

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6.3 Appendix 3: Theme 3 Publications: THERMOGRAPHY AND SKIN SURFACE RESPONSES TO CRYOTHERAPY

Appendix 3a: Copy of Publication 6.

Alexander, J., *et al,* (2019). Mapping of skin surface sensitivity and skin surface temperature at the knee over a re-warming period, following cryotherapy. *PRM+ Journal of Quantitative Research in Rehabilitative Medicine*. 2(1): 1-5.

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Mapping knee skin surface sensitivity and temperature following cryotherapy

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Abstract

Objectives

To investigate the effects of cryotherapy on knee skin surface sensitivity and temperature using monofilaments and thermal imaging.

Methods

Following a 20-minute cryotherapy exposure (crushed ice), knee skin surface sensitivity and temperature was mapped in 19 healthy participants using infrared camera and tactile sensory evaluation. The data were collected before and up to 20 minutes after cryotherapy exposure.

Results

Comparing to baseline, in women, significant decrease in skin surface sensitivity in the upper medial section of photographic knee pain map was observed up to 20-minutes after cryotherapy exposure. In men, the respective difference was observed only immediately after the explosion.

Conclusions

Crushed ice application may reduce skin surface sensitivity around a knee medial aspect and result in impeding return to play due to affected joint position sense following cryotherapy.

Keywords:

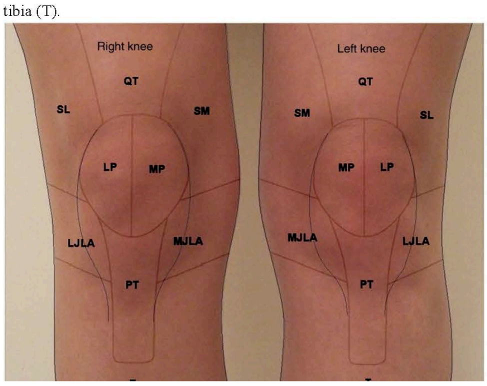
cryotherapy; cooling; knee; thermal imaging; skin sensation

INTRODUCTION

Cryotherapy decreases superficial tissue temperature via the removal of heat from the body (1). The pathophysiologic effects of topical modalities such as local cryotherapy include reductions in metabolism (2), pain, spasm, blood flow, inflammation, edema and tissue extensibility (1). It has been widely reported that nerve conduction velocity (NVC) is also decreased by local cooling (2,3). There has been conflicting evidence on the effects of local cooling on joint position sense (JPS) and the multifaceted stimuli of cutaneous receptor feedback in joint and soft tissue structures (4-6). The application of cryotherapy techniques is common in clinical practice and sport injury management (7,8). The therapeutic range for cooling has often been defined as skin surface temperature (T_{sk}) from 10°C to 15°C measured using non-invasive infrared thermal imaging (9). That temperature can be achieved by using crushed ice, wetted ice, gel pack, and cold-water immersion (10). The thermal properties of modalities vary in their cooling abilities and efficiency.

Afferent information feedback from skin receptors via tactile stimulation plays an important role in proprioceptive responses (11). Cutaneous receptors regulating a response to thermal and pressure changes include nociceptors, mechanoreceptors, and thermoreceptors (1). Tactile sensitivity has been reported to vary across different parts of the body (12). Cooling may penetrate to a depth of 2 to 4 cm decreasing the activation threshold of nociceptors and subsequently reducing painful stimuli (1). Cooling might affect the response from mechanoreceptors as well (1). Slowed impulse conduction and cutaneous sensation has been considered to reduce pressure stimuli following cooling (13). Although cutaneous receptors may play a lesser role in proprioceptive feedback than muscle spindles

Figure 1. Photographic Knee Pain Map developed and kindly agreed to be utilized in the study by Elson et al (2011) (21) for original use in collecting knee pain data.
Nine anterior zones: lateral joint line area (LJLA), medial joint line areas (MJLA), superior lateral (SL), superior medial (SM), quadriceps tendon (QT), lateral patella (LP) medial patella (MP), patella tendon (PT), and tibia (T).



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Conflicts of interest: None to declare

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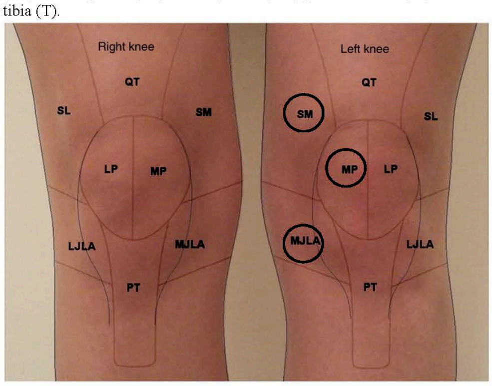
or joint receptors, Costello et al. highlighted that any alteration of tissue temperature following cryotherapy needs to be fully elucidated (14,15). Recently, Alexander et al. proposed that the accuracy of knee joint control might be reduced following a 20-minute crushed ice application (6). That suggests that cooling may affect skin stretch receptors playing an important role in joint position sense and proprioceptive acuity (14,16,17). Subsequently, deficits in proprioception may be accountable for increasing risk of knee injury (15,18). Relationship between skin surface sensitivity (SSS) patterns and JPS response before and after cryotherapy has not been reported so far.

The knee pain map has previously been suggested as a reliable method of recording the location of knee pain (20). Subsequently, it has evolved into a photographic knee pain map (PKPM) used for diagnostic communication and research purposes (21). The PKPM was used in the current study to define specific areas of the knee to explore the effect of cryotherapy on SSS. The aim of the study was to investigate the effects of cryotherapy on knee skin surface sensitivity and temperature using monofilaments and thermal imaging

Figure 2. Post-cryotherapy photographic knee pain map (PKPM) highlighting areas of decreased SSS highlighted by section for the entire sample (MJLA, SM), female (SM), and male (MP) data.
Nine anterior zones: lateral joint line area (LJLA), medial joint line areas (MJLA), superior lateral (SL), superior medial (SM), quadriceps tendon (QT), lateral patella (LP) medial patella (MP), patella tendon (PT), and tibia (T).



METHODS

Participants

Nineteen healthy volunteers who have regularly participated in land-based team sports and aged between 18 to 40 years. The participants did not have history of neurological disease, knee pain, visual or vestibular disturbance, lower limb injuries within the last six months, history of lower limb surgery, or common contraindications to cryotherapy like diabetic hypersensitivity to cold. All the participants provided written consent. The study adhered to the Declaration of Helsinki (22) and approved by the University of Central Lancashire ethics committee (STEMH).

Protocol

The study was set in a movement analysis laboratory. Room temperature was measured hourly during each day of data collection. The average ambient temperature was 21.7°C (0.4°C). This was a single-group pre-/post-test study. The data were collected before applying crushed ice to the anterior aspect of knee and every five minutes up to 20-minutes after that. Prior to the baseline data collection, a 15-minute acclimatization period ensured that steady state temperature had been reached. According to previous reports, a non-dominant limb is more prone to injuries during weight-bearing sporting tasks (23,24). As proposed by Surenkok et al., a dominant lower limb was defined as one that the participants naturally kicked a ball with (25).

To quantify SSS over the anterior aspect of the knee, Aesthesio®, Precise Tactile Sensory Evaluator (DanMic Global, LLC, USA) made of nylon monofilaments of different lengths and diameters was used. A linear scale of perceived tactile intensity ranged from 0.008 g up to 300 g divided in 20 levels. Initially, the participants were in comfortable supine position with their eyes open. The sensory evaluator was demonstrated to them applying 0.60 g pressure at the back of a participant's hand. After the demonstration, to reduce any sensory cues to gain vestibular or visual information, the participants were blindfolded during the testing (26). Before the intervention, T_{sk} was measured three times at two sites of interest – center of patella and tibialis anterior region (10 cm inferiorly and 2 cm laterally from the tibial tuberosity). The T_{sk} was measured using a non-contact infrared camera (FLIR Systems ThermoVision™ A40M, Sweden) following a previously published clinical protocol with emissivity set at 0.97 to 0.98 (6,19).

The PKPM (21) was used to define nine anterior zones of the knee (Figure 1). During sensory testing, the participants were laying in a supine sitting position with bolster support under both lower limbs. Monofilaments were pushed perpendicularly to the site of testing until bent. Starting with 0.008 g, the sensory evaluator was applied five times in each zone in random order following standardized testing protocols (27). If a participant felt the sensory evaluator touching his knee, he informed a researcher by saying "Yes" and pointing by hand at the area of sensation. If a participant did not feel any sensation after five repetitions in any of zones, a researcher applied the next levels of sensory evaluator until each zone on a knee map had five sets of recordings.

After SSS and T_{sk} baseline recordings, cryotherapy was applied over an anterior knee. To achieve a therapeutic T_{sk} between 10°C and 15°C (10), 800 g of crushed ice was applied to the anterior aspect of a participant's non-dominant knee for 20 minutes (8,10,28). Crushed ice in a clear plastic bag was covered by a damp single microfiber towel and held in place by a cling film wrap (6). Immediately after the intervention, T_{sk} measurements and SSS data were collected in exactly the same manner as at the baseline and the data were subsequently collected at 5-minute intervals up to 20 minutes. For consistency, the same researcher collected all the SSS data for all the participants. No adverse events occurred during the procedure. During the rewarming period, a participant remained in the same supine position without movement in a lower limb.

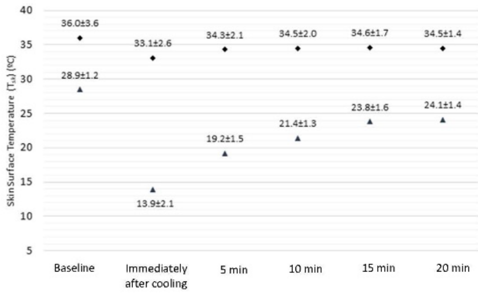
Statistical Analysis

The data were distributed normally. The T_{sk} estimates from patella and tibialis anterior were pooled. The repeated measures ANOVA and paired t-test (on gender) were performed using SPSS version 24 (SPSS, Inc., Chicago, USA) and setting significance at p=<0.05.

RESULTS

Figure 3. Skin surface temperature (T_{sk}) (°C) over the anterior knee after cooling (entire sample)

▲ Patella center ♦ Tibialis anterior



Of the 19 healthy volunteers, 11 were men and 8 were women. Their average age was 20.2 (1.6) years and body mass index (BMI) was 24.4 kg/m^2.

Mean T_{sk} at the center of patella significantly decreased (p=<0.05) achieving a therapeutic range of 10°C to 15°C (Figure 3 and Table 1). Respective decrease for tibialis anterior region did not achieve a therapeutic range. After 20 minutes, in both regions, the T_{sk} remained lower than at the baseline. The results were similar for the entire sample and for each gender. The SSS significantly decreased in superior medial area immediately and in medial joint line areas up to 10 minutes after the intervention (Table 1). Significant differences in SSS were also observed between genders (Table 1 and Figure 2).

DISCUSSION

Although frequently used in the management of injuries and recovery periods in sport, evidence is lacking as to the response in SSS following local cooling at the knee and the effect this may have on somatosensory mechanisms in consideration of proprioceptive feedback. The current study aimed to minimize the gap in knowledge as to the effect on crushed ice application to the anterior aspect of the knee on SSS. This information may be beneficial to further understanding of the impact of cryotherapy applications on neuromuscular feedback responses that can affect proprioceptive acuity and movement control.

Mapping of SSS as a baseline and monitored over a rewarming period of 20 minutes noted significant differences, presenting as a decrease in SSS for the SM section of the knee for whole group data (males and females) when comparing pre-intervention to immediately post intervention data (p=0.04) and 20-minutes post intervention (p=0.04). This concurs with data published in a recent study, whereby participants presented with decreased sensitivity following cooling application, with a lack of tactile sensitivity up to five minutes after the end of cryotherapy (28). Comparison directly between studies however is extremely limited due to location differences of cooling protocols between studies, (28) being assessed in the forearm not the lower limb. SSS in the current study did not return to baseline measurements for whole-group data after 20-minutes. The male only group reported significant reductions in SSS thresholds (p=0.02) for the MP section of the PKPM when comparing pre vs. immediately-post data; female only group recorded reductions in SM section of the PKPM (p=0.02) comparing immediately post to 5-minutes post intervention. An increase in SSS (p=0.02) occurred however between immediately post to 5 minutes post data but SSS did not return to baseline measures even after 20-minute rewarming period. Tsk fell to within therapeutic range recorded at immediately post intervention removal, supporting previous literature (10). Current findings warrant consideration when athletes are immediately returning to functional activity or competitive play following crushed ice cryotherapy applications as reductions in SSS may impair neuromuscular feedback mechanisms that heighten risk of injury.

The findings suggest that compared to lateral sections of the knee, as depicted by the PKPM, the medial regions respond differently through a significant reduction in SSS in comparison. This is reported in whole group data (p=<0.04), male (p=0.02) and female (p=0.02) data at different sections of the PKPM. An explanation of these results may consider the known anatomical structures of the knee, and attention to the neural pathways when comparing lateral to medial regions of the knee. The superficial saphenous nerve branches at the knee into the large infrapatellar nerve distributing over the medial to anterior region of the patella. Local cryotherapy applications report influential neurological changes including the increase in pain tolerance and threshold (3). Conduction velocity is reported to decrease following local cooling due to maintenance of action potential and increased refractory periods (3). A reduction subsequently in sensory perception results in changes in sensitivity due to modifications in neural pathways. In consideration therefore, of the superficial innervation of the saphenous and infrapatellar nerves on the medial aspect of the knee compared to the common fibular (peroneal) nerve on the lateral side positioned deeper and less anteriorly, receptor feedback over the region of the knee may differ in response to cold stimuli and pressure from the crushed ice pack. The difference in levels of reduced cutaneous sensitivity over the various sections as depicted by the PKPM may translate into proprioceptive deficiencies detrimental to knee JPS during functional activity. This however was not quantified in the current study. It may be postulated that deeper joint receptors would compensate for the reductions in skin cutaneous feedback in light of suggestions in current literature (15).

When comparing combined PKPM sections for the whole knee area, average male and female data appears to indicate that female participants had a lower threshold of SSS as a baseline measurement (VFH 5n) compared to males (VFH 1n). In consideration of the somatosensory system, hair and hair follicles play a significant role in

Table 1. Skin surface temperature (T_{sk}) (°C) and surface sensitivity (SSS)

Time point → / Area ↓	Baseline	Immediately after cooling	5 min	10 min	15 min	20 min
Section of PKPM / Monofilament level recorded (Mn)						
QT	2.403	2.983	3.227	2.903	3.045	2.716
SM	3.057[2]	3.682[1]	3.074	3.233	2.949	2.983
SL	2.824	3.449	2.903	2.716	3.403	3.324
LP	3.227	3.676	3.756	3.676	3.557	3.244
MP	2.949[3]	3.534	3.864	3.148	3.318	3.136
LJLA	3.295	3.585	3.091	3.045	3.045	3.545
MJLA	3.028	3.727[1]	3.415[1]	3.619[1]	3.574	3.261
PT	3.852	3.790	3.761	3.977	3.699	3.636
T	3.511	3.699	3.716	3.608	3.932	3.716
Skin Surface Temperature (T_{sk}) (°C)						
Patella center	28.9 (1.2)	13.9 (2.1)[1]	19.2 (1.5)[1]	21.4. (1.3)[1]	23.8 (1.6)[1]	24.1 (1.4)[1]
Tibialis anterior	36.0 (3.6)	33.1 (2.6)[1]	34.3 (2.2)[1]	34.5 (2.0)[1]	34.6 (1.7)[1]	34.5 (1.3)[1]

[1] Significant pre-/post difference for the entire sample; [2] Significant pre-/post difference for women; [3] Significant pre-/post difference for men

sensory feedback triggered by tactile stimuli (30). Generally, female participants presented with less hair on the knee, (over the area covered by the PKPM). Although not glabrous in presentation as the palmar region of the hand is, the reduction of hair over the knee region may have influenced the response from the tactile stimuli of the VFH on the skin surface. It is therefore difficult to compare male and female groups and a limitation in need of consideration in future studies when considering participant populations.

The current study followed a cooling exposure duration of 20-minutes in line with common clinical cryotherapy application recommendations (8). In sporting situations however, it may be unlikely a player is able to ice for a full 20 minutes before returning to play, due to common exposures during competitive play, half-time, pitch-side (8). Future research should consider shorter intervention durations to determine if differences still occur in SSS. Although minimal evidence are available for their use in the assessment of cooling and patterns of SSS at the knee using VFH, literature is accessible in the use of monofilament. Monofilaments have traditionally been used is the assessment of peripheral neuropathy (31), in particular diabetic patients (32). Literature recognizes their use in assessing SSS for peripheral neuropathy assessment some considered to be reliable in the measurement of SSS change (32). The use of VFH to measure SSS at the knee is supported by the current study; however, the encouragement of further research in this remit may develop data on the sensitivity and specificity of this tool for its application in clinical studies of cryotherapy.

Proprioceptive acuity is recognized to be more significantly affected by reductions in afferent muscle spindle feedback compared to cutaneous (14,17,33). Therefore, future investigations may want to consider the combined investigation of the effects of local cooling on SSS and functional joint position sense to note any potential correlation between levels of reduced cutaneous peripheral signals on proprioceptive feedback mechanisms. Further consideration of the assessment of force discrimination post local cooling of distal joints may also provide clarity on the effects of cooling on proprioceptive acuity in consideration of the multiple mechanisms that contribute to its maintenance. This would further the current evidence base on the effects of cryotherapy and whether and when it may be safe to return to functional weight bearing activities following cold exposure.

In consideration of the changes in SSS in different sections of the PKPM it may have been useful to map T_{sk} to individual sections to note any potential correlations between T_{sk} and SSS per section. The development of multiple regions of interest to measure T_{sk} for each segment of the PKMP would need to be established from baseline thermal imaging data capture.

CONCLUSION

Crushed ice application at the knee significantly reduces skin surface sensitivity around the medial aspect immediately post removal. Noted differences in skin surface sensitivity following cooling between males and females occurred. Skin surface sensitivity over the medial aspect of the knee in mixed sex group does not return to baseline after a 20-minute rewarming period following an application of crushed ice for a 20-minute duration over the knee. It is uncertain as to the extent reductions in SSS may have on proprioceptive acuity and further investigations are advised, although therapists should be conscious of changes in skin surface sensitivity that may impede return to play following pitch-side cooling exposures due to the effect on feedback mechanisms controlling joint position sense at the knee.

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Appendix 3b: Copy of Publication 7.

Alexander, J., *et al,* (2020). Comparison of cryotherapy modality application over the anterior thigh across rugby union positions: A crossover randomized controlled trial. *International Journal of Sports Physical Therapy.* 15(2): 210-220.

IJSPT

ORIGINAL RESEARCH

COMPARISON OF CRYOTHERAPY MODALITY APPLICATION OVER THE ANTERIOR THIGH ACROSS RUGBY UNION POSITIONS; A CROSSOVER RANDOMIZED CONTROLLED TRIAL.

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Daniel Birdsall BSc[1]
Prof. James Selfe DSc[3]

ABSTRACT

Background: In deliberation of the diverse physical traits of rugby union and the known interference adipose tissue has on the ability to cool deeper tissues, evidence is required to understand the effect of cryotherapy modalities to provide optimum outcomes post-injury.

Purpose: To investigate differences in the cooling ability of three different cryotherapy modalities in a rugby union population in an attempt to describe optimum cooling protocols for the anterior thigh.

Study Design: Within-subjects randomized control crossover.

Methods: Twenty-one healthy male rugby union players took part. Skin surface temperature measured via thermal imaging camera (ThermoVision A40M, Flir Systems, Danderyd, Sweden) alongside Thermal Comfort and Sensation questionnaires following interventions of either Wetted Ice (WI), Crushed Ice (CI) applied in a polythene bag secured by plastic wrap, or CryoCuff® (CC), applied for 20-minutes over the anterior thigh. Participants were grouped by their typical playing position for the sport of rugby union; i.e. forwards and backs.

Results: Significant differences ($p = < 0.05$) in T_{sk} for all modalities compared to baseline and comparing post T_{sk} between CI and CC ($p = 0.01$) and WI to CC ($p = 0.01$) were displayed. Significantly greater reductions in T_{sk} noted immediately-post in the *'forwards'* group ($p = \leq 0.05$) compared to the *'backs'* group for, all modalities ($p = \leq 0.05$). Thermal Comfort and Sensation scores demonstrated significant changes baseline compared to post for all modalities ($p = < 0.05$). No significant differences were found when comparing between modalities for Thermal Comfort ($p = 0.755$) or Sensation ($p = 0.225$) for whole group or between positional groups.

Conclusions: Physiological responses to cooling differed across modalities with WI producing the greatest decrease in T_{sk}. Significant variability in T_{sk} was also displayed between positional factions. Results uphold the importance of the individualization of local cooling protocols when considering physical traits and characteristics within a rugby union population. Findings provide further understanding of the physiological responses to cooling through T_{sk} quantification in specific populations, helping to guide sports medicine practitioners on optimal cooling application development in sport.

Level of Evidence: Level 2b

Keywords: Cryotherapy, Rugby Union, Thermal Imaging, Movement System

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INTRODUCTION

Selection and application of cryotherapeutic modalities in sport vary, with optimum exposure protocols still under debate in practice when considering clinical effectiveness and thermodynamics.[1,2,3,4] Common cooling modalities include ice variations such as crushed, flaked, cubed, and wetted (typically crushed ice mixed with water); ice packs, gel packs, cold sprays, frozen peas, cryotherapy cuffs (CryoCuff®) and cold-water immersion.[2,5,6,7] Modalities are often applied via several methods for example with or without compression adjuncts. No definitive consensus is available on individual parameters of optimal cooling applications, either clinically or applicable to pitch side injury. Understanding the implications of different local cooling exposures are imperative to the management of sports injuries,[5,8] with inadequate treatment paradigms being potentially detrimental to recovery timelines.[4] Key cellular and physiological changes following cryotherapy are well reported through the of heat extraction from the body to achieve therapeutic effects.[1,9,10,11] This includes an analgesic response and reductions in nerve conduction velocity,[10] metabolism and inflammation.[9] The efficacy of cryotherapy is often investigated through quantification of skin surface temperature (T_{sk}), via thermal imaging.[6,7,12,13,14] To what extent cryotherapy alters temperature of deep muscle tissue is of clinical importance and interest in the literature.[1,15] Although previously argued that T_{sk} was a weak predictor of deeper tissue temperatures,[1] subsequent research presented a significant quadratic relationship between T_{sk} and intramuscular temperature (T_{im}).[3] This developed knowledge regarding the physiological effects of cooling in areas other than T_{sk} relevant to cryotherapy applications in sport. Thermodynamic properties of cryotherapy modalities are reported with differences noted between the cooling abilities of crushed ice, wetted ice, and gel packs.[16] Further differences between frozen peas, crushed ice, gel packs, and ice-water immersion are also reported.[2] In addition, it has been suggested that pre-application modality temperatures do not influence the effectiveness of a cryotherapeutic modality in terms of T_{sk} reduction, however discerning the type of modality to be used with consideration of other variables in clinical decision-making is necessary.[2]

The magnitude of soft tissue temperature change caused by physiological response to cryotherapy is subject to the interaction of four factors.[17] These include consideration of Fourier's Law, length of cooling exposure, heat capacity of the cooled area relating to thermal conductivity, and the thermodynamic properties of the cooling modality.[17] Adipose tissue levels affect the clinical effectiveness of cooling[8] and therefore influence the decisions regarding cooling dose or choice of modality. Although magnitude and depth of cooling into T_{im} have been investigated,[1,2,3,8] research has not explored this in any sport specific context. Early literature examining temperature change in deep tissue inversely relates to skinfold levels (as a measure of body fat) and limb circumference.[18] However, several studies have failed to report on the heterogeneities of participant characteristics or physical properties of the cryotherapy modalities. A clinically important relationship between adipose thickness and required cooling time exists, suggesting that an adjustment to application duration of crushed ice is required to produce similar T_{im} temperature changes, dependent on skin fold measurements.[19] Lipocytes, present in adipose tissue and low in diffusivity and conductivity, conserve heat from underlying tissues therefore acting as an insulating layer.[3] Earlier authors have reported similar observations when exploring relationships between adipose, subcutaneous tissue, and depth of cooling achieved.[18,20] Although, to the authors' knowledge no profiling of T_{sk} data relating physiological responses to cooling within specific sporting positions in rugby union is available. Examining these factors may be useful in the design of appropriate cooling protocols in sporting contexts.

In the sport of rugby union, characteristics vary between playing position[21] demonstrating a diverse range of anthropometric attributes.[22] This multiplicity of bodily appearance across players supports the both the demands of each playing position and performance differences seen across the sport.[22] Homogeneity of form and performance attributes is less common in rugby union, presenting it as an 'atypical' sport in comparison to other team sports,[22] with playing positions commonly referred to as 'forwards' or 'backs'.[23] These positional differences are centered around game demands.[24,25] Subsequently, some authors have presented further differences in movement characteristics in these groups.[26,27] Consistent with previous research on physical traits of rugby union players the current study provides comparison regarding several anthropometric parameters and characteristics, such as body mass, which has been found to be greater in forwards compared to backs.[28] This larger size for forwards corresponds to the consideration of force-generation required in the scrum,[29] with extra mass traditionally consisting of adipose tissue rather than lean tissue.[22] However, in recent years, this has changed with forwards presenting with lower levels of body fat to enable increased mobility generally required in elite level participation.[30] Literature suggests that differences in body fat percentage between levels of play also exist, with non-elite populations presenting with higher levels of adipose tissue.[22] In consideration of the diverse physical traits present in rugby union players and the known interference between adipose tissue and the ability to cool deeper tissues, further evidence is required to determine optimal application of cryotherapy in this population. Additionally, comparison of cooling between commonly applied cryotherapeutic modalities in sport is insufficiently described. Therefore, the purpose of the current study was to investigate differences in the cooling ability of three different cryotherapy modalities in a rugby union population in an attempt to describe optimum cooling protocols for the anterior thigh.

METHODS

Design

Within subjects randomized crossover trial.

Participants

Inclusion criteria required participants to be male, take part in team, competitive rugby union across University, RFU National One or Two English league level. Due to consideration of gender differences in response to cooling an all-male population was sought.[31] All participants were required to Exclusion criteria included any contraindications to cryotherapy,[2] previous knee joint surgery, any lower limb injuries in the prior six months, or referred pain either to or from the knee. All participants provided written consent to take part in the study and completed a Physical Activity Readiness Questionnaire (PAR-Q) prior to participation in the study. The study was conducted according to the Declaration of Helsinki and approved by the host university ethics committee.

Procedures

Data were collected in a rugby union clinical setting with ambient room temperature collected to note any noteworthy fluctuations in room temperature during testing; mean ambient room temperature was recorded at 21.5±1.2°C. A 15-minute acclimatization period-allowed participant temperature equilibrium to take place prior to baseline data collection during which the collection of participants' height, weight, dominant leg, age, and thigh circumference was completed. Skinfold measures using Harpenden Skinfold Callipers (model HSB-BI; Baty International, Burgess Hill, West Sussex, UK), were used to estimate the percentage body fat based on the sum of skin fold thickness for adipose tissue measurements taken from the following sites: thigh, abdomen, medial calf, triceps, biceps, iliac crest, supraspinatus and subscapularis.[32] Quantification of anthropometric assessment commonly considers body fat percentage via the collection of skinfold measurement. Although errors in precision of skin fold testing occur, research suggests that it is common practice in elite groups of athletes across sports.[22]

Participants were randomly assigned following acclimatization, each participant to one method of cryotherapy intervention (Randomisation.com). Prior to application of cryotherapy, baseline measurements were taken, via three T_{sk} images of the anterior thigh, using a thermal imaging camera (ThermoVision A40M, Flir Systems, Danderyd, Sweden) and the mean of these measurements was used for data analysis. The anterior thigh location was chosen as the area to investigate because it is considered as a common site for contact injury, such as a contusion. In order to standardize an area of interest relevant to each participant in consideration of individual size differences and characteristics, wooden markers were applied to the non-dominant anterior thigh that defined a region of interest (ROI). This ROI was formulated by measuring the circumference of the thigh, 50% between anatomical points of the greater trochanter of the femur and lateral joint line of the knee; circumference of the thigh served as the horizontal axis of the ROI.[33] The vertical axis of the ROI measured from the anterior superior iliac spine to the superior pole of the patella.[34] Where horizontal and vertical axes merge, central ROI was determined.[33,34] Superior to inferior borders of the ROI represented as one third of the ASIS to superior pole of patella measurement. Medial to lateral borders of the ROI represented as 25% of the circumference of the thigh (Figure 2).[33,34] Once the ROI was determined, skin was marked with a washable pen and wooden markers applied to the determined locations (Figure 2), and pre-intervention images were taken.

Emissivity of the thermal imaging camera was set at 0.97-0.98 following standard medical protocols. Thermacam Researcher Pro 2.8 software was used to analyse skin temperature images. The thermal imaging camera positioned over a plinth, facing inferiorly to allow participants to remain in a semi-recumbent supine position during application of the intervention and for additional measurements of the T_{sk} over the anterior thigh. The camera was mounted on a tripod arranged at a distance between the camera and participant ranging from 1.5–2.m dependent on limb size for image focus.

Participants were exposed to three different cryotherapy modalities, Crushed Ice (CI), Thigh CryoCuff® (DJO Global, Surrey, UK) (CC), and Wetted Ice (WI) in a random order. Each modality was applied for 20 minutes.[4,19] CI consisted of 800g of crushed ice in a clear 22x40cm 1-mil polyethene bag with excess air removed secured over the anterior thigh with plastic wrap; WI consisted of 500g of crushed ice combined with 500ml of water in a 22x40cm 1-mil polyethene bag secured with plastic wrap; CC prepared using a thigh wrap attachment and the standard Cryo/Cuff® tub filled, half water and half crushed ice to the advised limit. A standard cling wrap held in place the CI and WI during testing. Each exposure was separated by at least seven days,[12] according to the within subjects randomized crossover design study. Subjects were asked to refrain from ingestion of caffeine, food or alcohol and energetic exercise and for at least two hours prior to the application of the icing modalities.[34]

Each participant recorded thermal sensation and comfort ratings[35] pre- and post-intervention for each condition (CI, CC and WI). Thermal sensation[35] was measured by asking the question: *'How are you feeling now?'* Participants responded by grading the sensation of temperature relevant to their anterior thigh, on a standardized scale from -4 to 4 (-4 = very cold, -3 = cold, -2 = cool, -1 = slightly cool, 0 = neutral, +1 = slightly warm, +2 = slightly hot, +3 = hot, +4 = very hot). Thermal comfort[12,36] was determined by asking participants the question: *'Do you find this…?'*. Participants answered using a five-point scale, where 0 = comfortable, 1 = slightly comfortable, 2 = uncomfortable, 3 = very uncomfortable, 4 = extremely uncomfortable. After completion of the 20-minute cryotherapy exposure and removal of the modality, five thermal images of the anterior thigh were taken and used for data analysis.

STATISTICAL ANALYSIS

Data were analyzed using a repeated measures model (SPSS Version 24, SPSS Inc. Chicago, IL), using data pre-exposure as a covariate when comparing between all three applications of cryotherapy, applying least significant pairwise comparisons. The distribution of data about the mean were assessed and found to be suitable for parametric testing for T_{sk}. Non-parametric Friedman tests were used for comparison of thermal comfort and sensation data to explore differences between applications of cryotherapy.[12]

RESULTS

Twenty-one rugby union players (20 ± 2.9 years, body mass 96.2 ± 16.7Kg, height 179.9 ± 7.1cm, BMI 29.7 ± 2.6kg/m2 and thigh circumference 62.5 ± 7.1cm) volunteered to take part in the study (Figure 1).

SKIN SURFACE TEMPERATURE (T_{SK})

T_{sk} *Whole Group*

When comparing whole group baseline T_{sk} to immediately post removal $T_{sk,}$ statistically significant reductions in T_{sk} occurred for all three applications, CI ($p = 0.000$), CC ($p = 0.000$) and WI ($p = 0.000$). A statistically significant difference was observed in T_{sk} when comparing post application CI to CC ($p = 0.000$), with CI producing significantly cooler T_{sk} than CC (Table 1). Additionally, a statistically significant difference in T_{sk} was noted when comparing post WI to CC ($p = 0.01$) with WI producing significantly cooler T_{sk} than CC (Table 1). No significant differences in

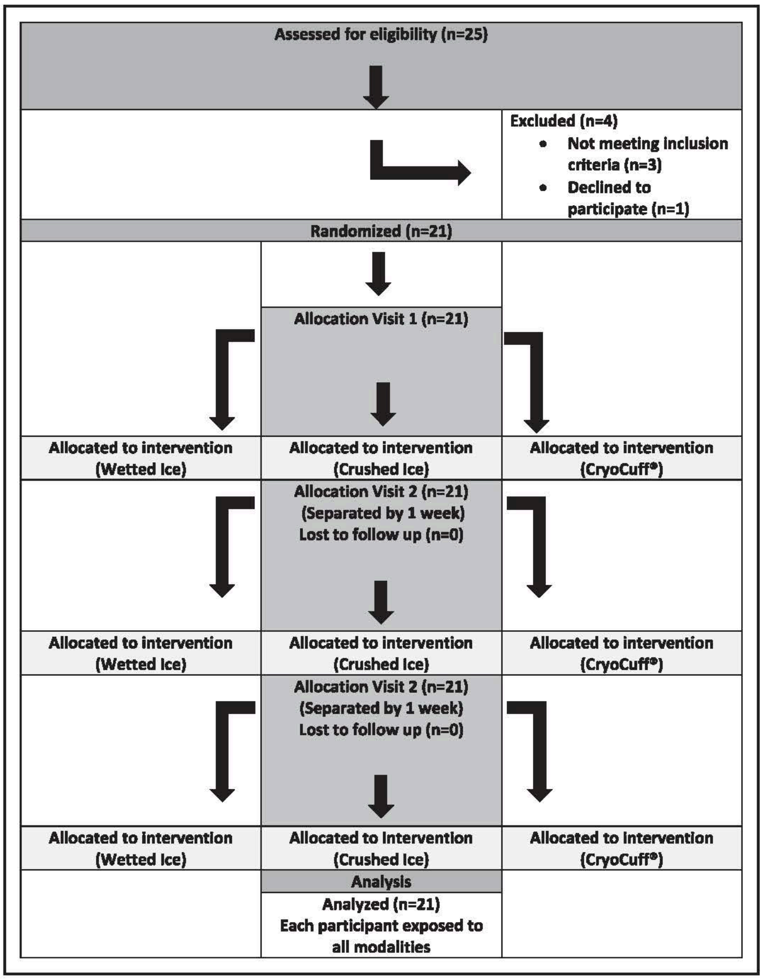

Figure 1. *CONSORT diagram, demonstrating flow of participant recruitment, allocation and analysis.*

T_{sk} were demonstrated when comparing between CI and WI T_{sk} post intervention ($p = 0.141$).

T_{sk} *Comparisons between Forwards and Backs*

Statistically significant differences in T_{sk} were noted when comparing playing positions, with significantly greater reductions in T_{sk} immediately post-intervention in the *'forwards'* position group ($p = < 0.05$) compared to the *'backs'* position group for, all three modalities ($p = < 0.05$), (Table 1).

Thermal Comfort and Thermal Sensation

Whole Group

There was a significant decrease in reported thermal comfort post intervention when compared to pre-intervention measures for CI ($p = 0.014$), WI ($p = 0.014$) and CC ($p = 0.025$). No significant differences were noted when comparing between modalities for thermal comfort ($p = 0.755$). There were significant decreases in reported thermal sensation post-intervention when compared to pre-intervention measures for CI ($p = 0.001$), WI ($p = 0.000$) and CC ($p = 0.000$). No significant differences were noted when comparing between modalities for thermal sensation ($p = 0.225$) (Table 1).

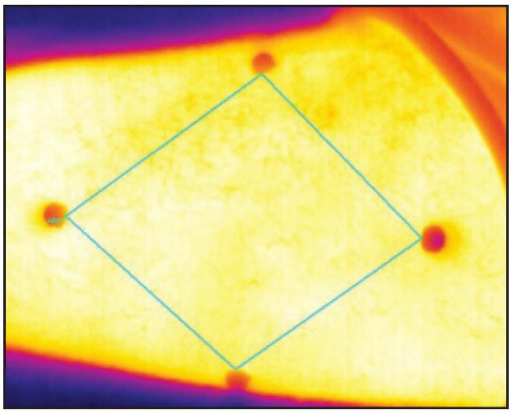

Figure 2. *Region of Interest (ROI) over the anterior thigh of the non-dominant limb determined by percentage circumference and anatomical location points for each participant.*

Thermal Comfort and Thermal Sensation for Forwards and Backs

With data collapsed into positional groupings of forwards and backs, a statistically significant decrease in thermal comfort post-intervention when compared to pre-intervention measures was displayed for WI in the forwards group ($p = \leq 0.05$). No significant change in thermal comfort was displayed for CI or CC in the forwards group ($p = > 0.05$) (Table 1). A statistically significant decrease in thermal comfort post-intervention when compared to pre-intervention measures was displayed for both WI ($p = 0.014$) and CI ($p = 0.014$) in the backs group. No significant change in thermal comfort was displayed for CC in the backs group ($p = > 0.05$) (Table 1). A significant decrease in thermal sensation was observed post intervention when compared to pre-intervention for CI, WI, and CC in both forwards and backs groups ($p = \leq 0.05$) (Table 1). No statistically significant differences were observed in thermal comfort or thermal sensation in both forwards and backs groups, when comparing between any modality ($p = \geq 0.05$).

Table 1. *Skin Temperature (T_{sk}), self-reported scale for thermal comfort and thermal sensation data for whole group, and rugby union positional groups of forwards and backs.*

Participant (Groups)	Body Fat %	Average Thigh Circumference (cm)	Time Point / Modality	T_{sk} (°C)	T_{sk} (p-value immediately post compared to baseline)	Thermal Comfort (Average Score)	Thermal Comfort (p-value immediately post compared to baseline)	Thermal Sensation (Average Score)	Thermal Sensation (p-value immediately post compared to baseline)
Whole group n=21	21.0±6.7	61.5±5.2cm	PRE INTERVENTION	29.9±1.1°C	-	0	-	0	-
			IP (CI)	13.0±2.1°C	p=0.000*	1	p=0.014*	-2	p=0.000*
			IP (CC)	15.8±1.4°C	p=0.000*	0	p=0.025*	1	p=0.001*
			IP (WI)	12.0±3.0°C	p=0.000*	1	p=0.014*	-3	p=0.000*
				-	-	-	-	-	-
Forwards n=12	23.3±6.3	64.3±7.9cm	PRE INTERVENTION	29.2±1.0°C	-	0	-	0	-
			IP (CI)	12.6±2.0°C	p=0.000*	0	p=>0.05	-2	p=0.000*
			IP (CC)	15.3±1.3°C	p=0.000*	0	p=>0.05	1	p=0.001*
			IP (WI)	10.9±2.6°C	p=0.000*	1	p=0.014*	-3	p=0.000*
				-	-	-	-	-	-
Backs n=9	15.4±4.1	57.8±2.4cm	PRE INTERVENTION	30.7±0.5°C	-	0	-	0	-
			IP (CI)	14.5±1.7°C	p=0.000*	1	p=0.014*	-2	p=0.000*
			IP (CC)	17.0±0.8°C	p=0.000*	0	p=>0.05	1	p=0.001*
			IP (WI)	15.4±1.6°C	p=0.000*	1	p=0.014*	-2	p=0.000*
				-	-	-	-	-	-

Tsk = Skin surface temperature. IP = Immediately post cooling. CI = Crushed ice. CC = CryoCuff®. WI = Wetted ice. Thermal comfort scale = five-point scale, from 0-4, a zero response represents a participants feeling of 'comfortable' in response to the cooling temperature of the modality, to level four representing 'extremely uncomfortable'. Thermal sensation scale = the scale grades the sensation of temperature from -4 – 4, with negative values reflecting subjective reporting of cooler sensations and positive values reflecting warmer sensations.
* = Significant difference reported compared to baseline measures.

DISCUSSION

Despite the common application techniques of cryotherapeutic modalities and their use in sports injury management, consensus for optimum protocols are inconsistent across literature.[1,2,3,4] The present study investigated a comparison of three cooling modalities frequently applied in the sporting context for pitch-side management of soft tissue injury in a rugby union population. CI, CC and WI were applied on separate occasions over the anterior thigh in a rugby union population, representing all playing positions, sub-grouped into *'forwards'* and *'backs'*. Results suggest differences in the ability to reduce T_{sk} to within the desired therapeutic range of cooling occurs between cryotherapeutic modalities, in line with similar investigations.[2] Comparison between modalities for whole group data, reported differences in T_{sk}, with WI displaying the greatest reduction of T_{sk} (12.0 ± 3.0°C) and CC offering the least reduction in T_{sk} (15.8 ± 1.4°C) recorded immediately post removal. Evaluation of T_{sk} between the two positional groups; *'forwards'* compared to *'backs'*, demonstrated significant differences in T_{sk} between positional groups and between types of applications ($p = > 0.05$). These findings have implications on optimal cooling protocol development and application choice when applied to a rugby union population.

When comparing whole group T_{sk} data to baseline, most modalities (CI, WI) demonstrated the ability to cool T_{sk} to within the desired therapeutic range of 10-15°C (Table 1).[37,38] T_{sk} findings suggest these modalities may be capable of initiating positive physiological responses within deeper tissues, such as intramuscular cooling determined through observation of T_{sk} in consideration of the proposed quadratic relationship reported in earlier literature.[3] Although, aside from T_{sk} measures, other physiological responses were not quantified in this study, therefore, the suggested responses can only be assumed to occur based on previous literature.[3]

Observations of T_{sk} displayed different responses between modalities supporting previous literature[2,5,17,39] with WI achieving the coldest average T_{sk} in whole group data (12.0 ± 3.0°C) compared to CC and CI. Interestingly, when comparing positional groups, WI application achieved the coolest T_{sk} in the 'forwards' group (10.9 ± 2.6°C), but not in the 'backs' group (15.4 ± 1.6°C) Forwards demonstrated a larger thigh circumference compared to backs (forwards = 64.3 ± 7.9cm; backs = 57.8 ± 2.4cm), which was accompanied by a higher body fat percentage (forwards = 23.3 ± 6.3cm; backs = 15.4 ± 4.1cm). Contrary to what was expected, forwards displayed lower T_{sk} across all modalities compared to the backs. Indicating, that an increased adipose tissue has an effect on superficial T_{sk} responses. Consideration of the process of conduction and the insulating dynamics that adipose tissue presents however provides an explanation as to why participants in the 'forwards' group illustrated lower T_{sk} It could be postulated that heat was more efficiently extracted in the group with lower adipose tissue (backs). Consequently, at the point of application removal (20 minutes) T_{sk} may have already begun to demonstrate 'rewarming' of the superficial tissues in this group (backs) due to efficient heat extraction from deeper tissues. This was represented by higher T_{sk} compared to the forwards group at the same time point. It was considered that the forwards groups displayed cooler T_{sk} because the higher levels of adipose tissue reduces efficient extraction of heat at the same capacity when compared to those with lower levels of adipose tissue. This would agree with earlier assumptions suggesting a dilution of net loss of heat lost to the cold modality[16]. With that in mind we assume that deeper tissues that are also of greater distance from the cooling modality were negatively affected in terms of intramuscular temperature reduction by the levels of insulating tissues. Although this principle is not unknown by any means, the discussion highlights that on the surface although data appears to show more efficient cooling of T_{sk} in the group with higher levels of adipose tissue (forwards) compared to the group with lower adipose tissue (backs), due to cooler T_{sk} reported. We presume on this basis that deeper physiological responses were likely affected differently amongst positional groups in the current study. Findings represent specific sporting populations not previously investigated. Sports physical therapists should consider these implications for optimal cryotherapy protocol development within specific population groups that present with distinct physical characteristic differences in relation to adipose tissue.

Comparison of cooling distribution between modalities as examined visually via thermal imaging may support the post-intervention T_{sk} values (Table 1), with CC demonstrating an uneven distribution in cooling of the anterior aspect of the thigh, compared to WI or CI. This appeared to be consistent among participants, regardless of position. This pattern of cooling may be due to the potential uneven contact between the CC modality and skin surface, potentially facilitated by the compression of the device around the limb when expansion of the wrap commences following the introduction of fluid flow into the cuff. Although considered perhaps as a negative when attempting to achieve a significant or consistent cooling response over skin surface, the CC modality is advantageous in respect to the size of the area covered and the ability to provide circumferential pressure around the entire thigh, compared to the smaller targeted anterior limb region covered by the applications of CI and WI (contained in polythene bags secured by plastic wrap). Optimal compression protocols are unknown and further investigation of contemporary cryo-compressive products are warranted in terms of magnitudes of cooling with the adjunct of compression. Furthermore, investigations that consider targeted treatment vs circumferential over not only muscle but joint structures may be beneficial for future development of optimal cryotherapy protocols in sport.

The differences in T_{sk} between modalities reported in the current study for whole group data (Table 1) may be explained by phase change capability. Phase change in terms of thermodynamics is explained as the efficacy of cooling modalities to absorb heat. Modes of cooling differ in respect to their phase change ability and consequently demonstrated by the magnitude of T_{sk} reduction achieved post application.[16,17] Findings in the current study are in line with previous literature that suggest CI is particularly effective in latent heat transfer.[2] Our results demonstrate lower T_{sk} temperatures for CI and WI compared to CC therefore suggesting greater phase change capability occurring in CI and WI modalities. Clearly the modality of water and crushed ice is efficient in reducing T_{sk}, therefore an explanation as to why CC did not achieve a therapeutic cooling range in whole group data may be explained simply as the poor conductivity of the interface material in contact with the skin consequently affecting the ability of the ice-water to extract heat. Again this may be mitigated by longer application dose, of which needs further investigation to develop optimal contemporary cryotherapeutic modality applications in sport. A dose of 30-minutes CI over the quadriceps in a similar fashion reported by Merrick et al.[16] achieved slightly cooler reductions in T_{sk} suggesting longer applications influence resultant T_{sk} This in turn has an effect on deeper intramuscular temperature. [3,16] In summary the results of the current study suggest that some modalities may be more appropriate for the acute management of sports injuries than others due to their phase change ability.

Thermal comfort and sensation outcomes demonstrated predictable reports in response to cooling and cold temperatures, that being self-reported reductions across both scores (Table 1) for the modalities with lower T_{sk} reductions (WI and CI). The modality with the lesser reduction in T_{sk} (CC) demonstrated no change in comfort scores despite reductions in T_{sk} occurring, however interestingly sensation was reported to increase from 0 (neutral) to 1 (slightly warm), evident across both whole group and sub group data (Table 1). When observing different responses in thermal comfort between forwards and backs, WI achieved the same response being 'slightly uncomfortable'. The backs group also reported this for CI, but forwards reported no change in comfort for that particular modality. With regard to why one application is perceived as more of less comfortable, the findings may be due to the insulating effects of adipose tissue, notably as discussed earlier typically this is higher in forwards compared to backs, which may have influenced level of comfort interpreted. Considering thermal sensation scores, both CI and WI applications influenced a predicated reduction in sensation of temperature in both groups but interestingly the forwards group reported a lower feeling of cold for WI compared to the backs. It is unsure why this occurred but the findings correspond to the observed reductions in T_{sk} reported post removal, that being lower in the forwards than backs (Table 1). Subjective response to cooling in terms of comfort and sensation amongst different modalities has implications on optimal cryotherapy applications.

Further investigation is required, and scores collected during application may be more beneficial rather than those collected once cooling had been removed.

It is difficult to compare current results with other published literature due to the number of variables, such as exposure times, thermodynamics of the modalities, population group, application protocol, and modality location in respect to T_{sk} responses. Although perhaps not directly comparable, the current results are likely relevant to contemporary discussions in the literature regarding optimum cooling protocols used both clinically and pitch-side for the management of injury.[40] Additionally these results offer relevance regarding cryotherapy considerations within specific sporting populations where physical traits vary within a squad. Results support previous literature when considering the impact adipose tissue has on the effects of cooling modalities.[1,8,19] Previous authors have encouraged clinicians to measure skinfold thickness in order to determine an appropriate cryotherapy duration.[39] Adherence to identification, marking, and measurement of the defined site of skinfold testing is essential for accurate quantification of adipose tissue levels.[41] Recommendations for treatment times based on target tissue depth suggest a minimum of 15 minutes of cryotherapy application to achieve 0-15mm target tissue depth for cooling,[40] but does not compare type of modality to best inform potential differences in application. Nor does the current evidence base investigate several modalities within specific sporting populations recognising the varying levels of adipose tissue related to positional characteristics. When collapsing the data into sub groups of forwards and backs, data indicates that adipose tissue levels representative of physical traits in the sport of rugby union affects T_{sk} response (Table 1). Findings are similar to previous literature and consider that adipose tissue levels dictate application dose.[19] With this in mind however it is important to consider that all applications in the current study followed the same duration protocol of 20-minutes, with resultant differences in average T_{sk} post removal. Although dose exposure length (minutes) was not investigated in the current study, it is clear that adaptations in application protocols between modalities to achieve desired cooling should be considered. To achieve optimal treatment outcomes in response to cooling in rugby union populations, adaptations to dose therefore may be required as well as choice of modality, when applied to the anterior thigh. This agrees with previous suggestions in literature in relation to altering cooling dose in respect to adipose tissue levels, although presumptuous in the current study, as dose was standardised.[19]

The choice of cooling modality is an important part of clinical decision making in terms of treatment.[2] Adaptations for individual cooling protocols not only regarding the choice of modality but also regarding the duration of exposure and dosage within safe limits is important. In a much larger sample, of multiple playing positions and elite levels, it may be advantageous to investigate positional subgroups further, such as the characteristics of forwards, such as props and locks compared to back row or hooker positions. Researchers have suggested that movement and game demands differ across playing positions,[25] affecting the physical characteristics and possibly the interference for application of modalities. The development of a framework representing optimal cooling applications requires consideration of multiple variables behind the mechanisms of cryotherapy. This may support individual approaches to optimum cryotherapeutic protocols defined specifically by type of application, adipose tissue levels,[19] the depth of target tissue to be cooled,[40] and the circumference of thigh in rugby union populations for example. Comparison of cooling duration and compression adjuncts in future studies is of merit utilizing contemporary technological advances available in cooling modalities. In consideration of current practice for the management of muscular injury, further development of cooling protocols that investigate contemporary cooling devices should consider the impact on latent intramuscular changes post application, which may fluctuate between modalities as T_{sk} does.

LIMITATIONS

The generalizability of findings may be limited due to the voluntary participation of a healthy all-male population group of rugby union players. Due to differences in thermoregulation, adipose thickness and that all participants were non-injured, the use of these procedures cannot be assumed in other populations, such as those of different academy age, females, or injured populations that may respond differently. Specific consideration of further study of temperature changes that occur in injured populations is required.

CONCLUSIONS

Variability in approaches of cryotherapy application by Sports Physical Therapists, demonstrates a lack of consensus due to limited data to substantiate cryotherapy guidelines.[40] The results of the current study concur with earlier research that suggests that differences in the cooling ability between cryotherapy applications exist. WI was able to produce the greatest decrease in T_{sk} corresponding with self-reported thermal comfort and sensation scores. The greatest implication of the current study supports recommendations to further the research in cryotherapy application to meet therapeutic goals through adaptation of protocols to each athlete.[42] The significant variability in T_{sk} between cooling in the two positional groups affirms the importance of the individualization of local cooling protocols when considering physical traits and characteristics within a rugby union population. Future research may consider extending observation beyond the dichotomy of forwards/backs and to other sports in which variability in physical characteristics vary across a squad.

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Appendix 3c: Copy of Publication 8.

Alexander, J and Rhodes D (2020). Editorial Commentary - Thermography for defining efficiency of cryotherapy modalities in sport. *Temperature.* 8(2):105-107.

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Temperature

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Thermography for defining efficiency of cryotherapy modalities in sport

Comment on: Alexander, J., Selfe, J., Birdsall, D., Rhodes, D. The effects of three different cryotherapy modalities on skin surface temperature across squad positions in a population of male, rugby union players. *Int J Sports Physical Therapy*. 2020;15(2): 210-220.

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Thermography for defining efficiency of cryotherapy modalities in sport

Comment on: Alexander, J., Selfe, J., Birdsall, D., Rhodes, D. The effects of three different cryotherapy modalities on skin surface temperature across squad positions in a population of male, rugby union players. *Int J Sports Physical Therapy*. 2020;15(2): 210-220.

Infrared Thermal Imaging (TI) is well evidenced for the quantification of skin surface temperature (T_{sk}) and abundantly used within cryotherapeutic research [1–4]. We have published several articles recently on the effects of local cryotherapy with the physiological effects quantified through T_{sk} via TI techniques [3,4]. The remit of those studies was based on two key themes: (i) T_{sk} response to contemporary cooling modalities compared to traditional applications (ii) T_{sk} and physiological response to contemporary cryo-compressive devices with varying pressure adjuncts for the management of musculoskeletal injury or as a recovery strategy in sport. Comparison of traditional methods of cryotherapy modalities to modern alternatives in sport provided justification to progress the knowledge in theme (i). Literature to support theme (ii) was evidently lacking and developed naturally to combine multiple contemporary cooling modalities that operate cooling and compression simultaneously. All of which quantified T_{sk} through infrared TI and followed guidance by Moreira et al. [2], for the setup of thermology capture.

Several investigations utilize infrared TI as an objective measure to quantify the efficiency of common cooling modalities used in sport by way of T_{sk}. Preferences on the choice of cooling modality often amount to whether optimal temperatures can be achieved in the target tissues and are quantified via T_{sk}. In our recently published manuscript in the *International Journal of Sports Physical Therapy* [3], we aimed to determine differences in the cooling ability of three different cryotherapy modalities (Wetted Ice, Crushed Ice and CryoCuff®), in a specific sports population through physiological measures of T_{sk} using TI. Physical characteristics vary between playing positions in rugby union due to the demands of the game, and in consideration of this, levels of adipose tissue vary and influence interference on the efficacy of local cooling applications. To date, although studies consider a comparison of multiple cooling modalities, typically methods fail to report heterogeneities of participants or properties of the modality. A therapeutic temperature range for target T_{sk} following local cooling applications of 10–15°C has previously been proposed [1]. This typically represents a T_{sk} range whereby physiological responses occur and are often referred to in publications related to cooling parameters achieved by cryotherapeutic modalities [1]. Results from our study [3] demonstrated differences in T_{sk} response to cooling with wetted ice displaying the greatest reductions. The main findings however highlighted not only the significant differences between T_{sk} when comparing between the three different modalities (Wetted Ice; Crushed Ice and CryoCuff®) but also across playing positions (forward and backs). Results suggest using TI, to determine the effects of such variable (physical characteristics) is useful to consider in relation to the efficacy of cryotherapeutic applications in the assumption that adipose tissue levels vary between these positional characteristics. This may appear obvious, and cooling applications in terms of duration should be altered to account for the insulating effects of adipose tissue. That said, no evidence was available that compared contemporary cooling to traditional methods, nor contemplated the physical characteristic differences in playing position in specific sports populations at the time. Evidently, analysis using infrared TI results indicates that potential phase change differences alongside characteristic variables may both be responsible for variance in target T_{sk} responses [3]. In terms of an applied practical impact, individualization of local cooling applications and choice of modality is imperative for optimal response. From an evidenced-based perspective, findings supported using TI have implications on the development of what may be optimal protocols of cooling in sport through thermology assessment; however, further research is required with methods of analysis considering individual response.

One tenet we did not consider in the study [3] was the effect of compression adjunct to each of the cryotherapy modalities applied. Pressure as a separate outcome was not quantified; however, it is apparent from the literature that compression may aid the magnitude of cooling. Evidently, this has implications on modality choice based on T_{sk} quantification through infrared TI. Therefore, further to this work we investigated cryo-compressive applications measuring T_{sk} following application [4] utilizing T_{sk} measures to determine differences between cryo-compressive modalities and cooling capabilities/magnitudes. This provided key evidence for the theme (ii) presented earlier. T_{sk} results using infrared TI demonstrated differences in the magnitude of cooling between modalities and pressure adjuncts, supporting earlier suggestions. Both studies [3,4] followed current guidelines by Moreira et al. [2] for the use of thermographic imaging in sports and exercise medicine (TISEM). The rationale for discussing both Alexander et al. [3,4] in this commentary was to acknowledge the impact of pressure adjunct noted through T_{sk} from contemporary cooling modalities typically used in sport, quantified through TI. Considering the findings, we propose that infrared TI provides an objective measure to quantify T_{sk} differences between various adjunct pressure options offered by contemporary pneumatic cooling modalities, as a safe noninvasive method. Comparison to other methods of thermology may be justified and while there is significant evidence of its use to quantify cooling applications typically applied in sport, recently the accuracy of TI has been challenged by Maley et al. [5], suggesting overestimation of skin temperature through re-warming periods using TI. A counterpoint made by Havenith and Lloyd [6], in the same journal however suggests this cannot be strongly affirmed based on current evidence. Furthermore, with their methods being anatomically specific to the upper limb [5], findings may not be translational across other regions, i.e. the measurement of T_{sk} was performed over the upper peripheral limb, hand, and fingers, not the lower limb such as in our studies [3,4] and the aim of their data was to compare against a skin thermistor. Although the authors might suggest that future studies should contemplate potential overoptimization of peripheral T_{sk} through TI during rewarming periods and make appropriate adjustments where necessary to risk/withdrawal criteria [5], there are many approaches in which the accuracy of thermographic cameras can be improved for their use in cryotherapeutic studies including; camera configuration, utilization of reference values, greater number of temperature pixels or advanced camera technology, summarized by Havenith and Lloyd [6].

In summary, TI is useful in quantifying the physiological effects of cooling modalities on T_{sk}; however, approaches for its use are dependent on the aim of the research. Individual measures of TI may provide useful data however future studies should consider multiple metrics that represent relevant parameters of investigation in sports-related cryotherapy investigations, beneficial simultaneously to infrared TI measures. Many studies do represent this, and we hope that future study design in our research group will continue to provide data with translational outcomes when investigating cooling protocols in sport. Consideration of individual response analysis rather than group average data is also important and would eliminate positional differences (as one example). Future studies could achieve these investigations through the utilization of multiple metrics combining physiological, such as TI, biomechanical and psychological measures, and individual data analysis, with the aim of greater impact to practice through optimal individualized approaches for contemporary cryotherapeutic applications. Evidently, infrared TI is beneficial in challenging preferences of contemporary cooling applications in sport through thermography for decision- making; however, further validation of methods is welcomed to provide accurate measurement of T_{sk} in the lower limb.

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6.4 Appendix 4: Theme 4 Publications: CONTEMPORARY CRYOTHERAPY APPLICATIONS AND RESPONSES

Appendix 4a: Copy of Publication 9.

Alexander, J., *et al,* (2021). Cryotherapy in Sport: A Warm Reception for the Translation of Evidence into Applied Practice. *Research in Sports Medicine.* 10: 1-4.

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Cryotherapy in sport: a warm reception for the translation of evidence into applied practice

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ABSTRACT

Research contributing to the understanding of the mechanisms that underpin cryotherapy application in sport are evident. The translation of impactful findings that contribute to the design and implementation of cryotherapy protocols which are advantageous to the athlete in an applied sport setting, however, are still being explored. The role of cryotherapy for acute sport injury management is challenged in recent literature and discrepancies around the periodisation of cooling to maximise injury management or recovery, contribute to the confusion around optimal applications of cryotherapy in sport. The purpose of this work was to provide a contemporary summary of current perspectives, challenges and approaches for the use, application and translation of cryotherapy evidence into applied practice in a sporting context. The intention being to stimulate further debate on the topic and highlight key considerations for future study designs that reflect current practices. For improved translation of evidence for or against the use of cryotherapy in sport, it is suggested that future study design and methodologies should reflect contemporary demands within sporting environments where cryotherapy protocols for injury, rehabilitation or recovery are a feature of athlete management through investigation of individual response, and multi-measures of well-being and performance.

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KEYWORDS
Injury; cooling; research; musculoskeletal; pain

The precise mechanisms behind cryotherapy applications for acute sport injury management are complex and remain to be fully elucidated due to multiple factors affecting "optimal" application in sporting contexts. Consequently, debate in the literature surrounding the efficacy of cryotherapy for sport injury management is evident and ongoing. Despite the common application of cryotherapy and understanding the mechanisms underpinning cooling available, confusion still exists in terms of the translation of underpinning mechanisms into optimal protocols advantageous to the athlete in an applied setting. Recently, Long and Jutte (2020) raised concerns regarding unverified claims on the negative comments against the use of cryotherapy in sport and health settings for acute soft-tissue injury. In the field of sports medicine and performance, practitioners should be cautious of unverified claims without consideration of best practice; more

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Table 1. Progression and explanation of acronym development, which incorporate cryotherapy (in local form "ice") for acute injury management and accompanying reference for summary.

Acronym	Explanation	Supporting reference
ICE	Ice, Compression and Elevation	Bleakley et al. (2012).
RICE	Rest, Ice, Compression, Elevation	Bleakley et al. (2012).
RICES	Rest, Ice, Compression, Elevation and Stabilization	Long and Jutte (2020).
PRICE	Protection, Rest, Ice, Compression and Elevation.	Bleakley et al. (2011).
POLICE	Protection, Optimal Loading, Ice, Compression and Elevation	Bleakley et al. (2012).
PEACE & LOVE	Protection, Elevation, Avoid Anti-Inflammatories, Compression, Education & Load, Optimism, Vascularization and Exercise.	Dubois and Esculier (2020).

importantly however, this raises the need for sustained, real-world implementation of translational knowledge into applied settings, which is lacking despite many robust and excellent studies available on the topic of cryotherapy application in sport. The successful act of bridging the gap between academia/science (research) and practice is recently acknowledged by Owoeye et al. (2020), highlighting the importance of "theory-driven translational research" to guide applied and current practices. Although high-quality research in the generalized topic of cryotherapy aims to reduce subsequent scepticism amongst practitioners influenced by weak, unverified or outdated approaches, methodological designs in "discovery research" that reflect current applications, encompass multi-measures and acknowledge several mechanisms of cryotherapy should be implemented which will consequently support translation of research findings successfully, whether for or against its use in sports injury management.

This leads on to highlight the current perspectives on contemporary cryotherapy applications are evolving and include recently published acronyms such as "PEACE & LOVE" (Dubois & Esculier, 2020) (Table 1), whereby the suggestion of removing cryotherapy from acute injury management is presented. Alternatively, Long and Jutte (2020) recommend cryotherapy as part of treatment protocol based on grounded physiological evidence, yet refer only to the historical acronym of "RICES" for practitioners to follow in terms of justification for cryotherapy application. As the authors suggest, there is a clear need to clarify twenty-first-century attacks on cryotherapy due to confusion amongst practitioners, and therefore, it seems pertinent to acknowledge the progressions of "RICES" to "PRICE", "POLICE" and most recently "PEACE & LOVE" acronyms (see full summary in Table 1) to provide a transparent presentation of contemporary approaches for/against its use in acute injury management. The latter acronym of PEACE & LOVE (Table 1) is suggested as a continuum of acute sport injury (PEACE) and rehabilitation (LOVE) management (Dubois & Esculier, 2020), yet not mentioned in the work by Long and Jutte (2020). Interestingly, Long and Jutte (2020) cite a robust evidence base supporting the use of cryotherapy to control the inflammatory process that occurs as a result of soft tissue injury. In contrast, Dubois and Esculier (2020) suggest that there is no strong evidence base to provision this approach. Importantly, these studies draw opposing conclusions in relation to the efficacy of cryotherapy on inflammatory response, yet consequently the evidence cited in both pieces of work questions the conclusions drawn. The elimination of cryotherapy ("ice") completely from acute sports injury management requires further investigation and contradicts earlier literature supporting the justification of ice within acronyms such as POLICE based on cold-induced analgesia (Bleakley et al., 2012). It is known that cooling has a beneficial effect on the perception of pain through the slowing of neural conductance velocity, with sensory neurons affected ahead of motor neuron contraindications on functional movement are secondary to the reduction of perceived pain (White & Wells, 2013). Hence, it is important to note the surrounding benefits of such modality in an applied practice situation for pain management alone following sport injury. Yet, the many acronyms presented in the literature only aid to the confusion in practice, and this communication hopes to stimulate the development of new research that rigorously examines such recommendations to provide clarity on the understanding and accuracy of credible evidence-based literature which influences applied practice.

Discrepancies in the role of cooling for sport injury make it difficult for practitioners to apply optimal applications in sport. Some approaches in studies may inhibit the translational delivery of findings into practice, perhaps due to methods not representative of an applied performance nature. Furthermore, several variables, such as dose–response or periodization of cooling, for example, which influence optimal sports injury mechanisms still require clarity. Peer-reviewed research reflecting contemporary cryotherapeutic approaches that challenge outdated concepts is important to develop modern-day practices and is required to bridge the gap between academia (research) and applied practice. The consideration of practices only becoming "evidenced based" may relate to methodologies in translational research which truly reflect current applied approaches and, as suggested by Owoeye et al. (2020), are executed through context-specific dissemination and implementation study design. Mechanisms behind cryotherapy include physiological, biomechanical, biochemical and psychological well-being responses and consequently play a part in optimal applications/protocol designs of such therapeutic modalities and should be investigated in synthesis. Conceptual approaches in cryotherapy research design considering ecological context and best translation of findings to key audiences are supported.

Optimal applications of cryotherapeutic modalities in sport are important to ensure maximum physiological benefit for injury and competitive advantage for performance. Holistic, multifactorial approaches to sports injury management and recovery are welcomed; however, if sports practitioners are encouraged to base their justification for therapeutic modality use on the best available evidence, then further research to support or refute contemporary approaches is warranted. Long and Jutte (2020) provide a relevant argument in support of cryotherapy, yet alternatively Dubois and Esculier (2020) provide constructive challenges to historical approaches for the optimal "timing" of cryotherapy for acute sport injury management. Contention, however, between whether the use of cryotherapy "does or doesn't work" is a simplistic and disputed approach as to its many positive beneficial mechanisms which are advantageous to the athlete. For the development of optimal cryotherapeutic protocols for sport injury, rehabilitation or recovery, methodological design of future studies incorporating biomechanical, biochemical, physiological and psychological mechanisms which reflect current multi-measures of performance and the examination of contemporary modalities with analysis which reflects individual response to interventions may provide more effective transfer of contemporary knowledge into applied practice due to the resemblance of current cryotherapy use in sport.

Disclosure statement

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Appendix 4b: Copy of Publication 10.

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IJTR REVIEW

Cryotherapy and compression in sports injury management: a scoping review

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Abstract

Background/Aims For the management of sports injury, cryotherapy is commonly applied, yet modalities differ extensively in application including levels of compression. The aim of this study was to provide a comprehensive review of the current position in the literature on contemporary cryo-compression applications for musculoskeletal sports injury management.

Methods A total of eight databases were searched: Sport Discus, Science Direct, CINHAL, Scopus, PubMed, Cochrane, ProQuest and MEDLINE. Publications were restricted to 30 years and had to be in the English language. Medical subject headings, free-text words, and limiting descriptors for concepts related to cryotherapy and compression for sports injury were applied. Inclusion criteria determined at least one modality of cryotherapy treatment applied simultaneous to compression or as a comparison, relevant to sports injury management. Modalities included cryo-compressive devices and gel/ice packs, in association with concomitant compression. Male, female, healthy and injured participants were included. Two reviewers independently selected eligible articles, resulting in 22 studies meeting the inclusion criteria following full-text appraisal.

Results Inconsistent methodologies, low sample sizes and variability in outcome measures provided uncertainty over optimum protocols. A lack of previous understanding in the protocols in the available literature for isolated cryotherapy/compression applications prevents understanding of the therapeutic benefits of combined cryo-compression. No definitive agreement behind optimal cryo-compression applications were identified collectively from studies other than the consensus that compression aids the magnitude of cooling.

Conclusions Although compression appears a useful adjunct to cooling modalities for the management of sports injury, no definitive agreement on optimum compression concurrent with cooling protocols were drawn from the studies. This was because of several methodological gaps in reporting throughout studies, highlighting a lack of studies that represent applications of compression and cryotherapy within a sporting context or applied nature within the available research.

Key words: Cooling; Cryo-compression; Modalities; Musculoskeletal; Physiological

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Introduction

An inflammatory response to musculoskeletal soft tissue trauma presents with characteristics that include pain, oedema and a proliferation in heat from increased blood flow (Capps and Brook, 2009; Rigby and Dye, 2017). The simultaneous application of cryotherapy and compression is thought to alter the inflammatory response by initiating therapeutic benefits (Capps and Brook, 2009). Cryotherapy often follows the Protect, Rest, Ice, Compression and Elevation (PRICE) guidelines (Bleakley et al, 2011), which has evolved into the mnemonic of 'POLICE' (Protection, Optimal Loading, Ice, Compression and Elevation) management (Bleakley et al, 2012). The purpose of cryotherapy is to lower tissue temperatures and occurs through the thermodynamic principles of heat withdrawal from deeper tissues (Chesterton et al, 2002). The rationale for cryotherapeutic application varies dependent on the aim (Bleakley et al, 2004), for example, immediate injury applications (Swenson et al, 1996; Mora et al, 2002; Galiuto, 2016), rehabilitative management (Bleakley and Hopkins, 2010) or post-exercise recovery (Du Pont et al, 2017). Physiological effects

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Table 1. Key variables to consider that may influence the optimisation of cryo-compressive applications		
Dose (duration)	**Aims of treatment**	**Adipose tissue levels**
Dose (frequency)	Response (biomechanical)	Location of cryo-compression
Dose (volume/mass)	Response (physiological)	Sex
Timing	Response (perceptual/ psychological/wellbeing)	Intensity (depth of immersion)
Surface contact (targeted/circumferential)	Response (biochemical)	Mode of cooling (in isolation)
Temperature (modality/target tissue temperature/controlled)	Individual response	Mode of compression (in isolation)
Phase change capability	Compression type (static/ intermittent/continuous)	Mode of cryo-compression (simultaneous)

of cryotherapy include analgesia (Ernst and Fialka, 1994), decline of nerve conduction velocity and metabolism (Bleakley et al, 2004; Nadler et al, 2004; Ho et al, 1995; Algafly et al, 2007), reduction of inflammation (Pournot et al, 2011) as well as decreased vascular permeability and vasoconstriction (Gregson et al, 2011).

Although widely accepted for use in sports injury management, cryotherapy modalities differ extensively and it is unknown as to whether an agreement exists concerning optimum protocols of using cryotherapy, with or without the addition of compression. The effectiveness of cryotherapy modalities may differ because of several variables (Table 1), which include:

- Efficiency (Merrick et al, 1993)
- Location (Kennet et al, 2007)
- Dosage frequency (Jutte et al, 2001)
- Contact area (Janwantanakul, 2009)
- Phase change and enthalpy of fusion ability of modalities (Merrick et al, 2003; Kwiecien et al, 2020)
- Level of compression (Alexander et al, 2020a)
- Targeted vs circumferential application (Alexander et al, 2021a).

Furthermore, the influence of external factors such as adipose tissue levels, desired target tissue temperature and therapeutic responses (Rupp et al, 2012) advocate that protocols should be modified on an individual basis to achieve greater outcomes and optimisation of response in sporting contexts (Alexander et al, 2021a).

Independently, compression aims to control oedema, decrease overall blood flow (Kraemer et al, 2004) and reduce clinical symptoms such as swelling or pain (Song et al, 2016). Principles behind the effects of external compression include the capacity of influence it has on the lymphatic system, including pressure gradients, gravity, contraction of skeletal muscle and reduction of oedema (Kraemer et al, 2004; Ostrowski et al, 2019). Compression is used to treat sports injuries because of its ability to manipulate external and internal capillary pressure, thus minimising the accumulation of swelling, reducing haematomas and providing mechanical support (Kraemer et al, 2004). Mechanical support through compression is important for recovery processes and achievable because of dynamic immobilisation. The literature suggests that this is because of improved neural input during compression applications (Kraemer et al, 2004). Pneumatic, static and intermittent compression, in association with several levels of pressure, are described across some of the studies reviewed in the present study (Mora et al, 2002; Janwantanakul, 2006; Knobloch et al, 2007, 2008; Holwerda et al, 2013; Ostrowski et al, 2018; Kwiecien et al, 2019), with compression as low as 14 ± 2 mmHg reported to affect the extent of cryotherapy modalities (Kwiecien et al, 2019).

Despite publications that have investigated simultaneous cryotherapy and compression applications (Holwerda et al, 2013; Du Pont et al, 2017; Kwiecien et al, 2019; Ostrowski et al, 2019), a lack of clarity is still evident for single applications of cryotherapy and compression. For the two modalities of cryotherapy and compression, the optimum dose for either application is not presently known. Therefore, it is difficult to determine potential combined interaction effects because of the complexity of multiple variables. Evidence for the combined application of cryotherapy and compression is lacking through applied studies, and its use in sport is commonly anecdotal (Kraemer et al, 2004).

Methodologies that isolate one of the variables (cryotherapy) with the other applied simultaneously (compression) may help to determine the effect of simultaneous application through quantification. Therapeutic effects gained from cryotherapy application combined with compression may play an extensive role in the recovery of tissue injury. Notably, former research considers the adjunct of compression with cryotherapy as positive, reporting beneficial outcomes through further reduction of tissue temperature (Merrick et al, 1993; Tomchuk et al, 2010) or recovery enhancement (Du Pont et al, 2017). Many recent technological advancements in cryo-compressive devices are available and allude to the physiological benefits of combining the two. The purpose of this scoping review therefore was to produce a comprehensive review of the present position in the literature on contemporary cryo-compression applications for musculoskeletal sports injury management.

Research question

What is the present position in the literature on contemporary applications of cryotherapy and compression for the management of musculoskeletal sports injuries?

In order to determine whether a systematic review would be of value to conduct, a scoping review was decided on initially to explore the available evidence over a broader topic area. With the aim to produce a comprehensive review of the present position in the literature on contemporary cryo-compression applications for musculoskeletal sports injury management, objectives determined three key outcomes:

1. To examine present research and summise the available evidence base for the applications of simultaneous cryotherapy and compression modalities typically applied in the management of musculoskeletal sports injury
2. To establish whether agreement exists in the optimal application of simultaneous cryo-compressive protocols for the management of musculoskeletal sports injuries
3. To highlight knowledge gaps in the present evidence base surrounding contemporary cryo-compression applications for musculoskeletal sports injury management that may help inform future research in the topic area.

Methods

Design and search strategy

This scoping review was conducted in accordance with the Preferred Reporting Items for Scoping Reviews (PRISMA-ScR) guidelines. Directed by the Arksey and O'Malley (2005) framework for scoping reviews, the following steps were completed:

- Identifying the research question
- Identifying relevant studies
- Determining inclusion/exclusion criteria and applying these
- Charting the data
- Collating, summarising and reporting the results (Arksey and O'Malley, 2005; Levac et al, 2010).

Two authors (JA and DR) performed searches to identify relevant studies. Sources searched included electronic databases, reference lists and the hand searching of key journals. The databases included: Sport Discus, Science Direct, ProQuest, CINHAL, Scopus, PubMed, Cochrane Library, and MEDLINE (via OVID), searched between 31 March to 1 September 2020 and a further search on 25 May 2021 to capture any new and relevant articles. A 30-year date (1990–2021) restriction representing the development of physiological justification of cryotherapeutic modalities in sport was applied to the search strategy and captured contemporary development of cryo-compressive modalities. Grey literature searching followed the initial database searches using ProQuest and Open Grey. Search terms included a mix of medical subject headings (MeSH), free-text words, and additional limiting descriptors for key concepts related to cryotherapy and compression for musculoskeletal sports injury. MeSH search terms for the Cochrane Library Database and Scopus searches did not apply; however, conditions of the search were carried out identically between those databases. A broad range of available literature established through wide classification of key words follows recommendations for scoping review methods (Arksey and O'Malley, 2005).

Inclusion and exclusion criteria

If at least one modality of cryotherapy treatment was applied simultaneous to compression or as a comparison to compression alone, the study was included. The application of simultaneous cryotherapy and compression in post-operative or surgical musculoskeletal management studies were not included. Cryotherapeutic treatment modalities could include any cold compression device or gel packs or ice (wetted/crushed/flaked/cubed) secured with elastic wraps or bandages that suggested concomitant mild, moderate or high compression. Studies could include both men and women, healthy or injured participants. The inclusion of studies that represented healthy participants was justified because of the limited availability of evidence for cryo-compressive applications on injured populations. Further inclusion criteria comprised articles written in English and all types of research from the last 30 years.

Exclusion criteria included articles with applications tested on animals, the inability to locate or access full-text articles or any study reporting post-operative application of cryo-compression modalities.

The search strategy was performed by JA and DR independently, and any disagreement relating to the inclusion or exclusion of literature was discussed afterwards. Figure 1 details the full process of article review. Screening of titles and abstracts indicated the subsequent reviews of full texts initially. If the title or abstract did not reveal enough information to determine appropriateness for inclusion to the scoping review, the full article was retrieved for full text review to determine inclusion. Articles were summarised and charted as per the combined framework by both reviewers independently (Arksey and O'Malley, 2005;

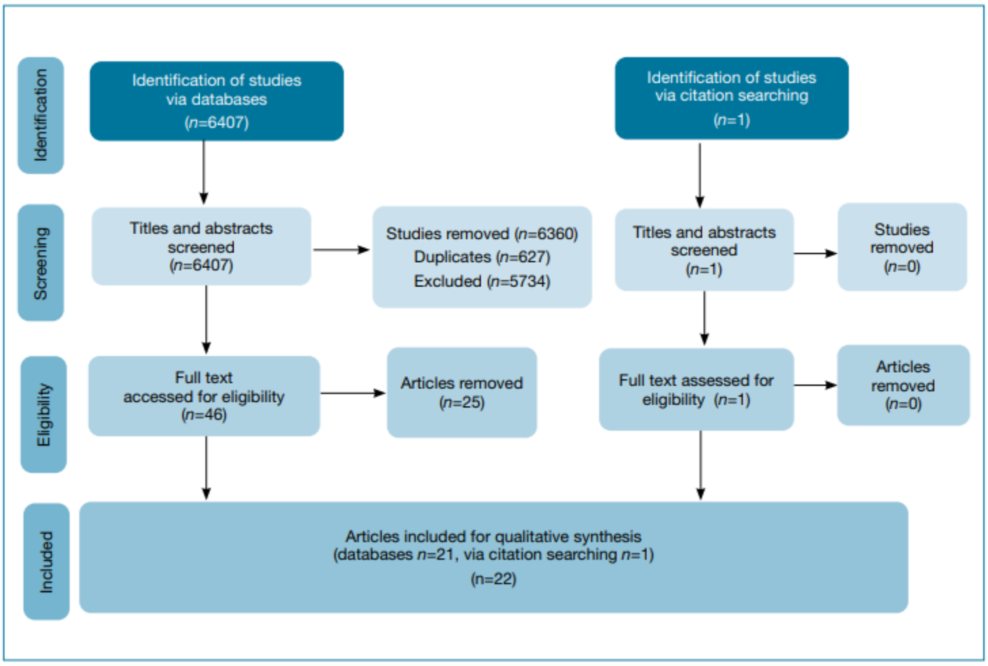

Figure 1. PRISMA flow diagram of included studies.

Levac et al, 2010). Manual cross-referencing was performed after all titles and abstracts from the search were downloaded to Excel to prevent any duplication of studies or missing literature. Reference lists examined from all articles identified additional potentially relevant research. Appropriate studies were assessed independently by both reviewers (JA and DR) and were included if they met the inclusion criteria. If any disagreements arose between reviewers, these were resolved by discussion and if any differences remained, a third reviewer (OG) settled any arbitration. No disagreements regarding the inclusion or exclusion of any publication occurred during the review process.

Data extraction

Extraction of data was completed by one reviewer (JA) and to ensure accuracy, data were assessed by a second reviewer (DR). A narrative synthesis was produced following the extraction of data to provide a summary description for each study, which included type of compression, cooling, dose in terms of cooling and compression (Appendix 1).

Results

From the initial searches, 6407 articles were found. After removing duplicates and studies deemed not appropriate from title and abstract screening, 46 potentially eligible studies remained. Full text review excluded a further 25 articles, with one additional article located through citation searching, leaving a total of 22 full text papers (Figure 1). A summary of characteristics and data extraction for articles included in the scoping review are represented in Appendix 1.

Study characteristics

The scoping review identified a wide variation in research design alongside several methodological differences and several variations in outcomes measures were found. The types of studies included:

- Systematic reviews (Bleakley et al, 2004)
- Observational studies (Wilkerson and Horn-Kingery, 1993; Janwantanakul, 2006, 2009; Knobloch et al, 2006a, b, 2007; Hawkins et al, 2012; Holwerda et al, 2013; Williams et al, 2013; Du Pont et al, 2017; Rigby and Dye, 2017; Ostrowski et al, 2018, 2019; Kwiecien et al, 2019; Alexander et al, 2020b)
- Randomised controlled trials (Merrick et al, 1993; Mora et al, 2002; Knobloch et al, 2008; Tomchuk et al, 2010)
- Narrative reviews (Capps and Brook, 2009; Block, 2010).

Largely, studies presented with low sample sizes or no control group, which may have reduced the ability to draw meaningful conclusions from individual investigations. Although a mix of male (*n*=229) and female (*n*=173) participants was evident across studies (mean age: 26.4 ± 8.5 years), mostly were predominantly of young male adults and yielded a total population of ~400 participants. This represented an average number of 22 participants per study reported. From the 22 papers presented, only 11 publications reported compression dose (mmHg) and 18 reported how long the interventions were applied (minutes).

Minimal overlap in study findings were noted because of the disparity in methodological processes, protocols investigated and outcome measures defined. Modalities across the studies included Cryo Cuff (*n*=5), Game Ready (*n*=5), Koldblue Cryo Bandage (*n*=2), ice bag (wetted, chipped, crushed, or salted) (*n*=11), Aircast with Cryo/Strap (*n*=1), Squid Go (*n*=1), Hyper Ice (*n*=1), gel pack (*n*=1), Aquilo Sports Cryo Compression (*n*=1), Power Play and wetted ice (*n*=2) and Power Play and gel pack (*n*=1). Some studies documented the levels of compression (mm Hg) and targeted skin surface temperature (T_{sk}) values within the method protocols; however, many failed to successfully report such details so that efficacy could not be determined. The studies that reported pressure values of compression adjuncts reported values that ranged from 5–75 mmHg, with consistent or continuous, pulsatile or intermittent variances in application techniques. With exclusion of the three review studies, all articles reported the length of cooling exposure. Exposure time varied between studies, ranging from 15 to 30 minutes. Some articles reported protocols that included a recovery period and repetition of multiple exposures, while others reported a single exposure of cryo-compression. Several different types of wrap were identified across studies, including elastic or plastic wraps, or custom designed sleeves held circumferentially with Velcro. The most commonly investigated protocols reported continuous pressure, at high levels (>50 mmHg) and 30-minute exposures with ice bag applications held in place with elastic or plastic wrap or the GameReady device; however, the type of ice (ie crushed, wetted, salted) was not always reported. Despite this, collective findings are not suggestive that these components are the most applicable to the management of musculoskeletal sport injury. Many do not reflect typical half-time or pitch-side use in terms of time and impact the feasibility of evidence-based knowledge into applied practice. However, the benefits of simultaneous compression adjuncts were acknowledged in all articles based on greater magnitudes of cooling ability with compression than without. Clarity of agreement on what may be the optimal application for cryo-compression was therefore difficult to establish.

Discussion

Studies generally indicated that cryotherapeutic modalities are one of the most commonly applied therapeutic modes used for musculoskeletal trauma management in sport, and the physiological responses of cold applications are well reported (Merrick et al, 1993; Ho et al, 1995; Jutte et al, 2001; Algafly et al, 2007; Bleakley et al, 2011; Gregson et al, 2011; Ostrowski et al, 2019). With several studies recognising the traditional principles of PRICE (Block, 2010; Bleakley et al, 2011; Bleakley and Hopkins, 2010; Galiuto, 2016), the adjunct of compression to cryotherapy appears beneficial across most articles, which acknowledged the positive effects of compression on the magnitude of cooling (Wilkerson and Horn-Kingery, 1993; Mora et al, 2002; Janwantanakul, 2006; Knobloch et al, 2006a; 2008; Capps and Brook, 2009; Tomchuk et al, 2010; Du Pont et al, 2017).

Differences between the terms 'mild', 'moderate' and 'high' levels of compression however were poorly defined within the literature with regards to the actual pressure (mmHg). Additionally, the failure to report T_{sk} values in several studies presented limitations in recognition of whether modalities met therapeutic T_{sk} ranges identified in previous literature (Kennet et al, 2007) for physiological effects to take place. The non-reporting of either pressure (mmHg) or T_{sk} has repercussions on the ability to define optimal protocols through objective measures of tissue response. However, studies published within the last 5 years (Rigby and Dye, 2017; Ostrowski et al, 2018; 2019; Kwiecien et al, 2019; Alexander et al, 2020b) all successfully reported measures of pressure (mmHg), T_{sk} and in some cases intramuscular temperature (T_{im}), apart from one article (Du Pont et al, 2017), demonstrating progressive methodological detail and recent popularity in the use of contemporary cryo-compressive modalities. One consideration making it difficult to assess the quality of studies is the lack of quality appraisal, for example with studies that are prone to bias through weak methodologies. The generalisability of findings was difficult because of the heterogeneous nature and flaws across methodologies; however, many studies concluded that there is potential to use contemporary cryo-compressive modalities.

This scoping review supports earlier work that highlighted that poor agreement across multiple studies may be because of the different combinations of cooling and compression applied and population groups investigated (Bleakley et al, 2004). A limitation across some of the literature in this scoping review refers to the inclusion of only healthy non-injured participants (Knobloch et al, 2006b; Janwantanakul, 2006; 2009; Hawkins et al, 2012; Holwerda et al, 2013; Rigby and Dye, 2017; Kwiecien et al, 2019). It is important to consider that different results may occur in response to simultaneous cooling and compression between healthy and injured tissues. Findings highlight minimal investigations available on the combination of treatment (cryotherapy and compression) for acute musculoskeletal sports injuries. However, until protocols are better understood in normative uninjured populations, metabolic changes associated with injury may be another variable to consider in the dose–response concept of cryotherapy or that of simultaneous cryo-compressive applications.

Different applications of compression exist, such as pneumatic or manual, intermittent or static. From the literature reviewed, it appears that both pneumatic and manual approaches may enhance the effect of local cooling across various cryotherapy modalities. That said, most methods of cryotherapy cannot be applied in isolation, for example there must always be some level of concomitant compression. Continuous compared to intermittent compression simultaneously applied with cold appeared more favourable, albeit weak in the two studies where this was reported, when comparing multiple modalities (Holwerda et al, 2013; Ostrowski et al, 2019), although Ostrowski et al (2019) noted equivalent T_{im} decreases across the comparison of salted ice bag with continuous elastic wrap compression, with intermittent compression via Game Ready, or PowerPlay devices. However, it is highlighted that application is dependent on treatment goals and stages of rehabilitation (Ostrowski et al, 2019), considered in relation to healing processes and physiological responses. When choosing between intermittent vs continuous compression applications, the consideration of physiological responses, such as oedema formation, were noted (Ostrowski et al, 2019).

Although the studies reviewed were in favour of continuous compression in reducing T_{sk} compared to intermittent pneumatic compression, this was only conclusive in two studies (Holwerda et al, 2013; Ostrowski et al, 2019). With distinct differences in outcome measures between the studies (Holwerda et al, 2013; Ostrowski et al, 2019), definitive conclusions were unable to be drawn without further investigation, suggestive of multiple modality, compression (level and mode) and relevant outcome measures study design, suitable to inform practice. Despite the availability of studies that also compared intermittent, pneumatic and static compression (Knobloch et al, 2008; Capps and Brook, 2009), physiological outcome measures differed, therefore making it difficult to directly compare the results. As highlighted earlier, a key deficiency observed across several study methods alludes to the lack of pressure (mmHg) reporting. With only 12 studies out of 22 presenting this information (Table 3), it is difficult to identify whether differences in compression dose or application resulted in the variable responses in those studies that failed to report such information. Therefore, with agreement not easily achieved, optimal cryo-compressive protocols are non-existent; further research is required in this area through study design and methodological protocol development.

From the studies reviewed, physiological responses to simultaneous cryo-compressive applications were reported; however, little is known about the effect these applications may have on biomechanical, perceptual or biochemical responses. Williams et al (2013) reported no further decreases in stability or functional performance, comparing simultaneous cryotherapy and compression to cryotherapy application alone. With only one study investigating this, it is difficult to provide any generalisability on the effect of variable compression magnitudes or variations such as constant or intermittent pressure on biomechanical measures relevant to current practice.

Studies that investigate the effects of cryotherapy on biomechanical parameters report findings in terms of the effect of cooling alone without measure of accompanying pressure, whether that be intended (cryo-compression modality) or concomitant to the cooling application. Investigation into simultaneous cryo-compression applications on biomechanical parameters whereby pressure is quantified alongside temperature would be beneficial to determine safe thresholds of movement or loading after application once optimal protocols of cryo-compression for targeted tissue temperature reduction are determined.

Previous literature has described the research available on the comparison between cooling with/without compression in sports injury management as having persistent inconsistencies in methodologies (Bleakley et al, 2004). A total of 13 papers reported in this scoping review consider comparisons of cooling with and without compression or compare multiple cryo-compressive modalities (Merrick et al, 1993; Mora et al, 2002; Bleakley et al, 2004; Knobloch et al, 2008; Janwantanakul, 2006; 2009; Capps and Brook, 2009; Block, 2010; Hawkins et al, 2012; Holwerda et al, 2013; Williams et al, 2013; Rigby and Dye, 2017; Ostrowski et al, 2019).

Most studies agreed the addition of compression to cooling is beneficial for physiological changes to occur (Merrick et al, 1993; Knobloch et al, 2008; Janwantanakul, 2009; Capps and Brook, 2009; Tomchuk et al, 2010; Bleakley et al, 2012; Ostrowski et al, 2019). However, it is still evident that a gap in the knowledge base represents a lack of high-quality research available that provides comparisons of variable compressions, contemporary cryo-compressive applications and outcome measures with sporting relevance.

Because of the limited volume of publications specifically comparing multiple contemporary cryo-compressive devices, this precludes the ability to comprehensively distinguish which application or protocol would provide optimal therapeutic response for musculoskeletal sports injury management. Further studies should investigate contemporary cryo-compressive modalities for musculoskeletal sports injuries to reduce the gap in knowledge and ensure that quality evidence on their efficacy and therapeutic effects can be applied in contemporary applied practice. Future studies might consider presenting both group and individual data for full interpretation of individual response to cryo-compressive interventions, particularly in athletic populations where positional characteristics or physical traits are known to influence the level of T_{sk} following local cooling applications, supporting the need for individualisation of cooling protocols (Alexander et al, 2021b). Yet, without a clear understanding of the effects of cryotherapy and compression applied separately, studies that investigate combinations of cooling and compression may fail to progress the remit of this topic successfully because of the gaps highlighted by the results of this review.

Limitations

This review has some limitations The methodological quality of the included papers was not considered; however, this approach follows the Arksey and O'Malley (2005) framework for scoping reviews. The authors appreciate that this limits the appraisal of the available studies that met the inclusion criteria, and that further critical appraisal for the methodological quality of papers may be beneficial in terms of a systematic review process in future. Furthermore, the search criteria excluded studies where cryo-compression was used post-operatively and therefore may have excluded studies that evaluate simultaneous cryo-compression in this scope. Potential bias to the selection process of papers in this scooping review may include the exclusion of papers in languages other than English. The generalisability of findings to injured populations is limited by the lack of studies that have investigated simultaneous cryo-compressive modalities.

Conclusions

Available research that investigates simultaneous cryotherapy and compression for the management of sports injury is limited, diverse and consequently difficult to summarise. Methodological differences surrounding the efficacy of cryo-compressive applications prevents the ability to provide a strong argument as to what may be optimum protocols in the management of musculoskeletal sports injuries. Suggestions that compression aids the efficiency of cooling is evident; however, studies should explicitly report compression pressure values (mmHg) to provide clarity on dose–response findings. There is no definitive understanding of individual parameters of optimal cooling temperature, time, or compression in isolation. Therefore, it is difficult to determine the combination of effects that may occur from simultaneous applications of cryotherapy and compression. This is as a result

Key points

- Differences in the efficacy of cryo-compressive applications is evident and influenced by several variables that should be considered when devising optimal cryo-compression applications.
- Studies generally agree that compression aids the magnitude of cooling.
- Definitive practices for the application of simultaneous cooling and compression cannot be drawn from the current available literature because of inconsistencies in methodological investigations.
- Lack of previous understanding around protocols for cryotherapy or compression applied separately is evident.
- Further studies of contemporary cryo-compressive devices and dose–response are required to develop optimal protocols for use in sports injury management and should consider multiple measurable outcomes and individual responses reflective of current applied practices.

of the multiple variables that require consideration for cryo-compressive application and the dynamic interplay that takes place with the body's homeostatic mechanisms. Further contemporary technological advancements in cryo-compressive modalities is needed. A focus on dose–response through the examination of variable compression pressures not yet defined in current literature may be beneficial. Defining contemporary protocols of simultaneous cryotherapy and compression applications is required to enhance understanding in current practice of cryo-compressive modalities. Unless full consideration of multiple variables that affect the interpretation of outcome measures are deliberated in future studies, the impact of findings into current practice will be limited. Furthermore, individual responses were not considered across studies and future research should observe this to optimise cryo-compressive protocols for sports injury management.

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Conflicts of interest

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Appendix 1. Study characteristics and data extraction of included articles

Author (year)	Study design and participants	Type of compression application and pressure measures	Type of cooling modality and temperature measures	Cooling dose (minutes) and compression dose (mmHg)	Summary of key findings
Merrick et al (1993)	Randomised controlled trial *n*=11 Sex: unknown Age: 23.5 ± 2.1 years Height: 175.3 ± 10.3 cm Weight: 40.4 ± 14.0 kg, Anterior thigh skinfold: 15.8 ± 3.7 mm	Continuous simultaneous compression Crushed ice alone placed over treatment area no additional compression Compression treatment alone 1.34m x 15cm elastic wrap Crushed ice and compression 15cm wide elastic wrap Control group (no treatments applied) Compression monitored using manometer (AirCast Inc, Summit, NJ)	Crushed ice Crushed ice with compression Compression alone Control group (no treatments applied) Crushed ice 1 kg of ice in a 10 L plastic bag Crushed ice and compression 1 kg of ice T_{sk} and T_{im} measured via thermocouple over the quadriceps	30 minutes (each modality) Compression maintained at 42–48 mmHg	Compression increases the effectiveness of ice in reducing tissue temperatures Crushed ice combined with compression produced significantly cooler temperature than crushed ice alone
Wilkerson and Horn-Kingery (1993)	Observational *n*=34 Men *n*=28, Women *n*=6 Age: 18–28 years	Continuous focal simultaneous compression	U-shaped liquid-filled device (Aircast with Cryo/Strap) applied over a cotton sock One group replaced thawed modality at 4-hour intervals No measurement of T_{sk}	20–30 minutes No pressure measures reported	Focal compression appears beneficial Increased frequency and duration of cryotherapy does not appear to enhance the rate of recovery in an inversion ankle sprain Mode of compression application may be an important factor that affects rate of recovery (following an inversion ankle sprain)
Mora et al (2002)	Randomised controlled trial *n*=24 Intervention group: Men *n*=11 Women *n*=3 Mean age: 29 years Control group: Men *n*=10 Women *n*=3 Mean age: 33 years	Pulsatile cold compression Continuous simultaneous compression	CryoCuff and AutoChill pump 50–60°F	Full day with water/ice changed every 6–8 hours removed at night 30–35 mmHg	Significant reduction in ankle circumference at 24, 48, and 72 hours compared to elevation alone Reduction of oedema with associated use of combined cryotherapy and pulsative compression

Appendix 1 .Study characteristics and data extraction of included articles (continued)

Author (year)	Study design and participants	Type of compression application and pressure measures	Type of cooling modality and temperature measures	Cooling dose (minutes) and compression dose (mmHg)	Summary of key findings
Bleakley et al (2004) (continued)	Systematic review Not applicable	Multiple variations of compression	Multiple variations of cryotherapy modalities	No average dose reported No pressure measures reported	Poor consensus across multiple combinations of studies that investigated ice and compression or ice and compression vs no ice or ice and compression vs ice alone Persistent inconsistencies across methodologies prevent conclusive consensus for comparisons Some evidence to suggest the combination of ice and compression appears significantly more effective than ice (post-operatively) to induce muscular analgesia
Janwantanakul (2006)	Observational *n*=40 Women *n*=40 Age: 21 ± 0.9 years Height: 1.6 ± 0.1 m Weight: 51.2 ± 5.5 kg BMI: 19.9 ± 1.9 kg/m^2	Cryotherapy with five different levels of compression 10cm x 2m elastic bandage Biofeedback to measure pressure	Ice pack 0.6 kg chipped ice *Tsk* measured via thermocouple over the quadriceps	20 minutes No compression (control), 14, 24, 34, and 44 mmHg	Ice application with adjunct compression leads to a greater magnitude of cooling compared to ice application with no compression Rate of cooling increases with higher compressive forces
Knobloch et al (2006a)	Observational *n*=26 Men *n*=13 Women *n*=13 Age: 32.3 ± 12 years Height: 177 ± 9 cm Weight: 81 ± 21 BMI: 25.4 ± 5 kg/m^2	Continuous simultaneous compression	Cryo/Cuff Filled with 15°C water in addition to crushed ice	10 minutes followed by a 10-minute recovery repeated three times No pressure measures reported	Beneficial effects on level of microcirculation including deep tendon oxygenation saturation, facilitated venous capillary outflow, capillary blood flow (Achilles tendon) following Cryo/Cuff application

Appendix 1. Study characteristics and data extraction of included articles (continued)

Author (year)	Study design and participants	Type of compression application and pressure measures	Type of cooling modality and temperature measures	Cooling dose (minutes) and compression dose (mmHg)	Summary of key findings
Knobloch et al (2006b)	Observational *n*=21 Men *n*=12 Women *n*=9 Age: 29 ± 10 years BMI: 24 ± 3 kg/m²	Continuous simultaneous compression	Cryo/Cuff Filled with 15°C water in addition to crushed ice No T_{sk} or T_{im} measures reported	30 minutes No pressure measures reported	Cryo/Cuff device (applied at the ankle) reduced superficial tissue oxygen saturation, superficial and deep post capillary venous filling pressures, and superficial and deep microcirculatory blood flow as a function of time
Knobloch et al (2007)	Observational *n*=30 Men *n*=12 Women *n*=18 Age: 33 ± 12 years BMI: 25.6 ± 5.3 kg/m²	Intermittent application with continuous simultaneous compression	Cryo-compression bandage No reporting of *Tsk* or *Tim* measures KoldBlue	10 minutes followed by 10-minute rewarming (three cycles) No pressure measures reported	Intermittent cryotherapy of three x10 minute KoldBlue cryo-compression bandage significantly decreases local Achilles tendon capillary blood flow At 2 minutes, rewarming oxygen saturation in the tendon was re-established
Knobloch et al (2008)	Randomised controlled trial *n*=60 Combined cryotherapy and compression group Men *n*=18 Women *n* =12 Age: 33 ± 12 years Height: 173 ± 0.1 cm Weight: 77 ± 18 kg BMI: 25 ± 5 kg/m² Cryotherapy only (KoldBlue) Men *n*=18 Women n=12 Age: 32 ± 11 years Height: 176 ± 0.1 cm Weight: 78 ± 18 kg BMI: 25 ± 4 kg/m²	Intermittent simultaneous compression	Cryo/Cuff KoldBlue Cryo-compression bandage Filled with 15°C water in addition to crushed ice	10 minutes followed by a 10-minute recovery repeated three times No pressure measures reported	Intermittent three x10-minute cryotherapy and compression is superior to cryotherapy alone in Achilles tendon microcirculation Increased tendon oxygenation achieved by combining cryotherapy and compression during recovery in contrast alone

REVIEW

Appendix 1. Study characteristics and data extraction of included articles (continued)

Author (year)	Study design and participants	Type of compression application and pressure measures	Type of cooling modality and temperature measures	Cooling dose (minutes) and compression dose (mmHg)	Summary of key findings
Capps and Brook (2009)	Narrative review Not applicable	Cryotherapy and intermittent pneumatic compression	Multiple cryotherapy modalities	No dose reported No pressure measures reported	Cryotherapy and compression modify the inflammatory response to soft tissue injury Therapeutic effects of cryotherapy enhanced by simultaneous application of compression Intermittent pneumatic compression provides therapeutic benefit that differs from static compression
Janwantanakul (2009)	Observational *n*=20 Men *n*=20 Age: 21 ± 1.1 years Height: 1.7 ± 3.4 m Weight: 61.6 ± 6.7 kg BMI: 20.7 ± 1.8 kg/m^2	Continuous simultaneous compression 10cm x 2m elastic bandage Biofeedback to measure pressure	Two different sizes of ice pack, with three variations of weight 18cm x 23cm, weighing 0.3, 0.6 and 0.8 kg of ice 20cm x 25cm weighing 0.6 kg of ice T_{sk} measured via thermocouple over the quadriceps	20 minutes 44 mmHg (± 2 mmHg)	Application of ice pack and combined elastic wrap compression containing at least 0.6kg of ice has a greater magnitude of cooling compared to 0.3kg Study fails to consider weight of ice pack as additional compression that may also affect magnitude of cooling
Block (2010)	Narrative review Not applicable	Intermittent and continuous simultaneous compression	Multiple cryotherapy modalities reviewed	No dose reported No pressure measures reported	Difficult to recommend the most appropriate and effective application of cold and compression for musculoskeletal injuries based on available literature Devices incorporating cold and controlled intermittent compression provides support in reduction of recovery time

REVIEW

Appendix 1. Study characteristics and data extraction of included articles (continued)

Author (year)	Study design and participants	Type of compression application and pressure measures	Type of cooling modality and temperature measures	Cooling dose (minutes) and compression dose (mmHg)	Summary of key findings
Tomchuk et al (2010)	Randomised controlled trial *n*=14 Men *n*=4 Women *n*=10 Age: 22.4 ± 1.8 years Height: 169.1 ± 8.2 cm Weight: 73.3 ± 18.5 kg Skinfold: 13.14 ± 1.61 mm	Continuous simultaneous compression No compression Elastic wrap Flex-i-Wrap	Ice bag with elastic wrap Ice bag with Flex-i-Wrap T_{sk} and T_{im} measured via thermocouples	30 minutes (each modality) No pressure measures reported	External compression combining ice bag and elastic wrap provides greater temperature reduction compared to ice bag and Flex-i-Wrap Intramuscular temperature was lower with compression than compared to no compression Intramuscular temperature was lower with elastic wrap and with Flex-i-Wrap Elastic wrap compression during ice-bag treatment creates a greater magnitude of tissue cooling
Hawkins et al (2012)	Observational *n*=30 Men *n*=15 Age: 26 ± 4 years Height: 180.7 ± 11.9 cm Weight: 80.7 ± 12.2 kg Women *n*=15 Age: 21 ± 2 years Height: 166.6 ± 8.4 cm Weight: 64.5 ± 7.9 kg	Intermittent and continuous simultaneous compression	Ice with compression Slush Bucket GameReady T_{sk} and Ti_m measured via thermocouples	20 minutes (each modality) No pressure measures reported	The GameReady (medium setting) applied at the ankle did not cool as well as traditional cryotherapy methods (ice with compression or slush bucket) over the sinus tarsi tissues for pain management Further research recommended with adjustments in compressive settings of the GameReady machine
Holwerda et al (2013)	Observational *n*=10 Men *n*=1 Women *n*=9 Age: 23 ± 3 years Weight: 70 ± 11 kg Height: 173 ± 10 cm Thigh skinfold: 11.3 ± 3.6 mm	Continuous simultaneous compression GameReady Knee sleeve No compression Medium (5–50 mmHg) High (5–75 mmHg) compression Pressure cycles approximately 3 minutes and 1.5 minutes to depressurise Ice with elastic wrap 6-inch double elastic wrap secured the ice bag	Ice with elastic wrap GameReady $T_{s}k$ T_{im} and T_{ORAL} measured via thermocouples	30 minutes GameReady No compression Medium (5-50 mmHg) High (5–75 mmHg) compression Ice with elastic wrap 30 mmHg	GameReady did not produce acute cardiovascular strain that exceeded strain produced by standard ice bag/elastic wrap applications Acute increases in cardiovascular strain noted in all modality applications

Appendix 1. Study characteristics and data extraction of included articles (continued)

Author (year)	Study design and participants	Type of compression application and pressure measures	Type of cooling modality and temperature measures	Cooling dose (minutes) and compression dose (mmHg)	Summary of key findings
Williams et al (2013)	Observational *n*=30 Men *n*=9 Women *n*=21 Age: 20.6 ± 1.0 years Height: 1.70 ± 0.1 m Weight: 67.5 ± 11.7 kg BMI: 23.7 ± 4.7 kg/m^2	Continuous simultaneous compression Plastic wrap applied for compression	Ice with and without external compression Control group (no ice/ compression) Ice bag filled with 1.1 kg crushed ice	20 minutes No pressure measures reported	Cryotherapy in combination with external compression did not decrease balance or functional performances compared to cryotherapy alone
Du Pont et al (2017)	Observational *n*=16 Control group=8 Age: 21.5 ± 1.7 years Height: 1.81 ± 0.09 m Study group Age 23.4 ± 2.2 years Height 1.77 ± 0.06 m	Continuous simultaneous compression Compression sensors to monitor pressure (Microlab PicoPress) Pressure-flow relationship	Cryo-compression device (Aquilo Sports) Application on days 1, 2 (+24 hours) and 3 (+48 hours) *Tsk* measured via thermal imaging camera (FLIR ONE) over quadriceps and gastrocnemius T_{sk} maintained to between 10 and 12°C	20 minutes 3 litres/min^{-1} and inlet pressure of 12 psi	Combination of cold and compression therapy is an effective method to help recovery from acute resistance exercises Sleep quality enhanced with cryo-compression as opposed to no intervention following heavy resistance exercise Markers for muscle damage, pain and soreness reduced with cryo-compression compared to no intervention following heavy resistance exercise
Rigby and Dye (2017)	Observational *n*=12 Men *n*=6 Women *n*=6 Age: 23.8 ± 2.5 years Height: 67.9 ± 3.3 in Weight: 153.6 ± 18.6 lbs	Continuous simultaneous compression or intermittent pneumatic pressure Pressure measurements monitored using Manometer (DJO, LLC, Visata, CA) HyperIce pressure maintained through release of excess air once fitted to the ankle Crushed ice held in place with 6-inch elastic wrap Game Ready intermittent compression	HyperIce GameReady Crushed ice with elastic wrap T_{sk} measured via thermocouple HyperIce filled with 1 kg of ice Crushed ice 1 kg ice GameReady set at coldest target temperature 2°C	30 minutes (each modality) GameReady High (5–75 mmHg) HyperIce 40–45 mm Hg (approximately) Crushed ice 35–40 mmHg (approximately) Control elastic wrap 50 mmHg (approximately)	GameReady's cyclic compression is less than traditional methods HyperIce produced more effective skin surface temperature reductions Similar compression noted across all devices with HyperIce recommended for immediate care GameReady best applied for post-intermediate care phase in rehabilitation of lower limb injury

Appendix 1. Study characteristics and data extraction of included articles (continued)

Author (year)	Study design and participants	Type of compression application and pressure measures	Type of cooling modality and temperature measures	Cooling dose (minutes) and compression dose (mmHg)	Summary of key findings
Ostrowski et al (2018)	Observational *n*=12 Men *n*=4 Women *n*=8 Age: 23.08 ± 1.93) years Height: 171.66 ± 9.47 cm Mass: 73.67 ± 13.46 kg Subcutaneous thickness: 0.90 ± 0.35 cm	Intermittent simultaneous compression	PowerPlay with wetted ice insert PowerPlay with gel pack insert PowerPlay with control PowerPlay with wetted ice insert (1500 ml cubed ice with 150 ml of water) Gel Pack 360° wrapped around the limb Ice packs in contact with one-third of the limb surface Ts_k and T_{im} measured via thermocouples	30 minutes 70 mmHg	PowerPlay using the wetted ice bag option produces greater rate and magnitude of intramuscular and skin cooling than the gel option PowerPlay with gel insert provided poor therapeutic levels of skin or intramuscular cooling and therefore not recommended
Kwiecien et al (2019)	Observational *n*=10 Men *n*=10 Age: 35 ± 8 years Height: 178.8 ± 6.2 cm Mass: 80.5 ± 4.8 kg	Continuous simultaneous compression	30 minutes High compression (60.6 ± 8.1 mm -Hg) Wetted ice pack Ts_k and T_{im} measured via thermocouples	Low compression (15.5 ± 4.0 mmHg)	No difference between high and low compression of a wetted ice pack on magnitude of intramuscular temperature at 1 and 3 cm depth or skin temperature No control group of wetted ice pack without compression
Ostrowski et al (2019)	Observational *n*=12 Men *n*=4 Women *n*=8 Age: 23.08 ± 1.93 years Height: 171.66 ± 9.47 cm Weight: 73.67 ± 13.46 kg Subcutaneous thickness: 0.90 ± 0.4 cm	Continuous compression compared to intermittent compression Salted ice bag secured with elastic compression maintained GameReady intermittent compression using knee sleeve PowerPlay intermittent compression with 360° sleeve	Salted ice bag GameReady PowerPlay Each applied to the non-dominant calf *Tsk* and *Tim* measured via thermocouples Salted ice bag, 2000 mL cubed ice and half teaspoon salt GameReady 3500 mL cubed ice and 2000 mL water PowerPlay with wetted ice bag insert, 1500 mL cubed ice and 150 mL water	30-minutes (each modality) Salted ice bag 50 mm Hg GameReady high pressure 5–75 mmHg with 3-minute inflation and 1-minute deflation PowerPlay 70 mmHg, 20-second inflation / 10-second hold / 20-second deflation	Salted bag with elastic compression may be more desirable than intermittent compression. Salted ice bag and GameReady produced desirable skin surface temperature to induce physiological effects. Salted ice bag, GameReady and PowerPlay™ ice bag produced similar intramuscular temperature

Appendix 1. Study characteristics and data extraction of included articles (continued)

Author (year)	Study design and participants	Type of compression application and pressure measures	Type of cooling modality and temperature measures	Cooling dose (minutes) and compression dose (mmHg)	Summary of key findings
Alexander et al (2020b)	Observational *n*=29 Men *n*=18 Women *n*=11 Age 22 ± 3.6 years Height: 168.2 ± 8.6 cm Weight: 67.4 ± 11.5 kg Thigh circumference 50.7 ± 6.7 cmts	GameReady intermittent compression using thigh sleeve Squid Go leg/knee system GameReady Protocol 2: temperature target set manually at 2° Squid Go protocol 1: cold gel pack Squid Go protocol 2: cold gel pack	GameReady Protocol 1: temperature target set manually at 2° Control group: no cooling/ compression	15 minutes (each protocol) GameReady Protocol 1: high pressure 5–75 mmHg with 3-minute inflation and 1-minute deflation GameReady protocol 2: no added compression Squid Go protocol 1: high intermittent compression (0–70 mmHg) Squid Go protocol 2: low intermittent compression (30 mmHg) Control group: No cooling/compression	Greater magnitudes of cooling can be achieved through compression adjuncts Muscle oxygenation saturation and skin surface temperature responses differ depending on pressure dose applied in conjunction with cooling Greater initial increases of muscle oxygen saturation were noted immediately-post removal of cryo-compression intervention and correlate to higher levels of compression Dose-response relationships between cooling and simultaneous compression should be considered for application and are dependent on the therapeutic aim of treatment Further investigation required for individual response

BMI : body mass index; T_{sk} : skin surface temperature; T_{im} : intramuscular temperature; T_{ORAL} : oral temperature; PCC: pulsatile cold compression.

Appendix 4c: Copy of Publication 11.

Alexander, J., *et al,* (2020). Physiological Parameters in Response to Levels of Pressure during Contemporary Cryo-Compressive Applications: Implications for Protocol Development. *Journal of Athletic Enhancement.* 9(1): 1-6.

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Research Article

A SCITECHNOL JOURNAL

Physiological Parameters in Response to Levels of Pressure during Contemporary Cryo-Compressive Applications: Implications for Protocol Development

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Abstract

Background: The effectiveness of simultaneous compression and cooling applications that cryo-compressive devices offer are of interest in the management of sports injury or post-exercise recovery. Dose-response in terms of physiological parameter is required to inform current practice in the remit of sports medicine to help define optimal protocols for application. The current study aimed to investigate the physiological effects and perceptual responses of different cryo-compression dosages offered by two cryo-compressive devices over a rewarming period. Methods: Twenty-nine healthy male and female participants (male n=18; female n=11) volunteered (mean ± SD: age 22 ± 3.6 years, height 168.2 ± 8.6 cm, weight 67.4 ± 11.5 kg and thigh circumference 50.7 ± 6.7 cm). Objective measures included skin surface temperature, muscle oxygenation saturation, perceptual thermal comfort and sensation. Data were collected pre, immediately post intervention and over a 20-minute rewarming period. Participants were randomly assigned to either Group A (Game Ready®); B (Squid®) or C Control group. Intervention groups received different cryo-compressive protocols for testing, but both received 15-minutes of cooling. Results: Significant reductions in skin surface temperature were displayed across the intervention groups for all time-points (*p≤0.05*). Analysis of all data displayed a significant effect of time (*p≤0.001*) on muscle oxygenation. Collapse of the data indicated significant differences in muscle oxygenation across the different modalities and pressure (*p≤0.05*). Conclusion: Muscle oxygenation saturation and skin surface temperature responses differ depending on pressure dose in conjunction with cooling. Higher initial increases of muscle oxygenation saturation immediately post intervention correlate to higher levels of compression. Greater magnitudes of cooling can be achieved through the adjunct of compression. Dose-response relationships between cooling and simultaneous compression should be considered and are dependent on the therapeutic aim of treatment. In order to develop optimum protocols for management of either injury or recovery parameters further investigation is required of contemporary cryo-compressive devices.

Keywords

Cryotherapy; Physiology; Muscle oxygenation; Skin temperature; Compression

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Introduction

Cooling for post-exercise recovery or injury management is common practice within sport, with the belief that recovery characteristics benefit from such protocols [1-3]. Symptoms of delayed onset muscle soreness (DOMS) for example reportedly reduce following cryotherapeutic interventions due to positive physiological responses [2,4]. Cryo-compressive devices aim to provide simultaneous cooling and compression for sports injury rehabilitation, and recent literature reports positive influences on performance recovery parameters also [5]. Nevertheless, several questions remain that surround the effects of cooling and simultaneous compression on physiological parameters such as SmO_2. Consequently optimal protocols are unsubstantiated from the variability in methodologies published in current literature. Thus providing confusing conclusions for sport medicine practitioners unsure on the differences that may exist between devices, settings and outcomes to ensure optimal applications can be applied. Previous literature reports decreases in SmO_2 following cold-water immersion [6,7] and it is suggested that compression aids the magnitude of cooling [8-10]. Conversely, isolated external compression is reported to increase SmO_2 [11,12]. To what extent the physiological response of muscle oxygenation is affected by such applications that combine cooling with compression therefore is still under contention.

Measurements of muscle oxygen saturation (SmO_2) and skin surface temperature (T_{sk}) support the understanding of the potential effects local cryotherapy may have on objective markers [3]. Prominently observed in literature, a local cryotherapy application initiates the reduction of T_{sk}, skin blood flow, and muscle oxygenation [13]. The ratio of oxyhaemoglobin concentration to total haemoglobin concentration in the muscle reported as a percentage, is useful in providing real-time physiologic feedback. Indicators of muscle metabolic activity can be noninvasively monitored by collating muscle oxygenation and haemodynamic, with such devices as MOXY sensors (MOXY, Swinco, and Zurich, Switzerland). Previously studies have demonstrated decreases SmO_2 following cooling applications of cold-water immersion [3,6,7]. Simultaneous dosages of compression (mmHg) and cryotherapy that cryo-compressive devices can offer are of interest in the management of sports injury or post-exercise recovery. Consequently, the effectiveness of these devices for injury or recovery management in sport is warranted. An insight as to whether different physiological effects occur after exposures to different cryo-compression dosages is important to inform current practice in the remit of sports medicine. Over a rewarming period, the current study aimed to investigate the physiological effects and subjective responses of different cryo-compression dosages offered by two cryo-compressive devices. We hypothesised that higher compressive dosages would result in greater magnitude of cooling, demonstrating larger reductions in T_{sk} and subsequently greater reductions in SmO_2

Materials and Methods

Participants

The host university ethics committee, in accordance with the Declaration of Helsinki, agreed approval of the study. Participants were provided with information regarding study protocol prior to

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providing written and verbal consent to take part. The sample size of participants was based on a recently similar methodology [3] and determined using G*Power (version 3.1.10). *A priori* power calculation conducted using pilot data completed by participants matching the criteria determined a minimum sample size of ≥ 21 players required to evaluate the interactions associated with all independent variables (for statistical power >0.8; p ≤ 0.05). Twenty-nine healthy male and female participants (male n=18; female n=11) volunteered for the study (mean ± SD: age 22 ± 3.6 years, height 168.2 ± 8.6 cm, weight 67.4 ± 11.5 kg and thigh circumference 50.7 ± 6.7 cm) meeting the recommended sample size. All participants took part in land-based university sports. Participants were excluded if they presented with any of the following; any current pain symptoms, reaction to cold (such as Raynauds), pre-existing lower limb injury; cardiovascular disease, cardiac pacemaker or arrhythmia, under any prescribed medication or were smokers. Participants were randomised to either intervention Group (A) (Game Ready®) or intervention Group (B) (Portable Therapeutix Squid Model One Compression device and Cold Pack "Squid") or the Control Group (C) *via* randomisation.com.

Experimental design

Ambient room temperature recorded at 21.5 ± 1.6°C, reported a relatively consistent environmental condition throughout testing. Participant's anthropometric data was collated during a 15-minute acclimatisation period. Data was captured from participants dominant limb, the participant's dominant limb was determined by asking each participant, "If you would shoot a ball on a target, which leg would you use to shoot the ball?" [14]. Baseline testing consisted of T_{sk} captured over the anterior thigh region determined by a region of interest (ROI) [15,16] and SmO_2 data from the rectus femoris muscle in the dominant lower limb. T_{sk} measures were captured using an infrared thermal imaging camera (ThermoVision A40M: Flir Systems, Danderyd, Sweden) following gold-standard recommendations [17,18]. The thermal imaging camera was positioned perpendicular to the anterior lower limb, set at a height of 132 cm from the ground and adhered to TISEM Guidelines [19]. To create the ROI, thermally inert wooden markers were applied to the anterior thigh to create a framework that was identifiable for analysis [15]. Markers were located superiorly (one-third between ASIS-Base of Patella), inferiorly (two-thirds between ASIS-Base of Patella) and central thigh, measured from thigh circumference located at 50% between ASIS and base of the patella [16]. To determine the ROI the markers were placed at a 10% distance from these points to distinguish the anterior thigh region for T_{sk} measurement.

SmO_2 measures were chosen due to extensive reports as a haemodynamic benefit arising from compression garments and devices in the same remit [20]. SmO_2 data was captured using MOXY sensors (MOXY, Swinco, Zurich, Switzerland) using near-infrared spectroscopy (NIRS). The MOXY instrument was held in place over the anterior thigh (vastus lateralis) by pre-cut hyper fix tape to help standardise the external pressure applied holding the device in place [21]. The MOXY device placed midway between the inguinal crease and proximal patella [22]. A small mark using a washable pen identified exact location of the MOXY on each participant's leg to maintain standardisation of MOXY location and re-location throughout testing. Baseline SmO_2 data was collected consistently for 1 minute prior to any intervention. Data capture was then repeated at immediately post (0 minutes) and continually over and up to 20 minutes post intervention time points. In addition, Thermal Comfort and Thermal Sensation were collated both during cooling application at 5 minute increments, and at immediately post and at 20 minute post exposure time points. Immediately after baseline data were recorded, participants in the Control Group were instructed to rest in a supine position on a plinth, remaining as still as possible for 15 minutes, replicating the equivalent period followed in both intervention groups (A) and (B). Participants in intervention Group (A) received a 15-minute application of the Game Ready®, set at a target temperature of 2°C simultaneously applied with either intermittent ~ high pressure (5-75 mm Hg) (Exposure Protocol 1) or no added pneumatic compression (Exposure Protocol 2) depending on randomisation allocation (Table 1). Participants in intervention Group (B) received a 15 minute application of Squid simultaneously applied with either intermittent ~ high pressure (0-70 mm Hg) (Exposure Protocol 1) or low pneumatic compression (0-30 mm Hg) (Exposure Protocol 2) depending on randomisation allocation (Table 1). Participants returned 1 week later for exposure to the alternative protocol within their specific group allocation. Participants allocated to the Control Group were required to attend only 1 session of data collection.

Thermal sensation and thermal comfort ratings

Both Thermal Sensation and Comfort assessments were carried out following ISO 10551 [23] (ISO Standardisation, Geneva, Switzerland). Participants were asked "How are you feeling?" Participants rated their thermal sensation in terms of temperature of the anterior thigh, according to the scale: 4=very hot, 3=hot, 2=warm, 1= slightly warm, 0=neutral, -1 slightly cool, -2=cool, -3=cold, -4=very cold. For Thermal Comfort ratings participants were asked,

Table 1: Group allocations and exposure protocols.

Group Allocation				
Intervention Group A (n=10)		Intervention Group B (n=10)		Control Group (n=9)
Exposure Protocol 1	Exposure Protocol 2	Exposure Protocol 1	Exposure Protocol 2	No Exposure
Game Ready® Duration 15 minutes	Game Ready® Duration 15 minutes	Squid Duration 15 minutes	Squid Duration 15 minutes	Supine laying on plinth duration 15 minutes
Manual Tsk target 2°C	Manual Tsk target 2°C	'Protocol 3'	'Protocol 1'	No Cooling
High Intermittent Compression (5-75 mm Hg)	No added Compression	High Intermittent Compression (0-70 mm Hg)	Low Intermittent Compression (30 mm Hg)	No Compression
Peak Pressure=75 mm Hg		Peak Pressure=70 mm Hg	Peak Pressure=30 mm Hg	
Rewarming period of 20 minutes	Rewarming period of 20 minutes	Rewarming period of 20 minutes	Rewarming period of 20 minutes	Rewarming period of 20 minutes

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"How do you perceive this?" Participants responded based on the feeling of the cryo-compression application using the following scale: 0=comfortable, 1=slightly uncomfortable, 2=uncomfortable, 3=very uncomfortable and 4=extremely uncomfortable. Questionnaire data were collected at baseline, and throughout the intervention applications (Groups A and B), at 5 minutes intervals, followed by immediately post (0 minutes) and 20 minutes post intervention removal.

Statistical analysis

All tests were performed in SPSS (Statistical Package for Social Sciences) version 26.0 (SPSS Inc, Chicago, IL, USA). Level of significance was set at $p \leq 0.05$. All data is expressed as means ± SD. To test for homogeneity of differences in variance, Mauchley's test of sphericity was performed. Normality was assessed *via* the Shapiro-Wilk test. SmO_2 was analysed using normalised values (% mean ± SD). A univariate repeated measures general linear model was used to quantify main effects for intervention and time. Partial eta-squared ($\eta^2_{partial}$) displayed the effect size and were classified as small, medium or large (0.1-0.29, 0.3-0.49 and >0.5 respectively) [24]. Interaction effects were also quantified and significant main effe cts for pressure were explored using post hoc pairwise comparisons and where appropriate a Bonferroni corrected post hoc analyses were applied. For Thermal Comfort ratings, a Wilcoxon signed-rank test analysed within-group differences and to analyse differences across timepoints for Thermal Sensation data the Friedman test was conducted.

Results

No significant differences we re re ported fo r he ight, we ight or body mass index between groups ($p \geq 0.05$).

Skin Surface Temperature (T_{sk})

No significant differences were reported for control group at any time point ($p \geq 0.05$) (Table 2). Significant reductions in T_{sk} were reported for Group A (Exposure Protocol 1=Game Ready® cooling with high compression) when comparing immediately post exposure to pre exposure data (p=0.00) and 20 minutes post exposure to pre exposure (p=0.00) (Table 2). Similarly for Group A (Exposure Protocol 2=Game Ready® cooling and no added compression) when comparing immediately post exposure to pre exposure data (p=0.00) and 20 minutes post exposure to pre exposure (p=0.01) significant values were reported (Table 2). Reductions in T_{sk} were reported for Group B (Exposure Protocol 1=Squid cooling with high compression) when comparing immediately post exposure to pre exposure data (p=0.01) and 20 minutes post exposure to pre exposure (p=0.02). Reductions in T_{sk} were reported for Group B (Exposure Protocol 2=Squid cooling with low compression) when comparing immediately post exposure to pre exposure data (p=0.00) and 20 minutes post exposure to pre exposure (p=0.01). Significant differences between Group (A) and Group (B) for Exposure Protocols 1 (high-compression), were displayed at immediately post time point only ($p \geq 0.05$).

Muscle oxygenation (SmO_2)

Figure 1 represents the effects of all protocols on SmO_2, with analysis of all data displaying a significant effect of time ($p \leq 0.001$; F=8.58; η^2=0.17). With the data set collapsed to consider each intervention protocol in isolation, Group (A) Exposure Protocol 1 displayed a significant effect of time (p=0.02; F=5.62; η^2=0.43). A significant increase in SmO_2 is also reported for Group (A) (Exposure Protocol 1) at immediately post exposure when compared to pre exposure data time points (p=0.04). Alternatively, when comparing immediately post exposure to 20 minutes post exposure a significant reduction in SmO_2 is displayed for Group (A) (Exposure Protocol 1) (p=0.005) (Figure 1).

Group (A) Exposure Protocol 2 displayed no significant effect of time ($p \geq 0.05$; F=3.28; η^2=0.30). Although a trend toward a decrease in SmO_2 is evident in Figure 1, no significant changes in SmO_2 were reported for Exposure Protocol 2 in the same group for immediately post exposure when compared to pre exposure data or when comparing immediately post exposure to 20 minutes post exposure time point ($p \geq 0.05$) (Figure 1). A significant reduction in SmO_2 was reported however at 20 minutes post exposure (p=0.03) when comparing to pre exposure data for Exposure Protocol 2 (Figure 1) in the same group.

Group (B) Exposure Protocol 1 and Exposure Protocol 2 displayed no significant effect of time ($p \geq 0.05$; F=0.176; η^2=0.19; $p \geq 0.05$; F=1.10; η^2=0.13) respectively. Although a trend toward an increase followed by a decrease in SmO_2 is evident in Figure 1 for timepoints, immediately post and 20 minutes post exposure respectively, no significant changes were reported in SmO_2 for Group (B) (Exposure Protocol 1) or Group (B) (Exposure Protocol 2) at any time point or within time points ($p \geq 0.05$). No significant effect of time ($p \geq 0.05$; F=0.01; η^2=0.001) were displayed for the control group. Furthermore

Table 2: Skin Surface Temperature (*Tsk*) for the Anterior Quadriceps (°C) for all groups and exposure protocols.

Group Allocation		Pre Exposure *Tsk* (°C) mean ± SD	0 Minutes Post Exposure *Tsk* (°C) mean ± SD	20 Minutes Post Exposure *Tsk* (°C) mean ± SD
Group A Game Ready®	Exposure Protocol 1 (Cooling+High Intermittent Compression 5-75 mm Hg)	28.8 ± 0.6	10.7 ± 1.2*‡	23.6 ± 0.6*
	Exposure Protocol 2 (Cooling with no added compression)	28.4 ± 0.7	14.2 ± 1.2*	25.3 ± 0.4*
Group B Squid	Exposure Protocol 1 (Cooling+High Intermittent Compression 0-70 mm Hg)	27.9 ± 1.2	16.6 ± 2.1*‡	25.4 ± 1.2*
	Exposure Protocol 2 (Cooling+Low Intermittent Compression 0-30 mm Hg)	28.1 ± 0.9	17.2 ± 1.6*	25.6 ± 0.5*
Control Group	Control Group (No cooling / No compression)	28.3 ± 0.6	28.1 ± 0.8	28.5 ± 0.7

□□□□□□□□□□ *sk* compared to pre exposure data.
□□□□□□□□□□ *sk* between immediately post exposure and 20 minutes post exposure data.
□□□□□□□ Defence in Tsk between groups for cooling + 'high-intermittent compression' applications.

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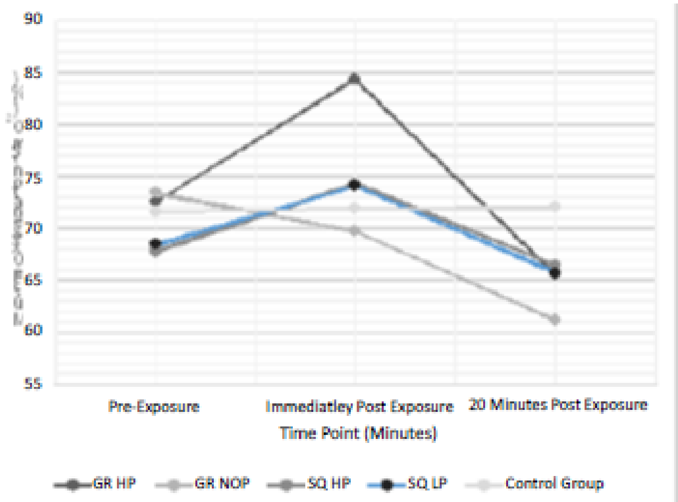

Figure 1: Muscle Oxygenation (SmO_2) (%) for two cooling modalities with variable compression settings over a rewarming period and a control group. (GR: Game Ready®; SQ: Squid; HP: High Pressure; NOP: No Pressure; LP: Low Pressure).

no significant differences were reported for the Control Group for SmO_2 at any time point or between time points ($p \geq 0.05$).

Thermal sensation and comfort scores

Significant reductions were displayed for intervention Groups (A) and (B) for Thermal Sensation scores when comparing throughout device application (at 5 minute increments), immediately post to pre-exposure timepoints ($p \leq 0.05$). Compared to Group (B) and control group, participants in the Group (A) reported to be feel significantly colder compared to pre-exposure scores at both immediately and 20 minutes post timepoints (p=0.05) and regardless of compression settings.

Significant reductions in Thermal Comfort scores were displayed when comparing both Group (A) and Group (B) to the control group and regardless of pressure setting ($p \leq 0.05$), however no significant differences were reported when comparing Group (A) and Group (B) ($p \geq 0.05$). Further comparison of Thermal Comfort scores between compression settings within and across intervention groups however displayed significant increases in discomfort when experiencing the higher pressure settings compared to lower/no pressure settings ($p \leq 0.05$).

Discussion

The aim of the investigation was to examine the physiological effects and perceptual responses of two different cryo-compressive devices on SmO_2, T_{sk} Thermal Comfort and Sensation, when applied circumferentially around the thigh. Primarily findings report physiological changes in SmO_2 following simultaneous cooling and compression protocols, with significantly greater reductions in T_{sk} occurring from the addition of compression. SmO_2 demonstrated an increase from baseline, immediately (0 minutes) after applications of combined cooling with compression, followed by a decline, in both intervention groups (A) and (B). SmO_2 demonstrated a decline immediately post exposure (0 minutes) in the group exposed to cooling only with no additional controlled compression. The trend displayed toward a decline in SmO_2 over the 20 minute rewarming period in groups (A) and (B) regardless of compression adjunct supports previous findings, albeit with varying methods of cryotherapy [3,6]. Relationships between pressure (mmHg), T_{sk} (°C) and SmO_2 (%) are observed. The implications of which may be of interest to sports medicine practitioners when considering the adjunct of pneumatic compression applied alongside cooling for injury or recovery management in sport.

Literature suggests external compression increases SmO_2 [11,12] with cryotherapy reducing SmO_2 [3] when observed independently. All protocols in the current study that applied simultaneous cooling and compression indicated an initial rise in SmO_2 followed by a decline. It may be assumed that once pressure is removed there is no longer an effect on SmO_2 and the effect of cooling dominates SmO_2 response. The initial increase in SmO_2 in response to pressure from the compression adjunct of the devices applied is interesting. It appears that compression counteracts the response of SmO_2 to the simultaneous cooling but only initially after removal this is noticed, as SmO_2 thereafter follows a pattern of decline recognised in literature in response to cold over the rewarming period [3,6,7]. The decline of SmO_2 seen up to 20 minutes post simultaneous cooling and compression is consistent with previous literature of similarity [3] and supports the hypothesis. We assume the similar pattern displayed by SmO_2 demonstrating a continual decline, is in response to cooling rather than compression if, as presumed compression no longer affects SmO_2 once removed.

Higher compression pressures (mm Hg) resulted in greater percentage increases in SmO_2 response immediately post exposures (0 minutes), but not necessary a greater decrease in SmO_2, thereafter. Interestingly exposure protocol 2 (Table 1) (no added compression) demonstrated the lowest SmO_2 value achieved at 20 minutes post exposure. Reasons for this contradict the proposal of a potential relationship between T_{sk} and SmO_2 as this particular exposure did not correlate to the lowest T_{sk} achieved immediate post removal (Table 2). Despite agreement that magnitude of cooling is enhanced by

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compression [10], and supported here, the added adjunct of pressure may in fact influence SmO_2 responses over a rewarming period; lessening the overall reduction in SmO_2 compared to cooling alone. Potentially dismaying the presumption that compression fails to affect SmO_2 once removed. Whether this is considered as a positive or negative reaction may be determined by the context in which cryo-compression is intended. Throughout the inflammatory phases of healing oxygen plays an important role [25]. For example, the demand for muscle oxygen varies at different stages of the natural inflammatory process of injured tissues [26], in turn influencing the choice of modality with/without compression adjunct and protocol applied.

Results illustrate that without the adjunct of circumferential compression SmO_2 is lower 20 minutes post exposure compared to those protocols with added compression at the same time point. As T_{sk} response fluctuated across modalities the impact on key physiological reactions known to occur in response to local cooling is assumed to also differ. Considerations should be made as to whether magnitude of cooling or reduction of SmO_2 is more important in the choice of protocol. Clearly different physiological responses occur in response to compression adjunct dosages. Therefore, despite higher pressures influencing an initial higher increase in SmO_2 it appears cooling affect takes over during the rewarming period, and although compression aids magnitude of cooling, colder T_{sk} achieved because of this does not necessarily mean lower SmO_2 results will be reported over a rewarming period.

Interestingly in Group (A) when no additional compression was applied (Exposure Protocol 2) SmO_2 did not increase initially as per protocols with combined compression (Figure 1). Instead, SmO_2 reduced at immediately post exposure and continued to decline, although not significantly, but following previous literature findings [6]. It is however difficult to compare results as previous literature uses cold-water immersion as opposed to circumferential local cryo-compressive devices. At 20 minutes post exposure all protocols demonstrated reductions in SmO_2, which did not return to pre exposure measures, with Group (A) Exposure Protocol 2 being the only application demonstrating significant decreases in SmO_2 at this time point. This was also the lowest value of SmO_2 recorded across the rewarming period for all protocols. Consequently, it is presumed that the addition of compression lessens the ability of SmO_2 to reduce perhaps as quickly from immediately post (0 minutes) to 20 minutes post exposure. The higher-pressure protocols achieved the lower T_{sk} and we presume greater magnitudes of cooling in deeper tissues based on previous literature [10]. The assumption that although T_{sk} is reduced and larger reductions coinciding with higher-compression dosages. the physiological effects of compression appears to override the effects of cooling on SmO_2. This was thought to be due to the known response of intramuscular temperatures over rewarming periods post removal of cooling [15].

Results in the current study agree that larger reductions in T_{sk} occur when cooling is combined with compression, in line with previous literature [10]. Larger reductions in T_{sk} correlated to higher compressive pressures across both devices. Significant differences were further observed for T_{sk} reductions between cryo-compressive devices and protocols ($p \leq 0.05$) (Figure 1). For example, at immediately post exposure time point for 'high' pressure protocols, Group A (Exposure Protocol 1) achieved a lower T_{sk} of 10.7 ± 1.2°C, meeting target therapeutic ranges for physiological effects to proceed, compared to Group (B) (Exposure Protocol 1) (16.6 ± 2.1°C) when the same dose (time) and similar pressure (mm Hg) was applied. Previously, research has examined the insulation effects of various external compressions

reporting compressive wraps with higher average atmosphere-interface temperature generate enhanced temperature decreases [10]. We consider this may have affected the differences found in the current study, in support of this, visual thermo-graphic differences when comparing high-compression protocols from each intervention group were also displayed. Differences in contact capability between the device and skin interface was anticipated and based on recent literature [27]. We consider that differences displayed in T_{sk} between the cryo-compression devices are also due to greater phase change ability of the device applied in Group (A) due to the mechanism of continuous cycles of circulating cool liquid compared to gel pack applied in Group (B). This would support known differences in cooling efficiency of cryotherapeutic modalities due to phase change capability of materials [8]. For all protocols, across both groups T_{sk} did not return to base line at 20 minutes post exposure. These findings are in line with previous literature reporting similar rewarming periods for local cooling over the thigh regions [16]. More efficient cooling therefore was demonstrated in Group (A) compared to Group (B), and applications of higher pressure produced lower T_{sk}, of which has implications on modality choice and optimal protocol development dependent on therapeutic aim of treatment or recovery.

Although not measured in the current study, intramuscular temperatures are known to continue to decline following removal of cooling [15] and studies report variable responses to compression adjuncts previously [10,28]. It may be proposed that a relationship exists similar to that of intramuscular and T_{sk} responses to cooling between SmO_2 and intramuscular cooling post application. Conversely, SmO_2 was not continuously measured during the intervention exposure, only immediately after removal. Therefore, it is unknown whether SmO_2 decreased or increased from baseline during the intervention applications (15-minute exposures) of either device where simultaneous pressure was applied in the protocol. The assumption based on previous literature and immediately post application SmO_2 values in the current study suggests an increase in SmO_2 values during the application period [11,12]. An immediate increase in SmO_2 for acutely injured soft tissue may be undesirable for tissue healing, however this is presumptuous, as only healthy populations were utilised in this investigation. Alternatively, the decline of SmO_2 following removal of simultaneous cryo-compression may not be as beneficial for tissues recovering from exercise induced fatigue, supporting previous literature [5]. Ultimately these findings continue the debate around cooling and compression in sports medicine, which evidently supports the need for the development of current contemporary cryotherapeutic protocols for sports injury management and recovery.

Perceptual responses for thermal sensation indicated significant differences between modalities regardless of compression levels. Participants reported exposure to Game Ready* to be significantly colder subjectively compared to the Squid. Furthermore, regardless of compression level, across both devices, higher pressure levels were associated with greater decreases in thermal comfort. These findings have implications on protocol or cryo-compressive product design and potentially athlete compliance to cryo-compressive applications. Future consideration in study design should adopt the reporting of thermal sensation and comfort during intervention applications rather than only after the removal of a modality. This method of data collection provides information taken directly during exposure that may consequently represent perceptual responses more accurately than retrospective memory once an intervention is removed.

Limitations

It is unknown as to how long after 20 minutes post exposure SmO_2 or T_{sk} would return to baseline, as data was not collected past a 20 minute rewarming period in the current study. Longer periods of rewarming observation may be warranted therefore. No direct comparisons of 'no pressure' between devices were reported as the option of no pressure as a pre-set application is available of the Squid device unless the device is applied only as a wrap. Actual pressure measure (mm Hg) for devices were not quantified, therefore it is assumed that levels of compression were as per the manufactures information provided. Future studies

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may consider the quantification of pressure setting using appropriate objective measures for pressure in relation to skin surface as compression (mm Hg) output may not be accurately represented. Relationships between pressure outputs from contemporary cryo-compressive cooling devices and physiological responses may be drawn from such data, however other factors such as levels of adipose tissue may also impede results and should be considered in future work.

Conclusion

In summary the investigation into the effects of multiple cryo-compressive applications, suggest SmO_2 and T_{sk} responses differ depending on pressure dose in conjunction with cooling. Higher initial increases of SmO_2 at 0 minutes post intervention correlate to higher levels of compression. Findings in the current study also agree with the consensus that greater magnitudes of cooling can be achieved through the adjunct of compression. With higher compression resulting in colder T_{sk}. This however does not necessarily result in the greatest reduction of SmO_2 when observed over a rewarming period up to 20 minutes. Although, it is thought that the cooling response over this period has a greater influence on SmO_2. Depending on therapeutic aim of treatment dose-response relationships between cooling and simultaneous compression should be considered in order to develop optimum protocols for management of either injury or recovery parameters. To establish a comprehensive understanding of dose-response relationships for cryotherapeutic modalities that combine cooling and compression further investigation is required across other modalities.

Key findings/Implications

- Greater reductions in T_{sk} are reported for simultaneous applications of cooling and compression in line with previous literature, where it is suggested that the magnitude of cooling benefits from added compression.
- The extent of physiological response varies depending on dosage of compression adjunct to cooling for T_{sk} and SmO_2.
- Protocols that apply simultaneous cooling and compression should be adapted in terms of compression dosage to meet target aim of application.

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6.5 Appendix 5: Theme 5 Publications: MULTIFACETED RESPONSES TO CRYOTHERAPY AS A RECOVERY STRATEGY IN ELITE SPORT

Appendix 5a: Copy of Publication 12.

Alexander, J., Jeffrey, J., and Rhodes, D. (2021). Recovery Profiles of Eccentric Hamstring Strength in Response to Cooling and Compression. *J Bodywork Movement Ther* 27: 9-15.

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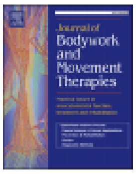

Prevention and Rehabilitation

Recovery profiles of eccentric hamstring strength in response to cooling and compression

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ABSTRACT

Introduction: The effectiveness of different forms of cryotherapy and combined compression (cryo-compression) commonly used in sport to enhance recovery following exercise are not fully understood. Therefore, the exploration of protocols that use contemporary cryo-compression is warranted. The purpose of the study was to investigate the effectiveness of using a cryo-compression device to recover hamstrings eccentric strength following a fatiguing exercise.
Methods: Eighteen healthy male adult footballers were randomly allocated to receive cryo-compression or rest following a lower limb fatiguing protocol. Cryo-compression was applied for 15-min, target temperature of 10 °C, and high intermittent pressure (5–75 mm Hg) using the Game Ready® device. Rest consisted of 15-min in a prone position on a plinth. To induce hamstring fatigue, participants performed the Yo-Yo intermittent fatigue test (IFT). Skin surface temperature (T_{sk}) and hamstring eccentric strength measures were taken at three time points; pre-IFT, immediately post-fatigue test (IPFT), and immediately post-intervention (IPI) (rest or Game Ready®). Participants returned one week later and performed the Yo-Yo IFT again and were exposed to the opposite intervention and data collection.
Results: Significant decreases in T_{sk} over the posterior thigh were reported for all timepoints compared to pre cryo-compression temperatures (*p*=<*0.05*). Overall data displayed no significant main effects for timepoint or condition for PT or AvT (*p*=<*0.05*). There was no timepoint × condition interaction for PT or AvT (*p*=<*0.05*). Collapse of the data by condition (CC/R) demonstrated no significant effect for time for PT or AvT (*p*=>*0.05*).
Conclusions: No significant changes in HES occurred after exposure to cryo-compression or rest applied immediately following the Yo-Yo IFT. Further investigations to maximise beneficial application of contemporary cryo-compression applications in sport are required. Multiple measures of performance over rewarming periods, within competitive training schedules after sport-specific training are required to develop optimal cooling protocols for recovery.

1. Introduction

Fatigue is a key aetiological factor associated with non-contact injuries in football and has been shown to have an adverse effect on football performance (Marqués-Jiménez et al., 2017). The lasting acute effects of hamstring fatigue during match play have been well documented, with current literature highlighting a reduction in eccentric function (Opar et al., 2012) existing up to 96 h post-fatigue. (Rhodes et al., 2018). Many interventions to reduce the incidence of hamstring injuries have been well researched (Bahr et al., 2015), with the consensus across literature indicating that training the muscle eccentrically and increasing its resistance to load has the greatest success (Bourne et al., 2018). Importantly, despite these interventions being employed, the occurrence of these non-contact musculoskeletal injures has not reduced (Hawkins et al., 2001; Ekstrand et al., 2016). Subsequently during eccentric loading or performance, athletes are often subjected to delayed onset muscle soreness (DOMS) (Nogueira et al., 2019) and

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muscle damage (Ihsan et al., 2016). DOMS as a result of exercise has been documented as a major contributory factor to decreased muscle function post fatigue, with deficits being reported up to 72+ hrs post exercise (Nogueira et al., 2019). Consequently, the importance of recovery strategies in football is evident and commonly cryotherapy is utilised to reduce symptoms of post-exercise fatigue to optimise subsequent performance through often congested training and fixture schedules.

It is considered that cooling modalities reduce the symptoms of DOMS by controlling the release of histamines and prostaglandins associated with the inflammatory response (Bleakley et al., 2012; Hohenauer et al., 2015; Chan et al., 2016). Although, contrasting evidence debates whether cooling improves acute recovery through facilitation of muscle metabolites (Ishan et al., 2016). Evidence further indicates that cooling induces a reduced pain response (Allan and Mawhinney 2017) and thus, may increase the perception of the athlete that recovery has taken place. Alternatively, research suggests that cooling shortly after resistance exercise may have a negative effect on muscle adaptation and could be detrimental to the long-term development of the athlete (Roberts et al., 2015). Predominantly research investigates cold-water immersion (CWI) despite cryo-compressive devices prominent in sports medicine and performance departments for recovery. Limited evidence is available on their use and effects (Holwerda et al., 2013; Hawkins and Hawkins 2016) consequently optimal recovery protocols using cryo-compressive devices are unknown.

The Game Ready® (Game Ready; Global, UK) device provides continuous circumferential cooling with compression through circulation of ice water and is commonly cited as an efficient recovery tool for injury or post-surgical management (Murgier and Cassard 2014). Intermittent pneumatic compression and cooling was applied to the hamstring region through a fabric wrap attached to the device which transports a mix of crushed ice and water pumped through to chambers of the wrap with air to provide compression. Manual manipulation through ratio of ice to water can be adapted to control target temperature. Cyclical inflation and deflation of the Game Ready® device (~3-min cycles) with variable pressure settings range between 5 and 75 mm Hg (Holwerda et al., 2013). Investigation of optimal periodisation of contemporary methods of cryo-compression compared to passive recovery is limited in the evidence base and research existing in this area is predominantly focused on CWI (Gill et al., 2006; Roberts et al., 2015) or whole-body cryotherapy chambers (Haq et al., 2018). Furthermore, measures to quantify the effect of cooling predominantly draw conclusions from physiological responses (Gill et al., 2006), whereas the addition of functional biomechanical investigation such as eccentric hamstring strength is limited. Biomechanical measurement of eccentric strength is often quantified through temporal changes in peak isokinetic torque via isokinetic dynamometry, with studies investigating lower limb strength outputs in relation to sports injury risk (Rhodes and Alexander 2018; Isik et al., 2018). Furthermore, previous reliability of the Nordic exercise is reported (Opar et al., 2013), with subsequent studies reporting the Nordbord® testing method as a reliable field-based method to quantify strength and assessment of imbalances (Opar et al., 2013; Buchheit et al., 2016). Notably physiological reductions of skin surface temperature (T_{sk}), is recognised following cryotherapy, through the application of Infrared Thermography (IRT), to obtain whether deeper physiological responses occur post superficial cooling (Moreira et al., 2017). To our knowledge however, no data exists that considers the effect of the Game Ready® as a recovery method investigating both physiological and biomechanical outcomes in footballers following fatiguing exercise.

The aim of the present study therefore is to investigate hamstrings eccentric strength (HES) responses following exposure to the Game Ready® cryo-compression device applied as a recovery modality after a bout of fatiguing exercise replicating the demands of football. We hypothesise that cooling will significantly reduce T_{sk} and that cryo-compressive exposure will affect levels of eccentric hamstring strength recovery profiles compared to passive intervention of rest. The findings of this study aid the understanding of the potential use of contemporary methods of cryo-compression to attenuate eccentric exercise fatigue in football populations, impacting decision-making of sports medicine and performance practitioners.

2. Methods

2.1. Trial design

This study was a randomised crossover design. Independent variables were the cooling intervention, population group, and fatigue protocol and time points between interventions. Dependent variables included skin surface temperature and eccentric strength of the hamstrings using the Nordbord®.

2.2. Participants

Eighteen healthy male football players volunteered to take part (23.8 ± 3.5 years, height 174.3 ± 8.0 cm, weight 71.2 ± 11.6 Kg, BMI = 23.4). Participants were included if they took part in first team of the British Universities & Colleges Sport standard (BUCS) football, with a minimum of training and competitive fixtures accumulative of 3–4 sessions per week, injury free and with a normal BMI (BMI = 18.5–25). Participants were not eligible if they presented with any lower limb pain, history of lower limb injury or surgery in the last six months, outside the age range of 18–40 years old or had any known neurological compromise to cold, such as Raynaud's. The process of this study commenced according to the 2013 Declaration of Helsinki and was approved by the university ethics committee. After reading the participant information, volunteers completed a Physical Activity Readiness Questionnaire (PAR-Q) and provided written and verbal consent prior to commencement of data collection.

2.3. Procedure

Data collection took place in a movement analysis laboratory. To minimise the influence of pre-existing fatigue from competitive fixtures or normal training schedules, participants were advised to not partake in any fatiguing exercise other than their normal training regime and playing fixture that week. Testing of the two conditions took place three days after a competitive fixture (match day +3). Participants were randomly allocated (randomization.com) to receive either cryo-compression (CC) or passive intervention (rest for 15-min in prone lying) (R), returning one week later for exposure to the opposite intervention. On arrival to the movement analysis laboratory, participants underwent a 15-min acclimatisation period supporting previous study methods (Rhodes and Alexander, 2018), to ensure a steady thermal state with anthropometric measurements collected during the acclimatisation period. Data was collected at three timepoints; pre-IFT, IPFT and IPI (CC or R). The term 'immediately' implies that all measures were taken within 10 s after exposure to fatigue or the intervention (CC or R).

2.4. Yo-Yo intermittent fatigue test (IFT)

Participants performed the Yo-Yo IFT (Level 1) protocol detailed previously (Bangsbo et al., 2008) with an aim to provide an overall measure of physical fitness initiating fatigue from high-intensity intermittent running. On completion of the IFT, measures of EHS and T_{sk} were collected and participants were exposed to receive CC or R as per the randomisation allocation.

2.5. Hamstrings eccentric strength

Quantification of the functional strength of the hamstrings was completed utilising the Nordbord (VladPerformance, Queensland, Australia), where bilateral strength metrics of AvT and PT were utilised for analysis. During the eccentric strength measures completed on the NordBord all participants were told to execute maximal effort, performing a single set of three repetitions. Prior to completion the anthropometric profile of the player is entered in to the ValdPerformance Scoreboard application. Measures included height (cm), weight (kg) and knee position on the NordBord (cm). A note of the players knee position was documented by the researcher to ensure standardisation from pre-post intervention testing during the protocol. Participants lower legs are hooked in to the 360° sensors, asked to cross their arms across their chests and keeping hips neutral lowering themselves down as far as they can or to the point of break where they are told to use their hands to stop themselves falling to the floor. Once completed the information from the sensors on the Nordbord is exported to the ValdHub software, where the individual player output is translated. An average score of the three repetitions was taken for analysis for both AvT and PT from the ValdHub.

2.6. Cryotherapy application

A clinically relevant cooling dose of 15-min via the Game Ready® device was applied, supporting previous cooling dosage representative of pitch-side or half-time applications in sports medicine (Bleakley et al., 2012). Target temperature was manually set to 10 °C and high compression (75 mm Hg) as per manufacturer options, with standard ~3-min pneumatic intermittent cyclic pressure application, applied to the dominant limb using the thigh wrap. Once the intervention period had finished, T_{sk}, and eccentric knee flexor strength data were collected in the same way as pre-intervention/pre-fatigue data collection.

2.7. Skin surface temperature (T_{sk})

Posterior thigh T_{sk} was collected via infrared thermology (IRT) (ThermoVision A40M, Flir Systems, Danderyd, Sweden) at pre-IFT, IPFT and IPI. Protocol for measuring T_{sk} followed the Thermographic Imaging in Sports and Exercise Medicine (TISEM) guidelines (Moreira et al., 2017). Participants were requested not to drink any alcohol, intake any stimulant beverage at least 12 h before testing commenced, avoid fatigue inducing exercise 24-h before testing, refrain from heavy meals, application of moisturising creams or exposure to UV-rays (De Oliveira et al., 2018). This process minimised external factors that may affect local cooling interventions and standardised the study protocol. The area of skin monitored over the dominant hamstring was determined via a region of interest (ROI) as recommended in the TISEM guidelines (Moreira et al., 2017). To create an anatomical region of interest over the posterior thigh, application of thermally inert skin surface markers formed a framework (Hardaker et al., 2007). Location of inert markers created a polygon shape for ROI analysis over the hamstring region. Originating from the ischial tuberosity, to both lateral and medial borders of the thigh, moving inferiorly to the condyles of the femur, eliminating the popliteal fossa. The thermal imaging camera was situated at a height of 135 cm from the ground, positioned perpendicular to the anterior lower limb, with participants laying prone on a soft mat. The setup follows standard clinical set up with an emissivity camera setting of 0.97–0.98 (Moreira et al., 2017). Ambient room temperature monitored at the point of testing for each participant was consistent. Thermographic images were analysed using software, Thermacam Researcher version 2.8 (FLIR Systems).

2.8. Statistics

A univariate repeated measures general linear model was used to quantify main effects for time and condition. Interaction effects were quantified, and significant main effects in recovery duration were explored using post hoc pairwise comparisons with a Bonferonni correction factor. The assumptions associated with the statistical model were assessed to ensure model adequacy. To assess residual normality for each dependant variable, q-q plots were generated using stacked standardised residuals. Scatterplots of the stacked unstandardized and standardised residuals were also utilised to assess the error of variance associated with the residuals. Mauchly's test of sphericity were completed for all dependent variables, with a Greenhouse Geisser correction applied if the test was significant. Partial eta squared (η^2) values were calculated to estimate effect sizes for all significant main effects and interactions. Partial eta squared was classified as small (0.01–0.059), moderate (0.06–0.137), and large (>0.138). All statistical analysis was completed using PASW Statistics Editor 26.0 for windows (SPSS Inc, Chicago, USA). Statistical significance was set at $P \leq 0.05$, and all data are presented as mean ± standard deviation.

3. Results

Mean ± SD data for temporal response of recovery on PT and AvT after cooling or rest is displayed in Table 1 and Figs. 1 and 2.

3.1. Skin surface temperature (T_{sk}) (°C)

T_{sk} data demonstrated statistically significant decreases following cryo-compression exposure over the posterior thigh ROI for all timepoints compared to pre cryo-compression temperatures, IPFT ($P = \leq 0.001$) (Table 1).

3.2. Isokinetic dynamometry

3.2.1. Peak torque (PT)

Overall data displayed no significant main effects for timepoint ($F = 0.329, P = 0.721, \eta^2 = 0.06$) or condition ($F = 0.253, P = 0.616, \eta^2 = 0.02$) were displayed for PT. There was no timepoint × condition interaction ($F = 0.105, P = 0.900, \eta^2 = 0.002$) for PT. Collapse of the data by condition (CC/R) demonstrated no significant effect for time (CC: $F = 0.419, P = 0.660, \eta^2 = 0.16$; R: $F = 0.190, P = 0.828, \eta^2 = 0.07$) for PT.

3.2.2. Average Torque (AvT)

Overall data for AvT displayed no significant main effects for timepoint ($F = 0.824, P = 0.441, \eta^2 = 0.16$) or condition ($F = 0.32, P = 0.858, \eta^2 = 0.00$) were displayed. There was no timepoint × condition interaction ($F = 0.53, P = 0.949, \eta^2 = 0.01$) for AvT. Collapse of the data by condition (CC/R) demonstrated no significant effect for time (CC: $F = 0.585, P = 0.561, \eta^2 = 0.02$; R: $F = 0.281, P = 0.756, \eta^2 = 0.11$) for AvT.

4. Discussion

The aim of the study was to investigate physiological and biomechanical responses of a cryo-compressive device applied as a recovery modality after a bout of fatigue compared to rest.

Table 1
Skin Surface Temperature (T_{sk}) (°C), Peak (PT) (N·m) and Average Torque (AvT) (N·m) for the dominant limb for each timepoints.

	Outcomes Measure – Skin Surface Temperature (T_{sk}) (°C)		Outcomes Measure – Average Torque (AvT) and Peak Torque (PT) (N·m)	
Time Point	Cooling Intervention – Game Ready® (15-min)	No Intervention – Rest (15-min prone lying)	Cooling Intervention – Game Ready® (15-min)	No Intervention – Rest (15-min prone lying)
Dominant Limb				
Pre-Fatigue Protocol	31.5 ± 0.65 °C	30.2 ± 0.5 °C	144.4 ± 35.2 (AvT) 174.1 ± 47.7 (PT)	144.4 ± 35.2 (AvT) 174.1 ± 47.7 (PT)
Immediately Post Fatigue Protocol	29.0 ± 0.4 °C	29.1 ± 0.5 °C	139.8 ± 33.9 (AvT) 170.6 ± 45.4 (PT)	139.2 ± 30.8 (AvT) 170.7 ± 41.7 (PT)
Immediately Post Intervention	16.5 ± 1.7 °C	31.4 ± 3.8 °C	132.5 ± 27.4 (AvT) 160.8 ± 37.7 (PT)	136.5 ± 27.0 (AvT) 165.4 ± 34.3 (PT)

* Significant reduction in skin surface temperature (T_{sk}).

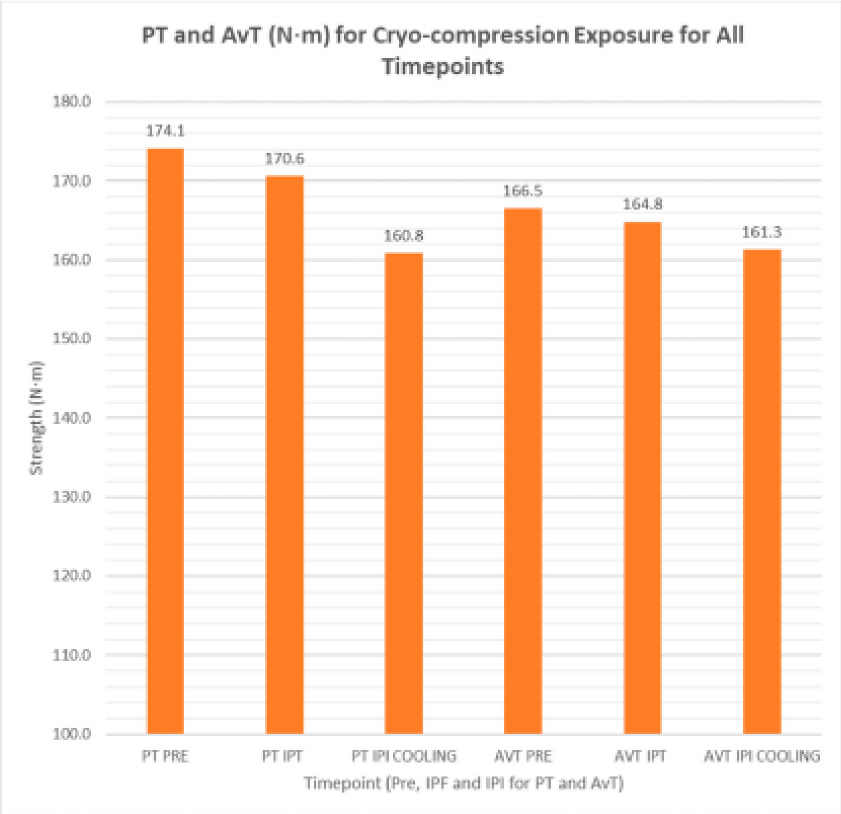

Fig. 1. Peak (PT) and Average Torque (AvT) (N·m) for cryo-compression across each timepoint.

Although mean differences were displayed in PT and AvT following the YoYo IFT and after each intervention (Table 1), no significant main effects were displayed in AvT or PT for HES immediately following either intervention (R/CC) compared to pre-IFT or IPFT measures. Significant decreases in T_{sk} were reported IPI for CC (Table 1), however temperature fell outside of the suggested therapeutic range for beneficial physiological responses to occur (Kennet et al., 2007). Biomechanical function was quantified through measures of EHS and physiological T_{sk} responses in a population of healthy male footballers. Results are indicative toward acute muscle strength loss over time following eccentric contractions (Douglas et al., 2017) although non-significant reductions displayed in the present study were not consistent with previous research highlighting reductions of 20–30% in hamstring strength post soccer specific protocols (Greig 2008). With the Yo-Yo IFT initiating only a 7–12% decrease in strength metrics in the current study suggest may be a reason for the insignificant reductions in strength and subsequent non-significant changes post intervention. This may be attributed to the exclusion of sprinting and high-speed multi directional running within the Yo-Yo IFT, potentially decreasing the exposure of the hamstrings to high velocity and high load movement patterns. Future research should consider high velocity; high load fatiguing protocols to induce higher levels of fatigue and determine further effectiveness of recovery strategies.

The non-significant changes may also be attenuated to the superficial skin temperatures achieved from the cooling modality and with only functional measure of hamstring strength taking place

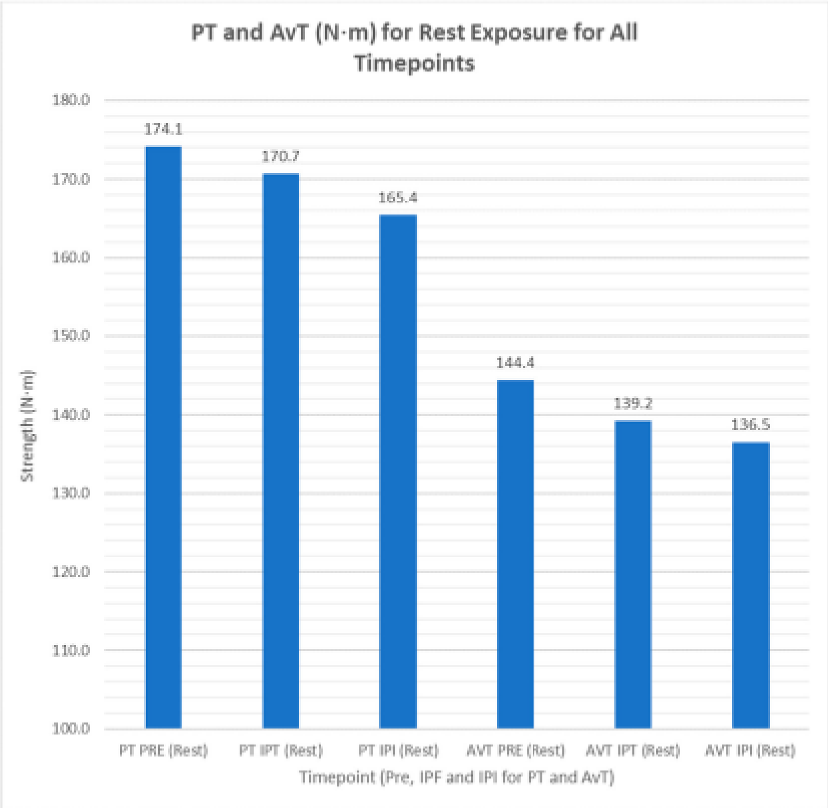

Fig. 2. Peak (PT) and Average Torque (AvT) (N·m) for rest across each timepoint.

immediately following exposure without consideration of a rewarming period of observation. Although statistically significant reductions in T_{sk} were reported post cryo-compression over the posterior hamstring (*P* = < *0.05*), average T_{sk} did not meet suggested therapeutic range of between 10 and 15 °C (Kennet et al., 2007), with the lowest T_{sk} recorded at 15.9 °C in the current study. Although reflecting shorter cooling exposures to imitate applied management of injury or recovery sessions in sporting environments (Chan et al., 2016), it is evident that to achieve therapeutic response a longer duration or cooler target temperature may affect resultant strength parameters. That said, phase change capabilities of cooling modalities influence T_{sk} response and consequently duration of exposure, and as such requires consideration for adaptation of cooling protocols. Modalities with more efficient phase change may produce lower T_{sk} for the same duration. Chan et al. (2016) applied a dosage time of 15-min in a comparable protocol to ours using the same contemporary cooling device as a recovery method following a maximal cycling test. Our findings are consistent with their results (Chan et al., 2016; Allan and Mawhinney 2017), whereby agreement that no significant differences in recovery markers were noted following the same intervention dose and cooling modality. Although differences in recovery outcomes measures and testing environment reduce direct comparison of results between the studies.

Cryotherapy following resisted exercise may cause attenuation of the desired adaptive muscle strength response (Douglas et al., 2017) and the avoidance of immediate cooling in this scenario is advised (Ihsan et al., 2020). Alternatively, acute strength output has been shown to be negatively affected by local cooling applications (Alexander and Rhodes, 2019). This is largely observed following exposure to CWI (Leeder et al., 2012; Fröhlich et al., 2014), or without the consideration of fatigue (Alexander and Rhodes, 2019), therefore it is difficult to confer whether the Game Ready® device produces synonymous effects on muscle strength parameters. Debate as to whether passive recovery is preferable to cooling following fatiguing exercise is evident, however due to the additional effects on perceived soreness and psychological influences, cooling remains a popular recovery option in sport and considered an effective way to reduce symptoms of acute onset post-exercise fatigue (Leeder et al., 2012). Perception of cooling in respect to recovery was not quantified in the current study however.

Suggestions in literature report a quadratic relationship between T_{sk} and intramuscular muscle tissue temperatures in response to superficial cooling (Hardaker et al., 2007); hypothetically, changes in muscle strength observed over a longer rewarming period may pose further consideration into the impact on strength recovery. In this context, recent studies report similar findings through investigation of concentric quadriceps strength following direct cooling over the anterior thigh whereby strength did not return to pre-intervention scores over a longer observed rewarming period (Rhodes and Alexander 2018; Alexander and Rhodes 2019). Further comparison with longer applications of cold via Game Ready® may achieve therapeutic skin temperatures consistent with previous studies and modalities such as CWI. Consequently, we assume greater or different effects on EHS in a recovery context. Observation of eccentric hamstring strength over a rewarming period may have been beneficial, as we assume that intramuscular temperatures may have continued to fall after the removal of cooling. In addition, consideration must be given to the timing of cooling and the justification for its use. This presents a contemporary debate within multi-disciplinary performance departments surrounding the timing and appropriateness of cooling modalities as a recovery intervention. Ultimately, sports medicine and performance practitioners need to consider possible risks and benefits offered by cryotherapy/cryo-compression for recovery. It is evident that time frame, mode and dose of cryotherapy/cryo-compression require further investigation in this context reflected through a battery of performance measures that reflect physical and psychological perturbations following fatiguing exercise. Future studies should aim to decipher the mechanisms of cryotherapy and consider the multiple variables influencing application and optimisation of cooling strategies using cryo-compression.

Justification to identify relevant recovery modalities using cryotherapy and to define optimum recovery protocols in sport are highly suggestive throughout current literature (Chan et al., 2016; Oakley et al., 2013). The current study supports the applied nature of research for practical applications; however, it is not without its limitations. Firstly, we anticipated the fatiguing protocol in the current study to effectively induce eccentric muscle fatigue in the hamstrings (Greig, 2008) and although reductions in strength following the IFT were noted in the data, the non-significant strength loss results make it difficult to determine the extent of the effect of conditions (CC/R) on eccentric strength recovery. Therefore, it may be more appropriate for future studies to investigate such interventions within real sports settings that replicate sport-specific training to induce fatigue using a range of multi-measure objective and subjective performance indicators. Future studies should consider follow-up measures at increments over a longer period to investigate further observations of change in eccentric strength. This may support further investigation of known biomechanical responses to cooling through rewarming periods and provide useful data through assessment of relevant applied clinical markers and outcomes measures advantageous in the field. Current results cannot be extrapolated to female subjects; therefore, future methodologies may consider gender response to similar practices of fatigue and recovery effect of such protocols. Future research considerations would benefit investigation of eccentric muscle strength after longer or cooler dose applications. The comparison of Game Ready® to Cold Water Immersion protocols for recovery may also be useful as both modalities are commonly applied in elite sport settings, yet agreement on optimal applications is not yet fully elucidated. This may present beneficial information to help determine optimal responses to different cryo-compressive modalities for lower limb recovery in sport.

5. Conclusion

Acute response in HES after exposure to cryo-compression or rest applied immediately following a fatiguing protocol reported non-significant changes. Consequently, several factors influencing these findings require further exploration to maximise beneficial application of contemporary cryo-compression applications in sport. The application of simultaneous cooling with intermittent compression significantly reduced T_{sk} over the posterior thigh, although longer dose durations may be recommended (>–15) to achieve therapeutic range. Consequently, this may influence beneficial physiological responses in deeper tissues optimising practical applications of cryo-compression as a recovery strategy in sport. The consideration of optimum application of cooling to enhance recovery from muscle-damaging exercise is required as the continuation of muscle strength declines is not desirable for subsequent performance demands in sport. Optimal recovery methods in sport, including the proposed benefits of contemporary cryotherapeutic protocols are yet to be determined and require sport-specific fatigue protocols or in-season data capture with multi-measures of performance representative of the sport to ensure greater ecological validity. Studies that compare multiple performance measures including perceptual response require further consideration, alongside the investigation of periodisation and dose-response of contemporary cryo-compression modalities to benefit individualised recovery approaches in sport.

5.1. *Clinical relevance*

- No significant changes in EHS reductions were noted following cryo-compression or rest following the YoYo IFT.
- Cryotherapeutic dose-response relationships applied after muscle-damaging exercise require further investigation to optimise understanding of cooling recovery strategies.
- Multi-measure of performance over rewarming periods, within competitive training schedules are required to develop optimal cooling protocols advantageous for recovery.

CRediT authorship contribution statement

J. Alexander: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **J. Jeffery:** Investigation, Resources, Writing – review & editing, Visualization, Dr David Rhodes, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization.

Declaration of competing interest

None.

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Effects of contemporary cryo-compression on post-training performance in elite academy footballers

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ABSTRACT: Fatigue is a predisposing risk factor for injury commonly investigated in elite football populations. Little evidence advocates the most beneficial recovery strategies including contemporary cooling applications. The aim of the study was to examine immediate effects of the Game Ready® on physiological and biomechanical measures in a population of elite male academy footballers, following a fatiguing training session mid-competitive season. Twenty, elite male footballers took part (180.2 ± 8.7cm, 75.0 ± 11.4kg, 18 ± 0.5years). Following a normal fatiguing training session, players were randomly assigned to receive either cryotherapy (Game Ready®) (20-minutes at medium compression (5–55 mm Hg)) or passive recovery (PAS). Data was collected at match-day+1, immediately post-training and immediately post-intervention. Performance measures included countermovement jump (CMJ), isometric adductor strength (IAS), hamstring flexibility (HF), and skin surface temperature (T_{sk}). Significant main effects for group for CMJ data following exposure to cooling were displayed ($p = < 0.05$). Individual group analysis displayed a significant reduction in CMJ performance in the group exposed to cryotherapy ($p = < 0.05$) immediately post, but not for PAS. No main effects were identified for cryotherapy or PAS group for IAS or HF ($p = > 0.05$). T_{sk} reduced significantly ($p = < 0.05$) in the cryotherapy group, meeting therapeutic T_{sk} range. Reductions in performance immediately following exposure to pneumatic cryo-compressive devices may negate the justification of this recovery strategy if neuromuscular mechanisms are required in immediate short term. Application of such recovery strategies however are dependent on the type of recovery demand and should be adapted individually to suit the needs of the athlete to optimise readiness to train/play.

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INTRODUCTION

To optimise post-training recovery response to fatigue is desirable and several strategies are proposed within the literature to prepare athletes for in-season training demands [1, 2]. Perceptions and practices used in the practical setting however are not always supported by validated recommendations from research and vice versa [1]. Without appropriate recovery strategies optimal competition performance may be hindered or result in an increased risk of injury [3, 4]. Between bouts of fatiguing exercise through competitive season training cycles, the maintenance of muscular performance and function is required, and choice of recovery strategy or modality to achieve this is important [3, 5]. The effects of cryotherapy as an acute recovery strategy, measurable by performance parameters in sport, are debated in terms of periodisation and impact following training [2, 6]. Typically, the application of cooling is often utilised with the aim to reduce the symptoms of fatigue [7, 8], mitigating the consequence of reduced performance levels or perceptual indices of recovery in elite football/soccer. Equivocal evidence however fails to consolidate understanding around the effects of cryotherapy on muscular function in relation to optimal recovery through performance markers.

A large proportion of practitioners administer CWI post daily training and base the choice of modality on practicality and accessibility [2]. Inappropriate periodisation or choice of cryotherapy modality however has the potential to impact negatively the adaptations intended from training [9, 10], despite known physiological benefits. Dose-response in terms of duration of application presents further disparities thus failing to present agreement on optimal recovery protocols using cryotherapy. Many studies report on the use of CWI [2, 11] on pertinent football performance parameters however the same cannot be reported for many contemporary cryo-compressive devices, such as the Game Ready® (CoolSystems, Inc). A consensus on optimal protocols in terms of periodisation of cooling applications using cryo-compressive devices is also absent.

To further the understanding on current recovery practices in elite sport settings with the aim to develop cryotherapy protocols for within-season post training recovery, the effects of contemporary cryotherapeutic cooling devices on common performance parameters requires investigation. Conjecture in the current literature recommends the investigation of cooling recovery modalities with the target of informing evidenced-based prescription around professional team sport schedules [2]. The aim of the current study was to examine the immediate physiological and biomechanical performance effects of the Game Ready® as a recovery strategy in a population of male elite academy footballers, following a fatiguing training session during mid-competitive season.

MATERIALS AND METHODS

Subjects

Twenty, elite male academy footballers volunteered to take part in the study (height: 180.2 ± 8.7cm, weight: 75.0 ± 11.4kg, age: 18 ± 0.5years). The purpose of the study was presented to each participant with an information sheet outlining the protocol. All players provided written and verbal consent to take part. All players met the inclusion criteria (academy age group footballer, healthy, male, no current injury to the lower limbs). Players were excluded from the study if they presented with; current / history of lower limb injury/ surgery in the last six months; female; outside academy age range, known neurological compromise to cold, such as Raynauds [12]. Ethical approval for the study was approved by the host university and adhered to the Declaration of Helsinki (2013), data collected was permitted for publication via the host football club. The same researchers collected each data from the physiological and biomechanical assessments throughout the study.

Testing Protocol

Data collection took place in a rehabilitation testing suite at the football club, mid-competitive academy season. Players were randomly allocated to receive either passive recovery (PAS) (Group 1) or cryotherapy intervention (CRYO) (Group 2) post fatiguing exercise coinciding with normal weekly training schedules (Table 1). Familiarisation of the biomechanical and psychological assessments were not required as these tests are regularly performed by the squad and participants therefore conversant of each outcome measure. Baseline measures were collected at match day+1 consisting of hamstring flexibility (HF) via sit and reach test (SRT) (Apollo Sit & Reach Box), neuromuscular function (NMF) through a countermovement-jump (CMJ) (OptoJump System, Microgate, Bolzano, Italy) and isometric adductor strength (IAS) quantified by a Sphygmomanometer (Disytest; Welch Allyn, Skaneateles, NY). Intervention of either PAS or CRYO commenced on match day+3 following a fatiguing training session (Table 1). PAS group consisted of 20-minutes laying still in a semi-recumbent position on a plinth. The cryotherapy intervention utilised in the CRYO group consisted of the Game Ready® pneumatic-cooling device applied to both lower limbs (circumferentially wrapped around the thigh) for a 20-minute dose with medium intermittent compression (5–55 mm Hg). One Game Ready® base unit was used and two lower limb cuffs connected with a splitter device allowing for the crushed ice and water contents to circulate both limb cuffs. Individuals remained in a supine semi-recumbent position on a plinth during application.

Physiological Measure

Thermal images were taken of the hamstring and quadriceps of both limbs before and after either intervention. Skin surface temperature (T_{sk}) collected using Infrared Thermal Imaging (ThermoVision A40M, Flir Systems, Danderyd, Sweden) followed standard protocol set up of the TISEM guidelines [13] capturing three images per region of interest (ROI) with analysis taking the mean average T_{sk}. Emissivity settings were 0.97–0.98 following normal clinical approaches with the thermal imaging camera situated at 134cm from the ground perpendicular to the lower limb [14]. Images of the anterior thigh were taken initially, followed by the posterior thigh turning from a supine to prone position on the plinth. Over the anterior thigh a ROI was determined by placing thermally inert markers providing a framework to quantify T_{sk} [15]. Location of markers included superiorly (one-third way between anterior superior iliac spine (ASIS) and base of the patella) and inferiorly (two thirds way between ASIS and base of the patella) with central anterior thigh determined by measure of thigh circumference, 50% between ASIS and base of patella [14]. Posterior markers were applied in a similar fashion, applied superiorly one-third from the ischial tuberosity to the lateral epicondyle of the femur and inferiorly two-thirds from the lateral epicondyle of the femur to ischial tuberosity. Centre of the posterior thigh determined by thigh circumference in the same approach as the anterior thigh marker placement. Markers were then placed at 10% medially and laterally from these marker locations to complete a ROI for the posterior thigh. To complete the ROI, markers were applied at 10% of the distance in lateral and medial directions from the centre of the thigh for both anterior and posterior regions.

Ambient room temperature monitored at the point of testing for each participant was measured to ensure consistency throughout testing and to monitor any fluctuations (21.8 ± 0.7°C).

Performance measures protocols

CMJ height as a form of quantifying neuromuscular function was performed. Excellent test-retest reliability (ICC 0.982–0.989) has been demonstrated for the Optojump system [16] for field-based assessment of CMJ with acknowledgement in contemporary literature as being the most accurate when comparing to other portable devices used to measure neuromuscular parameters [17]. To perform the CMJ participants positioned themselves in-between the infrared platform (OptoJump System, Microgate, Bolzano, Italy) with both feet (wearing trainers) on the ground, shoulder width apart with their hands on their hips throughout the full CMJ [18]. To execute the jump players flexed their knees to their preferred starting push-off position [19]. The decision to keep hands-on-hips was based upon the approach that suggests hands-on-hips isolates lower extremity force production and eliminating potential arm-swing and postural variations [18, 20]. Taking off from this position the participant was instructed to jump as high as they possibly could and landed back on both feet. Trials were validated by the researcher through visual inspection to ensure satisfactory landing and participants performed three trials, separated by 45 seconds of passive recovery [21]. Jump height of each player was calculated by flight time (cm) and best jump used for analysis [21].

Isometric Adductor Strength (IAS)

For IAS measures, participants lay in a semi-supine position, hips flexed at 45°, with the sphygmomanometer placed in-between both legs at the medial aspect of the knees [22]. The sphygmomanometer was set to 10 mm Hg tension prior to each session [22]. When relaxed participants then squeezed the cuff in between their legs as forcefully as they could for 3 seconds and a score was recorded.

Hamstring Flexibility (HF)

HF was quantified via the SRT (Apollo Sit & Reach Box). Participants removed their trainers to perform the SRT, in a half-sitting position with knees in full extension, and both feet flat against the SRT box. The bar was slowly pushed as far as possible with palms facing down and tips of fingers moving forwards [23]. To the nearest cm the range was calculated. Participants repeated the test once for analysis per each timepoint.

Statistical Analysis

Statistical analysis was performed using SPSS (Version 26.0) (SPSS Inc, Chicago, IL). The statistical significance was set at $p = \leq 0.05$ with all data presented as mean ± (SD) with 95% confidence limits. A univariate repeated-measures general linear model quantified the main effects across all timepoints and interventions for biomechanical and physiological measures. Post-hoc analysis with a Bonferonni correction for performance parameters explored any significant main effects. To assess residual normality for each dependant variable, q-q plots were generated using stacked standardised residuals. Scatterplots of the stacked unstandardized and standardised residuals were utilised to assess error of variance associated with the residuals. The assumptions associated with the statistical model were assessed to ensure model adequacy. Mauchly's test of sphericity were completed for all dependent variables, with a Greenhouse Geisser correction applied if the test was significant. Partial eta squared (η^2) values were calculated to estimate effect sizes for all significant main effects and interactions. Partial eta squared was classified as small (0.01–0.059), moderate (0.06–0.137), and large (> 0.138).

RESULTS

Physiological Measures (T_{sk})

Overall analysis identified a significant main effect of group and timepoint for quadriceps (Group: $F = 93.38$, $p = < 0.00$, $\eta^2 = 0.940$; Timepoint: $F = 84.69$, $p = < 0.00$, $\eta^2 = 0.966$); and hamstrings T_{sk} (Group: $F = 2136.41$, $p = < 0.00$, $\eta^2 = 0.997$; Timepoint: $F = 2060.27$, $p = < 0.00$, $\eta^2 = 0.999$). Significant interaction was displayed for group *x* timepoint for quadriceps ($F = 91.08$, $p = < 0.00$, $\eta^2 = 0.968$) and hamstrings T_{sk} ($F = 1993.0$, $p = < 0.00$, $\eta^2 = 0.998$). Statistically significant decreases in T_{sk} over the quadriceps and hamstrings ROI's immediately post-intervention, compared to immediately post-training and baseline temperatures for the Cryo group were displayed ($p = < 0.05$). No significant differences in T_{sk} were reported for the PAS group across any timepoint (Table 2).

Biomechanical Measures (CMJ, IAS, HF)

Overall analysis for the biomechanical data set displayed significant main effects group ($F = 5.005$, $p = 0.029$, $\eta^2 = 0.85$), but not timepoint ($F = 1.028$, $p = 0.365$, $\eta^2 = 0.037$) for CMJ. No

TABLE 1. Data collection protocol.

		Weekly Post Match Day Training Schedule		
		Match Day +1	Match Day +2	Match Day +3 Scheduled Training
Time Point (1–3)		1. Baseline Data Collected *	No data collected	2. Post Training 3. Immediately Post Intervention
GROUP	Group 1 (PAS)	Baseline Data Collected *	No data collected	Post training data collected * Immediately post (PAS) data collected *
	Group 2 (Cryo)	Baseline Data Collected *	No data collected	Post training data collected * Immediately post (Cryo) data collected *

*Data collection at all timepoints consisted of; Performance measures = Countermovement Jump (CMJ); Isometric Adductor Strength (IAS), Hamstring Flexibility (HF); Skin Surface Temperature (T_{sk}) of hamstring and adductors.

TABLE 2. Descriptive (mean ± SD) for hamstring and quadriceps ROI, for both PAS and Cryo groups across all time points.

Group	ROI**	Limb	Time Point: Baseline (T_{sk}) (°C)	Immediately Post Training (T_{sk}) (°C)	Immediately post intervention (T_{sk}) (°C)
PAS	Quadriceps*	LEFT	30.7 ± 1.5	30.2 ± 0.2	31.1 ± 0.8
		RIGHT	30.1 ± 1.2	29.9 ± 0.5	30.0 ± 0.5
	Hamstrings*	LEFT	30.9 ± 1.2	30.1 ± 0.9	30.2 ± 0.5
		RIGHT	30.5 ± 0.8	29.8 ± 0.8	30.1 ± 0.4
	Average T_{sk} (quadriceps and hamstrings both limbs) (°C)		30.5 ± 1.2	30.0 ± 0.6	30.2 ± 0.6
Cryo	Quadriceps*	LEFT	30.1 ± 1.2	29.9 ± 1.1	10.8 ± 1.1
		RIGHT	30.5 ± 1.3	30.1 ± 1.2	14.3 ± 1.2
	Hamstrings*	LEFT	29.8 ± 1.3	30.6 ± 1.1	11.3 ± 1.3
		RIGHT	29.5 ± 0.9	30.5 ± 1.2	12.8 ± 1.4
	Average T_{sk} (quadriceps and hamstrings both limbs) (°C)		29.8 ± 1.2	30.3 ± 1.2	12.3 ± 1.3

*Bilateral limb T_{sk} measures (mean ± SD). **ROI = Region of Interest. ***Significance at *p = < 0.001*

Table 3. Descriptive (mean ± SD) for biomechanical measures of CMJ, IAS and HF for both PAS and Cryo groups across all time points.

GROUP	PERFORMANCE PARAMETER	TIMEPOINT: Baseline (match day+1)	Immediately Post Training (IPT) (match day +3)	Immediately Post Intervention (IPI) (match day +3)	Percentage change (%) from IPT to IPI time point
PAS	*CMJ (Jump Height – cm)*	35.1 ± 5.1	34.7 ± 5.5	35.2 ± 5.1	+1.43%
	HF (cm)	24.0 ± 5.5	22.4 ± 5.3	22.6 ± 4.7	+0.88%
	IAS (mm Hg)	224.0 ± 41.9	231.9 ± 51.9	235.0 ± 55.8	+1.33%
Cryo	*CMJ (Jump Height – cm)*	33.2 ± 4.7	33.8 ± 5.1	29.3 ± 4.2*	-13.3%
	HF (cm)	24.5 ± 5.6	24.1 ± 5.9	24.2 ± 5.9	+0.41%
	IAS (mm Hg)	215.0 ± 41.9	215.0 ± 51.9	220.0 ± 71.3	+2.2%

CMJ = Countermovement Jump; IAS = Isometric Adductor Strength; HF = Hamstring Flexibility; *Significance at *p = < 0.05 data compared to baseline.*

significant main effects were displayed for group or timepoint for IAS (Group: *F = 0.977, p = 0.327,* $\eta^2 = 0.018$; Timepoint: *F = 0.112, p = 0.894,* $\eta^2 = 0.004$) or HF (Group: *F = 0.918, p = 0.342,* $\eta^2 = 0.017$; Timepoint: *F = 0.68, p = 0.935,* $\eta^2 = 0.003$). No significant interactions were displayed between group *x* timepoint for CMJ, IAS or HF (CMJ: *F = 1.345, p = 0.269,* $\eta^2 = 0.047$; IAS: *F = 0.030, p = 0.971,* $\eta^2 = 0.001$, HF: *F = 0.199, p = 0.820,* $\eta^2 = 0.007$).

Collapse of the data into physiological and biomechanical data for Cryo group displayed no significant effects for HF (*F = 0.016, p = 0.984,* $\eta^2 = 0.001$), CMJ (*F = 2.674, p = 0.87,* $\eta^2 = 0.165$), or IAS (*F = 0.026, p = 0.944,* $\eta^2 = 0.002$). For the PAS group no significant effects for HF (*F = 0.281, p = 0.758,* $\eta^2 = 0.020$), CMJ (*F = 0.018, p = 0.982,* $\eta^2 = 0.001$), or IAS (*F = 0.127, p = 0.881,* $\eta^2 = 0.009$). A significant difference is displayed between Cryo and PAS groups for CMJ (*p = 0.02*) regardless of timepoint. Significant reductions in CMJ were reported between immediately-post training and immediately-post cooling timepoints ($p = 0.04$) for the Cryo group (Table 3). No other significant differences at any other timepoint for Cryo group for CMJ data were reported ($p = > 0.05$). For the PAS group no significant differences were displayed for CMJ, HF or IAS data when comparing between each timepoint ($p = > 0.05$). The Cryo group displayed no significant differences between timepoint for IAS or HF ($p = > 0.05$).

DISCUSSION

The study aimed to investigate the effects of a contemporary cryo-compressive cooling device compared to passive recovery on physiological and biomechanical measures following a fatiguing training session within an elite male academy football population. With physical performance known to decline following competitive match play in football [24, 25], optimal recovery strategies are therefore paramount for readiness to train / play performance. Furthermore, the effects of congested schedules on performance and injury risk may be heighted due to accumulative fatigue and literature encourages the need for optimal recovery strategies [24]. Cryotherapy in many forms is used for recovery and is common practice within elite performance settings despite limited evidence for its efficacy or use [26]. The current study observed several parameters, both physiological and biomechanical in nature, representing typical monitoring techniques used during a competitive football season with results demonstrating significant main effects for group, for CMJ data following exposure to cooling (Game Ready®). Further analysis displayed significant reductions in CMJ performance (jump height) in the group exposed to cryotherapy (CRYO) ($p = < 0.05$) immediately post exposure following a fatiguing training session, the same was not demonstrated in the PAS group. No main effects were identified for the CRYO or PAS group for IAS or HF ($p = > 0.05$). Results have implications of decision-making for the use of the Game Ready® device to optimise its application as a recovery strategy compared to passive recovery in an elite football setting. Findings support the multifaceted approach of athlete monitoring in practice; replicated in research this helps determine response to common strategies applied in elite performance settings through relevant applied markers.

T_{sk} reduced significantly ($p = < 0.05$) in the CRYO group across both ROI's (hamstring and quadriceps), compared to IPT timepoint, meeting therapeutic T_{sk} range for physiological changes to ensue, according to previous literature [27]. Similar T_{sk} responses after Game Ready® applications are reported in recent literature [28] albeit varying slightly thought to be due to levels of compression adjunct between the available protocols offered by the device and differences in methodological approaches between studies. The Game Ready® protocol chosen in the current study represented a typical application of contemporary cryo-compression method used in the club where data was collected. Although T_{sk} was not consistent bilaterally (Table 2), results support this protocol if the target aim is to successfully reduce T_{sk} to within therapeutic range circumferentially over the bilateral thigh region in this population. We can only presume intra-muscular response as this was not quantified in this study however, we consider the significant reduction in CMJ in the CRYO group occurred due to physiological changes in deeper structures required for feedback, altering neuromuscular biomechanical output, resulting in a reduced jump height. The effectiveness of recovery protocols is often quantified by neuromuscular function through various assessment of contractile properties. Definitive conclusions as to the effects of cryotherapy on neuromuscular performance however are problematic to draw based on available literature [26]. Previous studies typically quantify the effects of CWI for recovery, using CMJ as a means of measuring neuromuscular performance [29, 30], this is the first study to our knowledge that explores the Game Ready® quantified in a comparable fashion. Results from the current study appear to represent similar findings by Hohenauer et al, (2016) [30], in terms of time-course recovery at immediately post cold exposure, although direct comparisons are limited due to differences in cold modality applied. Perceptual indices were not determined in the current study, which may, as [30] Hohenauer et al (2016) suggests, influence objective performance measures. Quantification of wellbeing parameters should be considered in future study designs of a similar nature to fully elucidate the impact and effects of recovery parameters.

Non-significant changes were displayed for IAS / HF for both groups, and only marginal trends suggesting better increases in IAS measures following cooling compared to PAS depicted by small percentage change from IPT to IPI (Table 3). It was considered, compared to CMJ response however, that players felt more able to better perform isometric contraction following cooling due to analgesic influence on muscle soreness levels, although perceptual responses were not quantified in this study. The choice of performance measure, such as IAS is identified as a useful outcome measure that sports medicine or performance practitioners may implement during a congested season for the assessment of players readiness to compete [31]. That said, eccentric contraction as a damaging exercise and functional assessment of strength may provide better representation of fatigue related to injury risk factors in football and should be considered in future investigations of this nature as a relevant performance measure. Hohenauer et al, (2015) [7] concluded that evidence suggests after muscle damaging exercise, compared to passive strategies, cooling is a superior for recovery, although this conclusion was based on subjective responses alone. Assessment of wellbeing through perceptual responses to fatigue and recovery interventions may be beneficial in future studies to consider alongside physiological and biomechanical indices. In agreement with Ihsan et al (2020) [32] the suggestion of CWI is contextual, and so should the application of cryo-compressive devices in the same setting. A multifaceted approach to research design and parameters of measures is key to fully elucidate the influences on performance both positive and negative that cryotherapy modalities have. The trend of a small incremental increase in HF depicted by percentage change from IPT to IPI in the PAS group, although non-significant, may be explained by the impact cooling has on muscle mechanical properties through reduced stretch in muscle tissue [33]. The combination of objective and psychological measures for overall athlete response to cryotherapy recovery strategies may provide further explanation of biomechanical performances after exposure to such modalities. In addition to this, and a potential limitation in the current study is the period of observation. It would be beneficial to consider further assessment of performance measures again at 24-hours post training/intervention for example given the known temporal patterns of fatigue reported in football [25]. Future study design is recommended over a longer period of investigation, considering multiple micro-cycles to determine cumulative effects of multiple bouts of cryotherapy on several performance measures. Comparison of this protocol using methods such as CWI may be beneficial in future investigations through the additional exploration of individual athlete response.

Beneficial physiological responses to cooling following fatigue are generally focused around the symptom reduction of delayed onset muscle soreness (DOMS) [34] or perceived fatigue [7]. Several mechanisms explain the benefits of across many modes of cryotherapeutic exposures, including minimising muscle damage, inflammation [32] and soreness [35]. Optimal recovery may be determined by complex training load, fatigue and adaptation interactions [10]. Modulated recovery therefore is complex and the effect on performance is contradictory in supporting the benefits for recovery [36]. The outcomes of the current study suggest cryo-compression may negate the potential to perform optimal neuromuscular function immediately post exposure. Despite the physiological benefits highlighted in literature, findings suggest biomechanical function is reduced through the effect on neuromuscular response to cold. Consequently, this may be detrimental to the athlete, emphasising the need for correct periodisation of cryo-compression for maximum benefits of this modality. Although the current study supplements current debate, it only observes the acute effects and a temporal pattern of response is required to examine the effects of cryo-compressive recovery strategies over time (during a typical weekly micro-cycle) or multiple dosages. Safer periods of rewarming prior to functional movements requiring optimal neuromuscular performance following cryo-compression requires further investigation to optimise understanding and periodisation.

Although not demonstrated in this exploratory study, individual analysis of response is important to establish. Average group analysis as portrayed in the current study provides an approach too broad to provide crucial understanding within an applied sports performance setting for individualisation of recovery protocols. In accumulation these considerations in future research would benefit decision making around not only periodisation of cooling modalities within normal training and playing schedules but the individual responses within elite populations. Baseline measures were taken at match day+1, not pre-training, additional data at this timepoint may be more beneficial as a comparison due to the expected reductions in objective performance parameters so soon following a competitive fixture. Table 3 therefore depicts percentage differences from IPT-IPI timepoints as an indication of the meaningful effects of the recovery strategies employed in the current study. These observations have implications on future study design considering at what point data is collected to optimally reflect key markers of athlete recovery within mid-season micro-cycles.

CONCLUSIONS

Variable responses following exposure to the Game Ready® (20-minutes, medium compression (5–55 mm Hg) bilateral (thigh)) compared to passive recovery across several performance measures suggest individualisation of recovery strategies is important. Significant reductions in neuromuscular performance immediately following exposure to pneumatic cryo-compressive devices may negate the justification of this recovery strategy if neuromuscular mechanisms are required in the short term. Application of such recovery strategies however are dependent on the type of recovery demand and should be adapted to suit the needs of the athlete to optimise readiness to train/play. Future investigation into periodisation of contemporary cryo-compressive modalities within training micro-cycles for recovery is required over longer periods to fully elucidate temporal patterns. Multifactorial measures generate better understanding to support or refute the application of such methods currently practiced widely in elite football performance settings. Future studies should consider individual data analysis to establish optimal cry-compressive applications which may be advantageous for the athlete in terms of individualisation of recovery programmes.

Conflict of Interest

There are no conflicts of interest to declare.

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Utilisation of performance markers to establish the effectiveness of cold-water immersion as a recovery modality in elite football

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ABSTRACT: Optimal strategies for recovery following training and competition in elite athletes presents ongoing debate. The effects of cold-water immersion (CWI) compared to passive recovery (PR) though a triad of performance measures after fatiguing exercise within a normal micro-cycle, during mid-competitive training cycle, in elite male footballers were investigated. Twenty-four elite footballers (age 20.58 ± 2.55 years; height 179.9 ± 5.6 cm; weight 75.7 ± 7.5 kg; body fat 6.2 ± 1.7%) were randomly assigned to CWI or PR following a fatiguing training session. Objective measures included eccentric hamstring strength, isometric adductor strength, hamstring flexibility and skin surface temperature (T_{sk}). Subjective measures included overall wellbeing. Data were collected at match day+3, immediately post-training, immediately post-intervention and 24 hrs post-intervention. Physiological, biomechanical and psychological measures displayed significant main effects for timepoint for eccentric hamstring strength, T_{sk}, overall wellbeing, sleep, fatigue, stress and group for eccentric hamstring strength, T_{sk} and sleep (groups combined). Group responses identified significant effects for timepoint for CWI and PR, for eccentric hamstring strength peak force, sleep, fatigue, and muscle soreness for CWI. Significant differences were displayed for eccentric hamstring strength (immediately post-intervention and immediately post-training) for peak force and between CWI and PR eccentric hamstring strength immediately post-intervention. Linear regression for individual analysis demonstrated greater recovery in peak torque and force for CWI. CWI may be useful to ameliorate potential deficits in eccentric hamstring strength that optimise readiness to train/play in elite football settings. Multiple measures and individual analysis of recovery responses provides sports medicine and performance practitioners with direction on the application of modified approaches to recovery strategies, within mid-competitive season training cycles.

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INTRODUCTION

Football requires multi-directional activity where players are exposed to high eccentric muscle loads, commonly associated with injury [1, 2]. Deleterious effects of fatigue post-match have been shown to continue for up to 47 hrs, with, albeit individual minimal recovery exhibited between 24–48 hrs in elite populations [3]. Accordingly, the importance of optimum recovery strategies that allow positive adaptation to competition, maximise performance and reduce the probability of injury [4] is emphasised. The fitness fatigue model [5] and general adaptation syndrome [6] both highlight the importance of recovery before the next competition exposure. Insufficient recovery within this period can heighten injury risk and/or reduce positive training effects [4]. Multifaceted in nature, recovery is a restorative process comprising of physiological and psychological elements, relative to time [7]. Regenerative (physical) and psychological recovery strategies with subcategories of modalities [7] and multifactorial approaches are frequently applied in contemporary elite football settings [8].

Cold-water immersion (CWI) is a common recovery modality used within elite sport to reduce symptoms of post-exercise fatigue [9–12]. Temperatures of CWI often represent between 10–15°C and exposure durations of between 10–15 minutes [13]. Importantly, consideration must be given to the rationale for its application [13]. Debate exists within literature with regards to the benefits of immediate post training CWI [14, 15]. Studies suggests deleterious or negative effects of cooling such as CWI may mitigate adaptive responses gained through resistance training particularly [11]. Therefore, types of training may be a factor to consider in achieving the desired response to cooling.

Commonly in elite sports environments varying measures are utilised to inform decision-making on a player's readiness to train/play. The combination of subjective and objective measures is more likely to determine fatigue status in team-sport athletes, with single measures insufficient in explaining fatigue status [16]. The literature examining the acute effects of CWI does not consider these measures and focusses heavily on physiological measures that can be affected by several factors. Decision-making around optimal recovery choice and application in a practical environment should consider numerous factors including physiological, biomechanical and psychological effects. Varying measures are utilised within football environments, that help effectively monitor and quantify player readiness to train [17]. These are often determined by the club budget and staff resources within the performance department. Some performance metrics alongside psychometric data are previously quantified [18], however the literature fails to synthesise multiple metrics that represent contemporary performance markers relevant to elite sport.

Generally, reductions in perceived symptoms of delayed onset muscle soreness (DOMS) in sport are positively reported following the application of various cryotherapy modalities [18, 19], highlighting the support of cryotherapeutic applications to enhance physiological recovery. Literature suggests CWI is superior to passive recovery (PR), in relation to reducing muscle soreness [20]. Consensus fails to agree on optimal implementations of recovery strategies with several variables influencing the best approach. Investigation into the effects of CWI on functional performance are still warranted [21] particularly in elite populations. Evidently, research into optimum periodisation of cooling applications such as CWI to understand dose-response are important [9], simultaneous to investigations that compare CWI to PR in applied sport settings to inform contemporary practice. The aim of the current study was to explore the effects of CWI post fatiguing exercise on multiple performance parameters in elite footballers, compared to PR during mid-competitive season.

MATERIALS AND METHODS

The study was approved by the host university ethical committee. The professional football club permitted the dissemination of anonymous data for publication. Twenty-four healthy, elite male footballers took part (age: 20.58 ± 2.55 years; height: 179.9 ± 5.6 cm; weight: 75.7 ± 7.5 kg) providing written consent. Participants were defined as elite in the current study through professional full-time footballer status, competing at national or international level and met recommendations for defining elite athletes [22]. All quantification measures that players were exposed to in the present study were regular measures taken within the club to monitor readiness to train and play. Participants were excluded if they had a history of lower limb injury/surgery or known neurological compromise to cold. Players were accustomed to all biomechanical measures which are representative of regular parameters of performance measures taken at the club throughout the season.

Testing Protocol

Testing protocol took place at the club's training facility corresponding with pre-determined weekly training schedules collected mid-competitive season. Players were familiar with all tests performed, wore normal training attire, refrained from caffeine intake, food, or exercise outside of normal schedules prior to testing. Ambient

TABLE 1. Testing protocol.

		Weekly Post Match Day Training Schedule			
		Match Day +1	**Match Day +2**	**Match Day +3 Scheduled Training**	**Match Day +4 Scheduled Training**
Time Point (1–4)		No data collected	No data collected	1. Pre-Training 2. Immediately Post Training 3. Immediately Post Intervention	4. 24 Hours Post Intervention
GROUP	**Group 1 CWI**	No data collected	No data collected	Baseline measures taken (Pre-training)* GPS Immediately post training data collected* Immediately post CWI data collected*	24 hours post CWI intervention data collection prior to scheduled training*
	Group 2 PR	No data collected	No data collected	Baseline measures taken (Pre-training) * GPS Immediately post training data collected* Immediately post PR data collected*	24 hours post PR intervention data collection prior to scheduled training*

*Data collection across all timepoints consisted of; Performance measures = Eccentric Hamstring Strength, Isometric Adductor Strength, Hamstring Flexibility. Psychological = Wellbeing Questionnaire (McLean et al, 2010). Physiological = Skin Surface Temperature (T_{sk}) (hamstring and adductors). GPS = Monitoring of training load during scheduled training session.

temperature was monitored to identify fluctuations in room temperature (21.0 ± 0.8°C).

Objective measures included; eccentric hamstring strength, isometric adductor strength, skin surface temperature (T_{sk}), hamstring flexibility and perception of wellbeing [23, 24]. Baseline data was collected on match day+3 pre-training, players then completed the training session. Subsequent measures were taken immediately post-training, immediately post-intervention and 24 hrs post-intervention (24 hrs PI). Training was quantified utilising time-motion analysis (Global Positioning System (GPS), Catapult ClearSky, Vector S7, Australia) measuring relative mechanical load (PlayerLoad™; Catapult Innovations, Australia) and distance to ensure standardisation of fatigue levels. Following training, players were randomised to Group 1 (CWI) or Group 2 (PR). Group 1 received an 11-minute exposure to CWI (RecoveryTub Solo), and target temperature of 10°C [25] and CWI temperature ranges reported in the literature [13], immersed up to sternum level. A digital multimeter (Voltacraft MT52, Wollerau, Switzerland) monitored water temperature to ensure maintenance of the targeted temperature, with ice added to maintain consistency [26]. Following CWI, immersed body parts were towel dried and dry shorts provided [27]. Group 2 (PR) lay still in a semi-recumbent position on a plinth for the same 11-minute period. Measures taken at 24 hrs-PI were completed at the same time as baseline to account for circadian variation (Table 1).

Physiological Measure (T_{sk})

T_{sk} using Infrared Thermal Imaging (ThermoVision A40M, FLIR, Danderyd, Sweden) and analysis (Thermacam Researcher V2.8, FLIR) followed Thermographic Imaging in Sports and Exercise Medicine (TISEM) guidelines [28]. The camera was situated 134 cm from the ground perpendicular to the limb [29] with 0.97–0.98 emissivity settings. Images for adductors and hamstrings bilaterally provided unilateral limb data for each region of interest combined to provide an average (Table 2). Region of interest were determined by placement of thermally inert markers, providing a framework for T_{sk} analysis [30] (hamstrings; adductors). Images of adductors were taken with the player laying supine on a plinth placing their lower limb into an externally rotated and flexed hip position, moving into prone to capture the hamstring region. Three images were taken per region of interest per timepoint for analysis. Posterior thigh markers were applied superiorly one-third from the ischial tuberosity to the lateral epicondyle of the femur and inferiorly two-thirds from the lateral epicondyle of the femur to ischial tuberosity. Central posterior thigh was determined by measure of thigh circumference, 50% between ischial tuberosity and lateral epicondyle of the femur thigh marker. Markers to define the adductor region for T_{sk} analysis were placed one third of the way superiorly from the medial epicondyle of the femur and one third inferiorly from the ASIS, with thigh circumference applied in a similar fashion to posterior thigh markers. Inert markers were placed 10% medially and laterally and from the centre of the thigh to complete each region of interest.

Biomechanical Measures (eccentric hamstring strength, isometric adductor strength, hamstring flexibility)

Bilateral eccentric hamstring strength was quantified using the Nordbord® and performed following a previous protocol [31]. Knee position was recorded for each player to standardise position at each timepoint. During the movement players were encouraged to execute maximal effort through verbal instruction by gradually leaning forward, resisting the movement at the slowest speed performing one set of three maximal repetitions [31, 32]. Hands were crossed over the chest with hips remaining in a neutral position [31]. Analyses of peak force and torque (PkF/PkT) measures from all repetitions were recorded per timepoint.

Isometric adductor strength was measured via a Biofeedback Cuff (Donjoy Chattanooga Stabilizer). Before each maximal effort, the biofeedback cuff was pre-inflated to 10 mm Hg and placed between the femoral condyles. Players were instructed to squeeze as hard as possible on each effort with a 15-second rest between each trial, and one-minute rest between each 45° hip flexion test position [33] with three trials performed per timepoint. If any of the following occurred during testing; head lifted off the plinth, hands moved away from the chest, slippage of the pressure cuff, pushing through heels or feet, trials were considered invalid and repeated [33].

Hamstring flexibility was quantified via the sit and reach test (Apollo Sit & Reach Box). Players positioned themselves in a seated position with feet against the testing box, knees in full extension. Players placed one hand over the other flexing forward as far as possible sliding their fingers along the measuring board on the box [34]. One measure was taken per timepoint.

Psychological Measures

A self-reported psychometric questionnaire sensitive to the fluctuations of daily training load [16, 24] quantified fatigue, sleep quality, general muscle soreness, stress levels and mood on a five-point scale [23, 24], 5 being the most positive score and 1 the least, in increments of 1, with one score reported per category per timepoint [23]. Perceived fatigue monitored with this scale has been related to total distance covered at high intensity in elite football populations [24].

Statistical Analysis

Data are presented as mean ± SD and 95% confidence limits. Statistical significance was set at $p = \leq 0.05$. Statistical analysis was performed using SPSS (V26, SPSS Inc, Chicago, IL). A univariate repeated-measures general linear model quantified main effects for all measures across all timepoints for both groups. Significant main effects were explored using post-hoc analysis with a Bonferonni and Wilcoxon signed-rank test correction. To assess residual normality for each dependant variable, q-q plots were generated using stacked standardised residuals. Scatterplots of the stacked unstandardized and standardised residuals were utilised to assess error of variance associated with the residuals. Assumptions associated with the statistical model were assessed to ensure model adequacy. Mauchly's test of sphericity were completed for all dependent variables, with a Greenhouse Geisser correction applied if the test was significant. Partial eta squared (η^2) values were calculated to estimate effect sizes for all significant main effects and interactions. Partial eta squared was classified as small (0.01–0.059), moderate (0.06–0.137), or large (> 0.138). Individual response for each metric were assessed utilising a linear regression model to determine recovery responses between timepoint immediately-post training to immediately-post intervention; and immediately-post intervention to 24 hrs PI. Proportion of variance (R^2), the linear relationship between the measures at listed timepoints (r) and significance of these relationships were identified for each metric.

RESULTS

Mean ± SD training load quantified through GPS was comparable between groups (CWI = 67.4 ± 6.1 m; PR = 70.5 ± 7.1 m), with total distance of 5862.4 ± 1297.6 m and HSRD of 111.83 ± 53.2 m. No significant differences were identified between training load for either group across all metrics or anthropometric data ($p \geq 0.05$). All measures and percentage changes compared to baseline are presented in Table 2.

Overall Analysis

Overall analysis for physiological, biomechanical and psychological measures reported significant main effects for time and group, for Adductor T_{sk} (Timepoint: $F = 102.0, p < 0.001, \eta^2 = 0.810$; Group: $F = 101.5, p = 0.001, \eta^2 = 0.585$), Hamstring T_{sk} (Timepoint: $F = 916.0, p < 0.001, \eta^2 = 0.947$; Group: $F = 1171.5, p < 0.001, \eta^2 = 0.942$), PkT (Timepoint: $F = 2.41, p < 0.05, \eta^2 = 0.48$; Group: $F = 25.43, p < 0.001, \eta^2 = 0.150$; Side: $F = 9.84, p < 0.05, \eta^2 = 0.64$), and PkF (Timepoint: $F = 2.41, p < 0.05, \eta^2 = 0.05$; Group: $F = 25.43, p < 0.001, \eta^2 = 0.15$; Side: $F = 9.84, p < 0.001, \eta^2 = 0.64$).

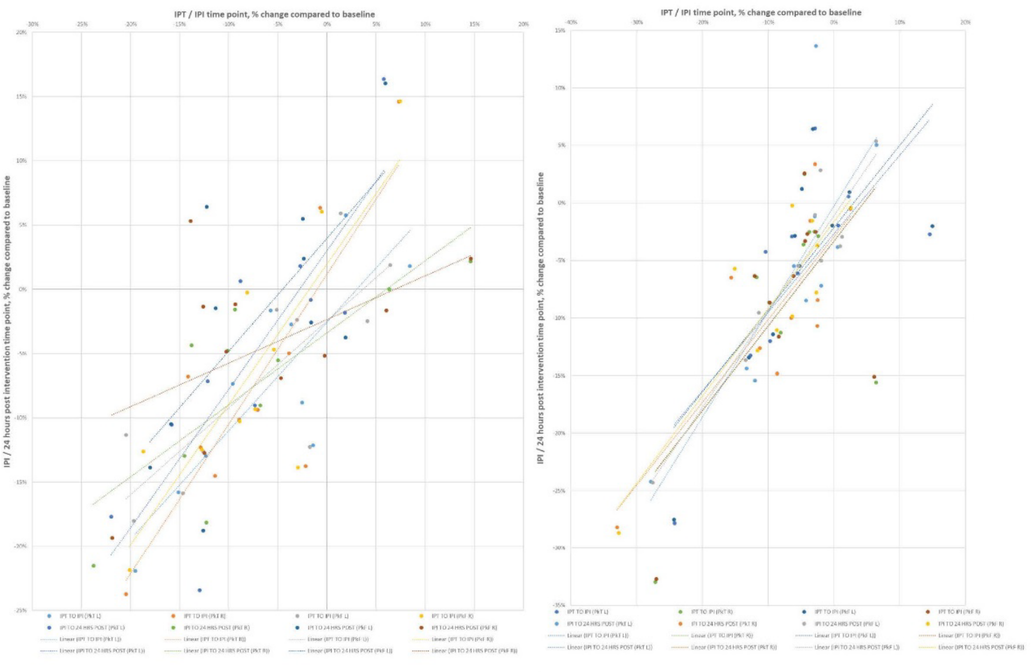

FIG. 1. Linear regression demonstrating % change for eccentric hamstring strength (PkT and PkF), left and right limbs between immediately-post training to immediately-post intervention and immediately-post intervention to 24 hrs PI for CWI group and PR group. (IPI=Immediately Post Intervention; IPT=Immediately Post Training; L=Left Limb; R=Right Limb).

TABLE 2. Physiological, biomechanical and psychological scores for all groups across all timepoints (mean ± SD) with significance, R, and R^2 values for CWI and PR following linear regression analysis.

GROUP	Performance Parameter	Time point: Baseline	Time point: Immediately Post Training	Time point: Immediately Post Intervention	Time point: 24HrsPI	Measure	Timepoint: Immediately Post Training to Immediately Post Intervention	Timepoint: Immediately Post Intervention to 24HrsPI
CWI	Eccentric Hamstring Strength (PkF) (N)	LEFT LEG = 382.3 ± 51.3	359.9 ± 37.1 (-6.01%)	359.2 ± 51.1 (-6.04%)	357.9 ± 42.9 (-6.4%)	Eccentric Hamstring Strength PkF (R)	$P < 0.001$; $R = 0.6368$; $R^2 = 0.4055$	$P < 0.001$; $R = 0.8785$; $R^2 = 0.7718$
CWI		RIGHT LEG = 417.4 ± 68.0	384.6 ± 61.7 (-7.9%)	382.7 ± 79.2 (-8.31%)	383.3 ± 72.4 (-8.16%)	Eccentric Hamstring Strength PkF (L)	$P < 0.001$; $R = 0.7514$; $R^2 = 0.5646$	$P < 0.001$; $R = 0.9473$; $R^2 = 0.8973$
CWI	Accumulative Eccentric Hamstring Strength (PkF) (left and right limb combined)	399.9 ± 68.0	372.3 ± 49.4 (-6.9%)	371.0 ± 68.0 (-7.2%)	370.6 ± 57.7 (-7.3%)			
CWI	Eccentric Hamstring Strength (PkT) (N)	LEFT LEG = 168.2 ± 27.4	156.9 ± 18.7 (-6.7%)	156.4 ± 24.1 (-7.0%)	155.7 ± 17.1 (-7.4%)	Eccentric Hamstring Strength PkT (R)	$P < 0.001$; $R = 0.6365$; $R^2 = 0.4051$	$P < 0.001$; $R = 0.8152$; $R^2 = 0.6645$
CWI		RIGHT LEG = 181.3 ± 30.9	168.0 ± 29.6 (-7.3%)	166.7 ± 35.6 (-8.0%)	166.6 ± 14.8 (-8.1%)	Eccentric Hamstring Strength PkT (L)	$P < 0.001$; $R = 0.7432$; $R^2 = 0.5524$	$P < 0.001$; $R = 0.8086$; $R^2 = 0.6539$
CWI	Accumulative Eccentric Hamstring Strength (PkT) (left and right limb combined)	174.3 ± 29.1	162.5 ± 24.2 (-6.8%)	161.6 ± 29.9 (-7.3%)	161.2 ± 25.3 (-7.5%)			
CWI	Isometric Adductor Strength (mm Hg)	115 ± 13.0	113 ± 16.3	115 ± 9.4	121 ± 15.6	Isometric Adductor Strength	$P = 0.004$; $R = 0.4772$; $R^2 = 0.2277$	$P = 0.024$; $R = 0.5027$; $R^2 = 0.2527$
CWI	Hamstring Flexibility (cm)	20.0 ± 8.0	20.0 ± 8.0	20.0 ± 8.0	20.0 ± 7.0	Hamstring Flexibility	$P < 0.001$; $R = 0.8014$; $R^2 = 0.6423$	$P < 0.001$; $R = 0.3738$; $R^2 = 0.1397$
CWI	Wellbeing Score (Overall)	3.7 ± 0.4	3.4 ± 0.5**	3.7 ± 0.3**	3.6 ± 0.2***	Wellbeing Score (Overall)	$P = 0.743$; $R = -0.4797$; $R^2 = 0.0159$	$P = 0.659$; $R = 0.1298$; $R^2 = 0.0168$
CWI	T_{sk} Adductors* (°C)	31.4 ± 0.8	30.1 ± 1.1	16.9 ± 1.1****	30.5 ± 1.0	T_{sk} (Adductors)	$P = 0.594$; $R = -0.4526$; $R^2 = 0.2049$	$P = 0.557$; $R = 0.3278$; $R^2 = 0.1075$
CWI	T_{sk} Hamstrings* (°C)	31.9 ± 0.3	29.9 ± 0.8	17.6 ± 1.4****	31.1 ± 0.2	T_{sk} (Hamstrings)	$P = 0.852$; $R = -0.7283$; $R^2 = 0.5304$	$P = 0.476$; $R = 0.5335$; $R^2 = 0.2846$
PR	Eccentric Hamstring Strength (PkF) (N)	LEFT LEG = 343.1 ± 35.2	319.5 ± 38.1* (-6.8%)	318.3 ± 32.3* (-7.2%)	334.6 ± 37.5* (-2.5%)	Eccentric Hamstring Strength PkF (R)	$P < 0.001$; $R = 0.8412$; $R^2 = 0.7076$	$P = 0.03$; $1R = 0.5047$; $R^2 = 0.2547$
PR		RIGHT LEG = 382.4 ± 30.2	351.6 ± 28.1* (-8.0%)	349.4 ± 43.9* (-6.5%)	364.4 ± 32.3* (-4.7%)	Eccentric Hamstring Strength PkF (L)	$P = 0.002$; $R = 0.8094$; $R^2 = 0.6551$	$P = 0.013$; $R = 0.6880$; $R^2 = 0.4734$
PR	Accumulative Eccentric Hamstring Strength (PkF) (left and right limb)	362.8 ± 32.7	335.6 ± 33.1 (-7.5%)	333.8 ± 38.1 (-7.9%)	349.5 ± 35.0 (-4.0%)			
PR	Eccentric Hamstring Strength (PkT) (N)	LEFT LEG = 145.6 ± 24.1	136.3 ± 22.8* (-6.4%)	133.5 ± 20.0* (-8.3%)	136.3 ± 17.7* (-6.4%)	Eccentric Hamstring Strength PkT (R)	$P = 0.001$; $R = 0.8461$; $R^2 = 0.7159$	$P = 0.002$; $R = 0.7833$; $R^2 = 0.6136$
PR		RIGHT LEG = 161.6 ± 21.9	148.5 ± 15.2* (-8.1%)	138.7 ± 17.9* (-14.2%)	148.2 ± 14.8* (-8.3%)	Eccentric Hamstring Strength PkT (L)	$P < 0.001$; $R = 0.8311$; $R^2 = 0.6908$	$P < 0.001$; $R = 0.8244$; $R^2 = 0.6796$

TABLE 2. Continue

Performance Parameter	Time point				Measure	Timepoint	
	Baseline	Immediately Post Training	Immediately Post Intervention	24HrsPI		Immediately Post Training to Immediately Post Intervention	Immediately Post Intervention to 24HrsPI
Accumulative Eccentric Hamstring Strength PkT) (left and right limb)	153.6 ± 23.0	142.4 ± 19.0* (-7.3%)	141.0 ± 19.0* (-8.2%)	142.3 ± 16.2* (-7.3%)			
Isometric Adductor Strength (mm Hg)	121.9 ± 16.1	117.3 ± 14.1	118.7 ± 16.6	122.6 ± 7.9	Isometric Adductor Strength	$P < 0.001$; $R = 0.8909$; $R^2 = 0.7937$	$P = 0.097$; $R = 0.326$; $R^2 = 0.1063$
Hamstring Flexibility (cm)	18.0 ± 7.0	18.0 ± 6.0	19.0 ± 6.0	20.0 ± 6.0	Hamstring Flexibility	$P < 0.001$; $R = 0.8899$; $R^2 = 0.7919$	$P < 0.001$; $R = 0.7207$; $R^2 = 0.5194$
Wellbeing Score (Overall)	3.7 ± 0.4	3.2 ± 0.5**	3.3 ± 0.6**	3.8 ± 0.4***§	Wellbeing Score (Overall)	$P = 0.299$; $R = -0.0457$; $R^2 = 0.0021$	$P = 0.435$; $R = 0.7786$; $R^2 = 0.6062$
T_{sk} Adductors* (°C)	31.2 ± 1.0	30.6 ± 0.8	31.4 ± 0.8	31.7 ± 0.7	T_{sk} (Adductors)	$P = 0.47$; $R = -0.684$; $R^2 = 0.4673$	$P = 0.191$; $R = 0.645$; $R^2 = 0.4157$
T_{sk} Hamstrings* (°C)	32.3 ± 0.3	31.0 ± 0.2	32.0 ± 0.2	31.2 ± 0.3	T_{sk} (Hamstrings)	$P = 0.003$; $R = 0.8909$; $R^2 = 0.7937$	$P = 0.184$; $R = 0.326$; $R^2 = 0.1063$
Wellbeing Score Groups Combined	3.7 ± 0.4	3.2 ± 0.5**	3.3 ± 0.6**	3.8 ± 0.4***§			

PkF = Peak Force, PkT = Peak Torque, (%) = Percentage difference compared to baseline scores for Eccentric Hamstring Strength for PkT and PkF, unilateral and bilateral limb data. * = Significant difference compared to baseline time point. ** = Significant difference in overall wellbeing scores compared to baseline scores. *** = Significant difference in overall wellbeing scores compared to post-training scores. § = Significant difference in overall wellbeing score compared to post intervention score. T_{sk} for adductors and hamstrings represent bilateral limb measures combined (mean ± SD). ****Significance at $p < 0.001$.

Biomechanical Measures (eccentric hamstring strength, isometric adductor strength, hamstring flexibility)

Isometric adductor strength and hamstring flexibility measures reported no significant effects of group (Isometric adductor strength: $F = 1.471$, $p > 0.05$, $\eta^2 = 0.020$; hamstring flexibility: $F = 0.785$, $p > 0.05$, $\eta^2 = 0.11$) or timepoint (Isometric adductor strength: $F = 0.708$, $p > 0.05$, $\eta^2 = 0.029$; hamstring flexibility: $F = 0.31$, $p > 0.05$, $\eta^2 = 0.49$).

Psychological Measures

Perceptual recovery displayed significant effects of time for sleep, fatigue and stress (Sleep: $F = 10.00$, $p < 0.001$, $\eta^2 = 0.43$; Fatigue: $F = 6.42$, $p < 0.001$, $n2 = 0.33$; Stress: $F = 3.03$, $p < 0.05$, $\eta^2 = 1.86$), with sleep displaying a significant effect of group ($F = 10.00$, $p = 0.003$, $\eta^2 = 0.20$). No significant effects for time or group were identified for muscle soreness or mood (Muscle soreness: Time: $F = 2.34$, $p = 0.08$, $\eta^2 = 0.150$: Group: $F = 0.98$, $p = 0.33$, $\eta^2 = 0.24$; Mood: Time: $F = 0.417$, $p = 0.74$, $\eta^2 = 0.03$: Group: $F = 4.00$, $p = 0.52$, $\eta^2 = 0.91$). No significant effects for group were identified for fatigue or stress (Fatigue: $F = 0.000$, $p = 1.00$, $\eta^2 = 0.00$; Stress: $F = 1.47$, $p = 0.23$, $\eta^2 = 0.04$).

Significant interactions were displayed between group *x* timepoint for T_{sk}, sleep, fatigue and stress (Sleep: $F = 10.0$, $p < 0.001$, $\eta^2 = 0.43$; Fatigue: $F = 5.19$, $p = 0.004$, $\eta^2 = 0.28$; Stress: $F = 5.24$, $p = 0.04$, $\eta^2 = 0.282$). No other significant interactions were identified between group/timepoint/side for metrics taken ($p > 0.05$). Collapsing of biomechanical and psychological data displayed significant effects for timepoint for CWI for fatigue, muscle soreness, sleep and PkF (Fatigue: $F = 7.25$, $p = 0.002$, $\eta^2 = 0.521$; Muscle soreness: $F = 2.69$, $p = 0.02$, $\eta^2 = 0.512$; Sleep: $F = 7.45$, $p = 0.002$, $\eta^2 = 0.565$; PkF: $F = 3.74$, $p < 0.05$, $\eta^2 = 0.049$). No other significant differences were detected between timepoints for all other metrics. For PR, significant effects for timepoint were reported for fatigue, sleep, stress, PkF and PkT (Fatigue: $F = 5.135$, $p = 0.009$, $\eta^2 = 0.435$; Sleep: $F = 10.00$, $p < 0.001$, $\eta^2 = 0.600$; Stress: $F = 5.287$, $p = 0.008$, $\eta^2 = 0.442$; PkF: $F = 10.66$, $p < 0.05$, $\eta^2 = 0.087$; PkT: $F = 1.636$, $p < 0.05$, $\eta^2 = 0.064$), but not for muscle soreness, mood, isometric adductor strength or hamstring flexibility (Muscle soreness: $F = 2.098$, $p = 0.113$, $\eta^2 = 0.239$; Mood: $F = 0.143$, $p = 0.933$, $\eta^2 = 0.021$; Isometric adductor strength: $F = 0.291$, $p > 0.05$, $\eta^2 = 0.024$; hamstring flexibility $= 0.50$, $p > 0.05$, $\eta^2 = 0.004$). Significant effects for

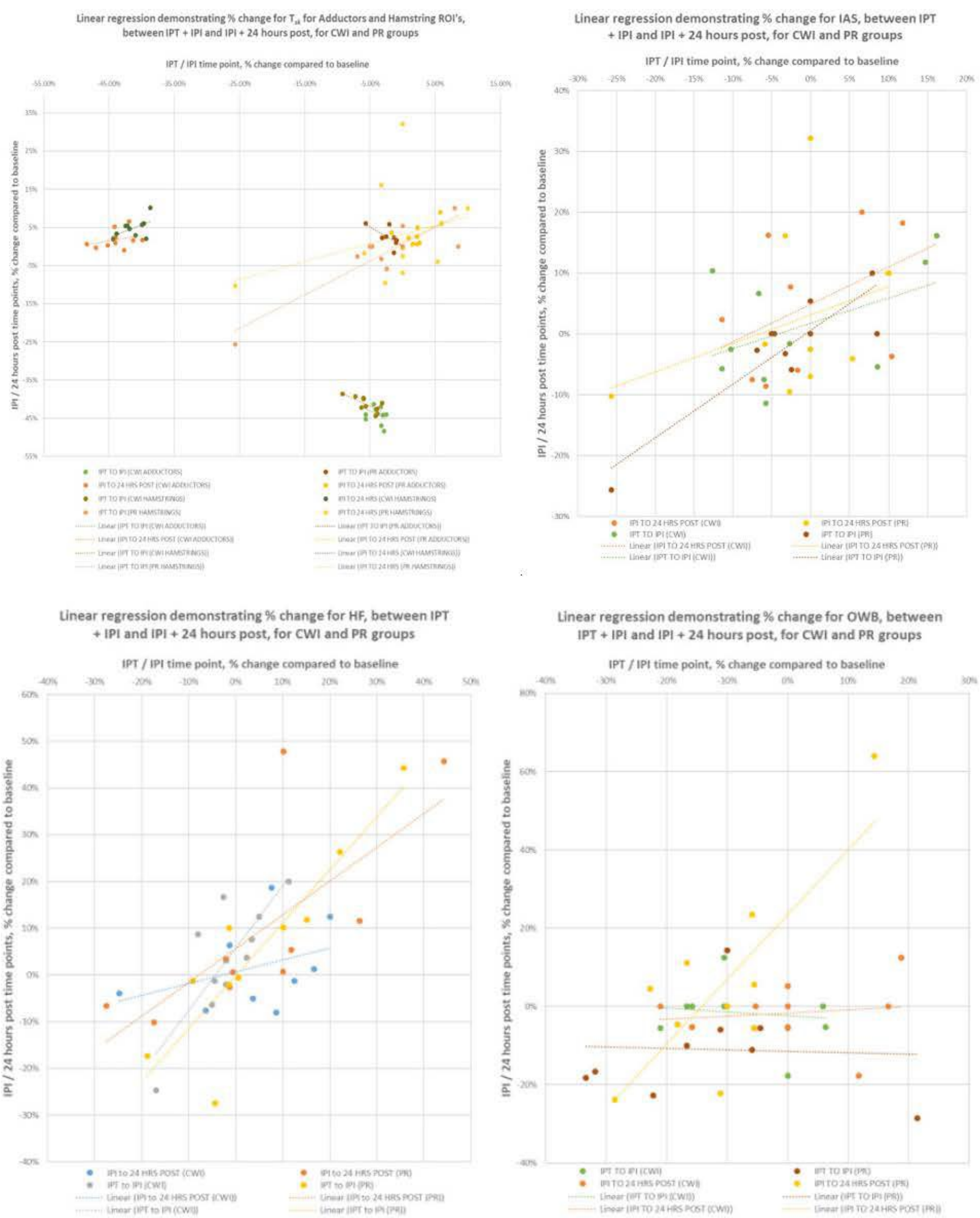

FIG. 2. Linear regression demonstrating % change for isometric adductor strength, hamstring flexibility, overall wellbeing scores and Tsk between immediately-post training to immediately-post intervention, and immediately-post intervention to 24 hrs PI, for CWI and PR groups. (IPI=Immediately Post Intervention; IPT=Immediately Post Training; OWB=Overall Wellbeing).

PkT and PkF for side (PkT: $F = 8.880$, $p = 0.004$, $\eta^2 = 0.110$; PkF: $F = 17.84$, $p < 0.001$, $\eta^2 = 0.199$) were reported. No significant interactions were identified for either group between timepoint or side ($p > 0.05$).

Collapse of the data into CWI and PR displayed significant T_{sk} reductions for hamstring and adductor regions following CWI between immediately-post intervention, immediately-post training and baseline ($p \leq 0.001$). No significant differences were displayed across hamstring or adductor regions of interest when comparing all timepoints for PR ($p \geq 0.05$). No significant differences between any timepoints for PkT, Isometric adductor strength or hamstring flexibility ($p \geq 0.05$) for either group were reported. For PR, significant differences were displayed between baseline and immediately-post training ($p = 0.023$) and intervention ($p = 0.03$) timepoints for PkF. A significant difference was reported when comparing CWI to PR at immediately-post intervention ($p \leq 0.001$). No significant changes in T_{sk} were reported for any other timepoint between groups.

Linear regression modelling for individual responses to training are displayed for eccentric hamstring strength (PkT, PkF) (Figure 1), and isometric adductor strength, hamstring flexibility, overall wellbeing scores and T_{sk} (Figure 2). Significance, R and R^2 values are represented in Table 2.

DISCUSSION

The aim of the study was to investigate the effects of CWI compared to PR on readiness to train measures, within an elite population of male footballers following a football specific fatiguing training session during mid-competitive season. Previously only a handful of components that quantify readiness to train are examined, limiting interpretation and the ability to draw agreement on optimal recovery methods, effect of immediate application or implementation of them in an elite performance environment. Through a triad of markers commonly employed within an elite sport setting the present study quantified biomechanical, physiological and psychological factors with analysis of the overall data displaying significant main effects for timepoints for eccentric hamstring strength, T_{sk}, overall wellbeing, sleep, fatigue and stress. Further significant main effects of group were identified for eccentric hamstring strength, T_{sk} and sleep. Individual group response identified significant effects for timepoint in both groups for PkF, sleep and fatigue, with CWI displaying significant effects of muscle soreness. No effects were identified for isometric adductor strength or hamstring flexibility. Interestingly, significant differences were displayed for eccentric hamstring strength (PkF) at immediately-post training and immediately-post intervention, with significant differences displayed between CWI and PR eccentric hamstring strength at immediately-post intervention. It is important to note these findings were based on group averages. Therefore, additional linear regression modelling of% change to baseline scores were completed. Important considerations in relation to individual analysis and magnitude of linear regression for each measure demonstrated greater recovery in PkF, PkT, for CWI and changes in isometric adductor strength and hamstring flexibility for PR between immediately-post training to 24 hrs PI. For effective transfer of knowledge into practice this style of analysis was important to illustrate individual response. Findings have implications on decision-making utilising CWI as a recovery strategy, individualisation of approach and ideal periodisation of this modality compared to PR in an elite football setting.

Significant reductions in T_{sk} occurred after CWI exposure, although not meeting therapeutic range (10–15°C) considered in literature to induce several physiological effects [35]. CWI was standardised in respect to current dose recommendations and target water temperatures [13, 25, 36]. Average T_{sk} for hamstrings (16.9 ± 1.8°C) and adductors (17.61 ± .4°C) respectively are in line with previous CWI exposures of similar duration and modality temperatures [37]. Overall analysis indicated reductions in T_{sk} appeared to influence biomechanical recovery outputs with trends in eccentric hamstring strength demonstrating larger continued declines caused by fatigue following PR compared to CWI. When considering individual response, linear regression analysis displayed greater recovery for timepoints immediately-post intervention-24 hrs PI for eccentric hamstring strength metrics for CWI exposure (CWI: $r = 0.81–0.95$; PR: $r = 0.50–0.82$). Percentage change between timepoints compared to baseline data represented in Figure 2. More positive influences on eccentric hamstring strength with a consistently stronger individual response noted for CWI compared to individual analysis for PR where metrics for eccentric hamstring strength responded in a haphazard fashion.

It is reported that cooling negatively affects strength output [29]. The current study presented contrasting findings in relation to strength measures, highlighting contemporary issues for decision-making within performance departments. CWI group reduces further detrimental declines in eccentric hamstring strength following a football specific training session [3], with CWI exposure displaying higher strength output compared to PR, up to 24 hrs PI. Contrastingly isometric adductor strength and hamstring flexibility function for both groups displayed no significant change, indicating no effect of CWI exposure on these parameters. Although, analysis of the data trends associated with these measures is interesting. CWI exposure resulted in a rapid return to baseline post intervention, however this was not displayed for PR. Further analysis of individual response between timepoints immediately-post intervention-24 hrs PI supported this with further improvements detected following CWI (CWI: $r = 0.50$; PR: $r = 0.30$). Reduced decrements to isometric adductor strength following fatigue reveals a positive response to CWI seen in previous literature [38], albeit in different muscle groups. Findings in relation to strength parameters highlighted in this body of work can be associated with the physiological mechanisms caused by cooling [38, 39], although these mechanisms are speculative within the limitations of the current study as simultaneous indices of muscular inflammation were not attained.

Although it may be assumed that attainment of lower T_{sk} may instigate better outcomes in recovery responses, Vieira et al [26] reported that warmer CWI temperatures (15°C) produced superior benefits in performance recovery compared to cooler CWI (5°C) temperatures despite lower T_{sk} reported in the group exposed to 5°C CWI. Therefore, the recommendations to meet T_{sk} ranges of between 10–15°C may appear more fitting for acute injury management rather than recovery, as the detrimental effects of fatigue on specific biomechanical measures (eccentric hamstring strength) were ameliorated through CWI in the current study, despite this. Though it is acknowledged that CWI is best avoided immediately following resistance training [13], current findings agree with the suggestion by Ihsan et al [13] that there is a place for CWI in recovery following other types of training. This may be during mid-competitive season where fixture congestion applies enhanced pressure on players during training both physically and mentally. Importantly the contrasting findings with regards quantifying strength output highlight the importance of relating measures to the functional demands placed on the athlete when performing.

Variance within the physical outputs of athletes could be associated with the players perception of their current physical status post fatigue exposure or physical stress of the test. Psychological overall wellbeing scores suggested accumulative scores of the five categories were maintained for CWI, whereas following PR, scores worsened significantly at the same timepoint. Interestingly at 24 hrs PI overall wellbeing scores significantly improved following PR above baseline, comparatively following CWI a decline to below baseline was displayed. The effectiveness of CWI to improve perceptual recovery is well documented [38], and current results agree in terms of an immediate increase in overall wellbeing scores post CWI response. The inability however to maintain or return overall wellbeing scores at 24 hrs PI following CWI is interesting and may reflect that although a 'halt' on the effects of further biomechanical fatigue (eccentric hamstring strength) was achieved, perhaps one exposure of CWI fails to impact wellbeing continuously to the point of measurement at 24 hrs PI. It would be wise to consider that detrimental functional deficits of eccentric hamstring strength are reported to last up to 40–47 hrs post-fatigue [3], and at this timepoint eccentric hamstring strength had not returned to baseline measures in the current study, therefore impacting overall wellbeing scores. This may explain CWI overall wellbeing results, but not PR responses. Improvements in overall wellbeing scores at 24 hrs PI for PR may be associated with the increase noted in biomechanical measures of hamstring flexibility. Psychological response mechanisms to CWI may be dependent on dose i.e. number of exposures or representative of a placebo effect. Through linear regression analysis greater change for PR between timepoints immediately-post intervention-24 hrs PI for overall wellbeing was reported (CWI: $r = 0.13$; PR: $r = 0.78$) (Table 2). Collectively, observation of eccentric hamstring strength, isometric adductor strength, hamstring flexibility and overall wellbeing results suggest that group analysis may not optimally identify nor account for individual responses, which consequently indicate some measures are more advantageous to the practitioner than others in terms expediency. It may be inappropriate to employ a standardised approach of recovery strategies across a whole squad based on these directives.

To facilitate optimal recovery strategies, a single battery of tests is not yet recognised in practice that would best inform optimal individualised approaches for readiness to train/play. We agree that the method of applying multiple performance measures to quantify fatigue and intervention response is a resourceful approach providing an inclusive picture of the effects of recovery modalities across one cohort. Current findings advocate the application of multiple components of testing aligning to the recommendations in other literature [17]. This approach better expedites the understanding around optimal strategies to improve readiness for training/play. That said, not all tests best represent 'readiness to train' and consideration needs to be given to the choice of performance measure most beneficial to provide applied data that supports the ability to modify tailored recovery strategies in elite performance settings. Variables that impact dose-response in terms of multiple exposures, duration of cooling and temperature of CWI should be evaluated within practical settings, utilising appropriate fatigue monitoring measures with the intention to develop decision-making of sports medicine and performance practitioners for injury risk reduction and recovery strategies.

Some evidence is supportive in the application of cooling such as CWI, to enhance performance post-competitive fixture fatigue [12, 14], conversely agreement over the appropriate window to expose players to this modality is debateable. In many elite performance settings decision-making tools based around fitness-fatigue models whereby an ideal relationship between training and performance is developed [40] instigates a recovery phase which may include exposure to such modalities as CWI. It is important to note that participants were exposed to football specific training and quantified in the current study, not resistance training, highlighting the potential for different outcomes in performance response following CWI. Collectively findings may dictate when CWI is applied but insufficient evidence is available that considers periodisation around such schedules or variables that affect decision-making of this kind. In contemplation of the current results, whereby positive effects on some biomechanical parameters were seen after exposure to CWI (eccentric hamstring strength) and others after PR (hamstring flexibility), and type of training, future research may consider investigating the combination of both CWI followed by a window of PR, or multiple exposures of both interventions sequentially to develop optimal periodisation of CWI. This supports our earlier recommendations based on the current findings, of tailoring recovery strategies to the individual requirements of the player to optimise subsequent performances.

Whilst current findings provide insight for sports medicine and performance practitioners as to the effects of within-season exposure to CWI following fatiguing exercise on multi-measures of performance, there are limitations to this study which the authors recognise. It is impossible to blind players to the conditions (CWI/PR), a common acknowledgement within applied cryotherapy research, although investigators were blinded. Players had used CWI previously although were not accustomed to regular exposure within a scheduled recovery session. A follow up of measures would have been beneficial at up to 48 hrs representative of post-match fatigue effects [3] and to that effect we recommend further applied investigations on the application of CWI in elite sport environments.

CONCLUSIONS

Despite conflicting evidence regarding the effectiveness of CWI and PR, current findings suggest CWI may be useful to ameliorate potential deficits in eccentric hamstring strength that may optimise readiness to train/play in consideration of congested levels of exposure to fatiguing exercise during mid-competitive football seasons. A focus on individual response should be observed in future studies with judgement of cryotherapy effectiveness made through a battery of measures to determine factors that affect choice and periodisation of recovery strategies, applicable to a practical setting with individual athlete approaches in mind. Practitioners should be mindful of which measures best define functional performance and typical stresses which the athlete is exposed with an emphasis of psychological impacts on biomechanical measures. Variable responses to functional performance parameters indicate the need for further investigation of multiple CWI exposures over longer periods to account for the known temporal patterns of fatigue reported for hamstring function in elite football populations. Optimal periodisation of recovery strategies in response to fatigue on an individualised basis requires the implementation of appropriate methods of monitoring and analysis which may positively influence performance and readiness to train/play in elite performance settings.

Key Points Summary:

– Cold water immersion and passive recovery are common recovery modalities used within elite sport to reduce symptoms of post-exercise fatigue.
– Several performance indicators are used in sport to determine readiness to train/play yet the effects of recovery strategies on multi-measures are limited aiding confusion around optimal protocols for cold water immersion or passive recovery.
– Our results suggest cold water immersion may be useful to ameliorate potential deficits in eccentric hamstring strength that optimise readiness to train/play in elite football settings.
– We suggest that multi-measures and individual analysis of recovery responses provide sports medicine and performance practitioners with direction on recovery strategies within mid-competitive season training cycles.

Conflict of Interest Declaration

No conflicts of interest.

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Appendix 5d: Copy of Publication 15.

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The Effect of Three Different (-135°C) Whole Body Cryotherapy Exposure Durations on Elite Rugby League Players

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Abstract

Background: Whole body cryotherapy (WBC) is the therapeutic application of extreme cold air for a short duration. Minimal evidence is available for determining optimal exposure time.

Purpose: To explore whether the length of WBC exposure induces differential changes in inflammatory markers, tissue oxygenation, skin and core temperature, thermal sensation and comfort.

Method: This study was a randomised cross over design with participants acting as their own control. Fourteen male professional first team super league rugby players were exposed to 1, 2, and 3 minutes of WBC at −135°C. Testing took place the day after a competitive league fixture, each exposure separated by seven days.

Results: No significant changes were found in the inflammatory cytokine interleukin six. Significant reductions ($p<0.05$) in deoxyhaemoglobin for gastrocnemius and vastus lateralis were found. In vastus lateralis significant reductions ($p<0.05$) in oxyhaemoglobin and tissue oxygenation index ($p<0.05$) were demonstrated. Significant reductions ($p<0.05$) in skin temperature were recorded. No significant changes were recorded in core temperature. Significant reductions ($p<0.05$) in thermal sensation and comfort were recorded.

Conclusion: Three brief exposures to WBC separated by 1 week are not sufficient to induce physiological changes in IL-6 or core temperature. There are however significant changes in tissue oxyhaemoglobin, deoxyhaemoglobin, tissue oxygenation index, skin temperature and thermal sensation. We conclude that a 2 minute WBC exposure was the optimum exposure length at temperatures of −135°C and could be applied as the basis for future studies.

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Competing Interests: The use of the mobile Cryochamber, liquid nitrogen and specialist operator were provided free of charge by BOC Linde throughout the testing. This does not alter our adherence to all the PLoS ONE policies on sharing data and materials.

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Introduction

Whole body cryotherapy (WBC) is the therapeutic application of extremely cold dry air, usually between −110°C and −140°C [1,2]. WBC is becoming popular amongst athletes, coaches and clinicians across a variety of sports in order to prevent injury and promote recovery. Typically the timescale of exposure is reported as between 2 3 minutes [2]. Although a number of studies [1,3 8] have investigated the physiological effects of WBC, the optimal WBC protocol required to initiate beneficial physiological responses is unknown [2,9]. This is due to the lack of randomised controlled clinical studies investigating either exposure duration or number of treatment cycles [2,9]. One of the more commonly reported beneficial changes following WBC is a reduction in inflammatory markers [2,10,11,12]. Recently the acceleration of recovery from exercise induced muscle damage (EIMD) was reported after three WBC exposures [13]. However Costello and colleagues [1] reported ineffective results of WBC when administered 24 hours following eccentric exercises in order to help alleviate muscle soreness. Furthermore the enhancement of muscle force recovery was demonstrated to be ineffective in this study [1,3]. One previous study has evaluated various physiological changes in professional rugby players, demonstrating changes in haematological profiles, following a protocol of 5 WBC exposures over 5 consecutive days [14]. However this study lacked a control group, therefore it is difficult to discriminate WBC effects compared to the cumulative effects of training. Rugby league is a contact sport, with a match consisting of two, forty minute halves of play where players engage in high intensity activity, intermittent with periods of low activity [15]. Due to the physical demands placed upon rugby league players which result in symptoms of fatigue and muscle performance decrements [15], WBC has recently become very popular as a recovery modality within this sport. The purpose of this study was to determine optimal WBC exposure duration and to measure physiological and perceptual responses following a 1, 2 and 3 minute WBC exposure at −135°C in elite rugby league players the day after a competitive fixture.

Materials and Methods

Ethics Statement

The study was conducted according to the Declaration of Helsinki (WMA, 2008), was approved by UCLan Built, Sport and Health Ethics Committee (BuSH 128) and by the Club Player Welfare officer. Participants provided written consent to take part in the study.

Participants

Fourteen (24 years; mean weight 77.6 kg; mean height 183.2 cm) professional rugby league players from Wigan Warriors RLFC volunteered, all were participating at first team level mid competitive season.

Experimental Protocol

This study was a randomised cross over design with participants acting as their own control. Three WBC exposures, separated by seven days following a competitive fixture the previous evening. Each WBC exposure consisted of 30 seconds precooling at −60°C then randomised (randomization.com) exposure for either 1, 2, or 3 minutes at −135°C in a liquid nitrogen cryochamber installed on a trailer (JUKA, Poland), owned and operated by BOC Linde. Prior to each WBC session, participants were prepared according to the standard BOC Linde operating protocol [16].

Inflammatory Markers

Baseline venous blood samples were taken three days prior to the first WBC exposure. Venous blood samples were collected 20 minutes prior to and 20 minutes post WBC exposure (Table 1). All samples were collected from the antecubital vein using standard venepuncture techniques and the S-Monovette blood collection system (Sarstedt). The anticoagulant was potassium EDTA. Samples were centrifuged at 1200× g for 10 minutes and plasma was removed and stored as aliquots at −20°C until analysis. Plasma levels of interleukin six (IL-6) were analysed using a quantitative sandwich enzyme immunoassay as per manufacturer's instructions (Aviva Systems Biology), using a Perkin Elmer Enspire plate reader. All standards and samples were analysed in duplicate and interleukin six (IL-6) levels were interpolated from the standard curve using 4 parameter logistic curve fit. The immunoassay had a sensitivity to detect a concentration of at least 1 pg/mL.

Tissue Oxygenation

A dual-channel continuous wave near-infrared spectrometer (NIRS) (NIRO-200 Oxygenation Monitor, Hamamatsu, Japan), with a sampling rate of 6 Hz, assessed for changes in muscle oxygenation. To evaluate muscle oxygen content, 1 emitting laser diode and 2 detecting photodiodes, absorbencies of 775, 810, and 850 nm, were used to measure the ratio of oxygenated haemo-

Table 1. Timing of data collection.

Data	Base line	Pre exposure	Immediately post exposure	→5 minutes	5 minutes post exposure	→10 minutes	10 minutes post exposure	→15 minutes	15 minutes post exposure	→20 minutes	20 minutes post exposure
Core Temperature		•	•								•
Thermal Image (Tsk)		•	•		•		•		•		•
Thermal Sensation		•	•		•		•		•		•
Thermal Comfort		•	•		•		•		•		•
Blood Sample*	•	•									•
NIRO		•	•	•		•		•		•	

• = Parameter measurement protocol at each time point of testing.
*Baseline blood sampling taken three days prior to the first exposure as a normative comparison for 20 minutes post WBC exposures blood sampling.
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globin to total haemoglobin [17]. Tissue oxygen saturation and haemoglobin content were determined using a modified Beer Lambert law [18]. Measurement sites were wiped with an alcohol wipe prior to optode placement. One optode was attached to the muscle belly of the left gastrocnemius at the widest point and one optode was placed on the left vastus lateralis (VL) midway between the promixal patella and the inguinal crease. Optodes were held in place using transparent double sided hypoallergenic sticky tape and covered with a bandage. An optode spacing of 4 cm was used and the differential path length factor applied for the gastrocnemius and vastus lateralis were 4.65 and 5.99 respectively (17). Key measurements were change in oxyhaemoglobin (O2Hb); deoxyhaemoglobin (HHb) in $\mu mol \cdot L^{-1}$ from an arbitrary zero value; tissue oxygenation index (TOI) expressed as a percentage value. Data was sampled and averaged from 3×5 minute intervals pre and, every 5 minutes up to twenty minutes post WBC exposure (Table 1).

Skin Temperature

Skin temperature (Tsk) was measured via noncontact, digital, infrared thermal imaging (TI). A ThermoVision A40M Thermal Imaging Camera (Flir systems, Danderyd, Sweden) emissivity set at 0.97 0.98 was used according to standard medical protocols [19]. The camera was mounted on a tripod height 1.2 m; distance 3.5 m from participants and connected to a laptop running Thermacam Researcher Pro 2.8 software (Flir systems, Danderyd, Sweden). To define regions of interest (ROI) wooden markers were attached mid clavicle and anterior superior iliac spine [20]. Four ROI were defined: anterior triangle of the neck (ROIA); torso (ROIB); lower abdomen (ROIC); back (ROID). Thermal images were recorded pre, immediately post and every five minutes post WBC exposure, up to 20 minutes (Table 1).

Core Temperature

Core temperature was recorded via ingestion of a core temperature pill (CorTemp® Wireless Ingestible Temperature Sensor-Product No. HT150002. HQInc. Florida. USA.) Core temperature data was then recorded by a hand held device (CorTemp® Data Recorder-Product No. HT150001) (Table 1). Participants arrived 40 minutes prior to their allocated WBC exposure, to swallow the core temperature pill. Core temperature pills are normally swallowed 6 hours prior to measurement, however the club did not consent to this, correspondence with the pill manufacturers' confirmed that data would still be valid.

Thermal Sensation and Thermal Comfort Questionnaires

Each participant recorded thermal sensation ratings [21] once pre, immediately following WBC and every 5 minutes up to 20 minutes (Table 1). Participants were asked 'How are you feeling now?' and answered by pointing to a scale from −4 to 4. (−4 = very cold, −3 = cold, −2 = cool, −1 = slightly cool, 0 = neutral, +1 = slightly warm, +2 = slightly hot +3 = hot, +4 = very hot). Thermal comfort [22] was also assessed prior to and immediately after WBC using a five point scale. Participants were asked 'Do you find this' and answered by choosing: 0 = comfortable; 1 = slightly comfortable; 2 = uncomfortable; 3 = very uncomfortable; 4 = extremely uncomfortable.

Statistical Analysis

Continuous data were analysed using a mixed method model SPSS (version 19.0, SPSS Inc, Chicago, IL), using the data pre exposure as a covariate to determine changes from pre and all other time points, applying least significant difference pairwise comparisons. With the fixed factors being time points and exposure. The distributions of the data values about the mean were assessed and the data found to be suitable for parametric statistical testing. The use of an adjustment for multiple comparison was considered to be too aggressive for this exploratory study. Nominal data from the questionnaires were analysed with Friedman Tests to explore differences between all three exposures and Wilcoxon sign rank tests were used as a post hoc comparison between exposures and time points.

Results

Inflammatory Markers

No significant changes were recorded for the inflammatory cytokine IL-6 (Table 2).

Tissue Oxygenation

The mixed methods model showed significant reductions ($p < 0.05$) in HHb occurred in gastrocnemius, between pre and 0 5 minutes post WBC (Table 3). Gastrocnemius HHb demonstrated a significant increase ($p<0.05$) between 0 5, 5 10, 10 15 minutes post WB compared to pre WBC. VL O2Hb demonstrated a significant reduction ($p<0.05$) when comparing a 1 minute to a 3 minute WBC exposure (Table 2). Significant differences ($p<0.05$) were found in HHb for VL when comparing pre WBC and 0 5 minutes post WBC and comparing 0 5 post WBC and 5 10, 10 15 minutes post WBC (Table 3). A significant reduction ($p<0.05$) in TOI for VL, between pre and 0 5 minutes post WBC occurred.

Skin Temperature

Significant reductions ($p<0.05$) occurred in average Tsk when comparing 1, 2 and 3 minute WBC exposures (Table 2), when using a mixed methods model. When comparing average Tsk changes over time, significant differences ($p<0.05$) were found between pre exposure and all post exposure time points (Table 3). Significant differences ($p<0.05$) in average Tsk were found when comparing ROIC (lower abdomen) with ROI A, B and D. No significant differences were found in average Tsk between ROIB and ROID.

Core Temperature

No significant differences were found in core temperature.

Thermal Sensation and Thermal Comfort Scoring

The Friedman tests for the mixed method model demonstrated significant changes in thermal sensation ($p = .008$) and thermal comfort ($p = .004$) The Wilcoxson post-hoc comparison between 1 and 2 minute exposure indicated a significant reduction ($p<0.05$) in thermal sensation (Table 2). No significant differences were reported when comparing 1 and 3 minutes or 2 and 3 minutes. Comparison of pre and immediately post thermal sensation scores for all exposure times demonstrated significant reductions ($p < 0.05$). No significant differences were found in thermal comfort when comparing WBC exposure times.

Adverse Incident

On the first day of testing a Samoan player with intolerance to ice packs underwent a three minute WBC exposure. The player did not disclose his cold intolerance to the study team or BOC personnel. He suffered a mild superficial skin burn bilaterally on the mid portion of the anterior thigh. The skin damage consisting of erythema and minor blistering appeared in a horizontal strip

Table 2. Comparison between WBC exposure times for all testing parameters and significant values.

Measurement	WBC Exposure Time (minutes)	Compared to WBC exposure time (minutes)	Mean Difference	Sig.
Interleukin Six (IL-6) (pg/mL)	1	2	0.37	0.81
	1	3	0.14	0.93
	2	3	−0.23	0.89
Tissue Oxygenation Gastrocnemius HHB (μmol·L $^{-1}$)	1	2	−2.50	0.58
	1	3	−0.41	0.93
	2	3	2.09	0.64
Tissue Oxygenation Gastrocnemius TOI (μmol·L $^{-1}$)	1	2	−0.87	0.45
	1	3	−1.98	0.08
	2	3	−1.11	0.33
Tissue Oxygenation VL O2HB (μmol·L $^{-1}$)	1	2	2.24	0.37
	1	3	5.93	0.02
	2	3	3.70	0.14
Tissue Oxygenation VL HHB (μmol·L $^{-1}$)	1	2	−3.82	0.14
	1	3	−2.53	0.33
	2	3	1.29	0.62
Tissue Oxygenation VL TOI (μmol·L $^{-1}$)	1	2	−0.28	0.84
	1	3	1.78	0.19
	2	3	2.06	0.13
Tsk (°C)**	1	2	1.21	0.00
	1	3	1.70	0.00
	2	3	.50	0.00
Core Temperature (°C)*	1	2	0.51	0.20
	1	3	0.72	0.08
	2	3	0.20	0.62

***Core Temperature (°C) average mean difference for all time points (pre up to 20 minutes post WBC exposure).**
****Tsk (°C) average mean difference for all regions, for all time points (pre up to 20 minutes post WBC exposure).**
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approximately 2 cm high and 10 cm wide the day following WBC. The player was able to train normally and played competitively the following week, although willing to continue in the study, he was excluded by the study team. This adverse incident occurred despite the following safety measures. 1. The study information sheet explicitly stated that there would be an exposure to extremely cold air (−110°C to −140°C). 2. The study consent form asked about medical conditions that may affect participation. 3. The BOC screening protocol included a specific question about intolerance to cold. This incident raises an important issue, consequently we recommend that all participants receiving WBC are screened, acknowledge the contraindications of WBC and are made aware of the potential risks of exposure.

Discussion

To our knowledge, this is the first study which has examined duration of exposure time of WBC at −135°C and effects on inflammatory marker (IL-6), tissue oxygenation, skin and core temperature, thermal sensation and comfort.

Inflammatory Markers

Strenuous exercise is known to induce a rapid, exponential, increase in IL-6 [23]. In agreement with previous research [24] our findings revealed elevated levels of IL-6, 10 16 hours post-game. An interesting observation from our IL-6 data was the individual variability in IL-6 levels demonstrated by the high standard deviations. This variance may be explained by the lack of similarity in player movement and loading experienced during rugby league play. Several studies have shown that there are differences in player activities, and loading, as defined by position [25,26,27]. An appreciation of positional differences is recommended when further investigating rugby league. In the present study, a single WBC exposure, irrespective of duration, did not significantly alter IL-6 levels. This is in line with previous literature [4] investigating a 3 minute exposure, at −110°C. Our 20 minute post exposure collection point was the shortest used when compared to similar studies [7,13,28]. Blood sampling at 20 minutes post WBC may have been too early for any changes to have occurred in the haematological markers, and this warrants further investigation. A previous study [28] reported that blood samples were taken 30 minutes post 3 minute WBC exposure, with no reports of inability to collect blood samples. An interesting challenge to the collection of venous blood samples was the partial 'shutdown' of the peripheral vasculature, particularly the median veins of the antecubital fossa. It appeared that vascular shunting from upper to lower limbs took place especially following 3 minute WBC exposure. Despite the target veins being visibly distended, as expected in very lean, muscular athletes; venous blood flow was severely impaired in several participants. Venepuncture was successful in all cases, yet an appropriate level of peripheral blood flow was often compromised, particularly following the 3 minute

Table 3. Comparison of parameters between time points, pre, immediately post, +5, +10, +15 and +20 minutes post WBC exposures for all exposures.

Time Point*	to Time Point	Core Temp °C**	Sig.	Tsk °C***	Sig.	Blood IL-6	Sig.	NIRO G O2HB	Sig.	NIRO G HHB	Sig.	NIRO G TOI	Sig.	NIRO VL O2HB	Sig.	NIRO VL HHB	Sig.	NIRO VL TOI	Sig.
0	1	−0.50	0.21	8.85	0.00			4.28	0.31	12.79	0.03	2.36	0.11	−1.70	0.60	6.85	0.04	3.81	0.03
0	2			3.40	0.00			−2.15	0.61	−3.05	0.60	1.78	0.23	−3.74	0.25	−0.43	0.90	2.20	0.21
0	3			2.59	0.00			−1.62	0.70	−7.83	0.18	1.19	0.42	−1.80	0.58	−2.59	0.44	2.44	0.16
0	4			2.19	0.00			2.33	0.58	−6.52	0.27	0.95	0.52	−1.18	0.71	1.24	0.71	1.54	0.38
0	5	−0.38	0.35	2.01	0.00	0.15	0.91												
1	2			−5.45	0.00			−6.43	0.13	−15.85	0.01	−0.58	0.69	−2.04	0.53	−7.28	0.03	−1.61	0.35
1	3			−6.26	0.00			−5.90	0.16	−20.62	0.00	−1.17	0.43	−0.10	0.98	−9.44	0.01	−1.38	0.43
1	4			−6.66	0.00			−1.95	0.64	−19.31	0.00	−1.41	0.34	0.52	0.87	−5.61	0.10	−2.28	0.19
1	5	0.12	0.76	−6.84	0.00														
2	3			−0.81	0.00			0.53	0.90	−4.77	0.41	−0.59	0.69	1.95	0.55	−2.16	0.52	0.24	0.89
2	4			−1.21	0.00			4.49	0.29	−3.46	0.55	−0.83	0.57	2.56	0.43	1.67	0.62	−0.66	0.70
2	5			−1.39	0.00														
3	4			−0.40	0.09			3.96	0.35	1.31	0.82	−0.24	0.87	0.61	0.85	3.83	0.26	−0.90	0.60
3	5			−0.58	0.02														
4	5			−0.18	0.46														

***Time points for all lengths of WBC exposure: 0 = pre WBC exposure, 1 = Immediately post WBC exposure, 2 = 5 minutes post WBC exposure, 3 = 10 minutes post WBC exposure, 4 = 15 minutes WBC exposure and 5 = 20 post WBC exposure.**
****Core temperature (°C) average mean difference.**
*****Tsk (°C) average mean difference.**
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WBC exposure. This led to incomplete inflammatory myokine profiles being generated for some participants.

Tissue Oxygenation

NIRO data demonstrate that a 3 minute WBC exposure differed significantly to a 1 or 2 minute WBC exposure. Results suggest localised tissue hypoxia in VL occurred as O2Hb decreased with a subsequent increase in HHb. (Figure 1). In gastrocnemius, a decrease in blood volume, 0–5 minutes post WBC occurred (Figure 2). O2Hb and HHb both increased to above pre WBC exposure measures over the remaining 15 minutes, indicative of venous pooling. These findings are supported by previous research that suggests extreme cold exposure reduces cardiac output and therefore produces a shift in blood volume to the venous circulation leading to pooling and reduced venous return [29]. Results indicate that gastrocnemius was more susceptible to pooling at all exposures than VL, possibly due to a weaker vasoconstriction response rather than active vasodilation. Vasoconstriction of peripheral blood vessels to maintain core temperature is generally observed with moderate cold exposure [30]. Initial responses during the present study demonstrate this physiological response. However, under extreme cold exposure the body endeavours to protect the extremities. As deeper muscles lose heat to the surface, cold-induced vasodilation (CIVD) can occur [31]. The exact mechanisms leading to CIVD are not fully understood. However, an increase in peripheral blood flow/volume followed by pooling of the blood has been observed [32] as was evident following a 3 minute WBC exposure in the present study. CIVD is thought to initiate when core temperatures rise above 36°C [31]. In the current study, core temperature changes although insignificant demonstrate a rise to 37°C immediately post WBC, this would potentially lend support to the concept of CIVD response. Although supporting previous literature [33], caution is needed when using CIVD as an explanation of our data as we did not have continuous data on blood flow, Tsk or core temperature.

NIRO is sensitive to small movements and as a result of participants standing for 10 minutes pre and 20 minutes post WBC, some contraction of the muscles would have occurred. It is impossible to avoid movement, however some participants may have moved around more than others, affecting the results. Future research should take this in to account and have participants resting on a plinth.

Skin and Core Temperature

All exposure times of WBC reduced Tsk in all four ROI. Previous studies have shown the effectiveness of WBC in the reduction of Tsk [21]. The lowest Tsk recorded in the current study was 12.1°C in two out of the nine participants, following a three minute exposure in ROI 'C' (lower abdomen). As reported in previous studies, an extended phase of rewarming occurred following WBC exposure, no significant changes in Tsk occurred beyond 10 minutes post exposure and mean Tsk at 20 minutes post WBC did not reach mean Tsk pre WBC [34,35] (Figure 3). Although core temperature did not show any significant changes following WBC, core temperature displays a predictable relationship with Tsk; where the maximum post WBC drop in Tsk occurred, a small rise in core temperature was observed for all exposure times (Figure 3). The core temperature pill was ingested 40 minutes prior to WBC exposure and although a longer time is normal, results did demonstrate change in core measurement temperatures. The pattern of change in Tsk and the slight rise in core temperature suggests vascular shunting to maintain the functions of vital organs.

Thermal Sensation and Thermal Comfort Scoring

Prior to WBC participants rated their thermal sensation as 'neutral' or 'slightly warm'. Following all WBC exposure times significant reductions in thermal sensation were noted, in most cases participants rated themselves as 'very cold' or 'cold'. No significant differences occurred between 2 and 3 minutes exposures for thermal sensation, however between 1 and 2 minute exposures there was a significant reduction ($p<0.05$) in thermal sensation scores. Immediately post 1 minute WBC exposure participants reported feeling 'slightly cool' compared 2 minutes where participants reported feeling 'cold' or 'very cold'. The

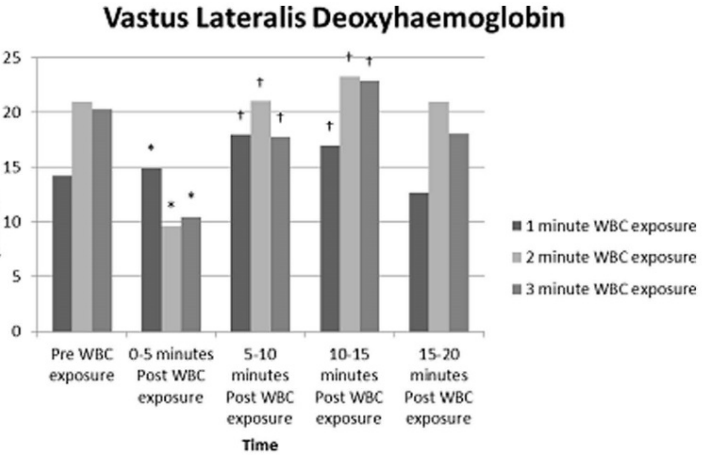

Figure 1. Mean NIRO values for VL, pre and post WBC exposure for all three WBC time exposures (1, 2 and 3 minutes). Values are means (N = 9). Statistical significance ($P<0.05$) observed over a period of time (pre, immediately post exposure, +5 minutes, +10 Minutes and, + 15 minutes post exposure. * indicates significantly different to pre WBC; †indicates significantly different to 0–5 min post WBC.
doi:10.1371/journal.pone.0086420.g001

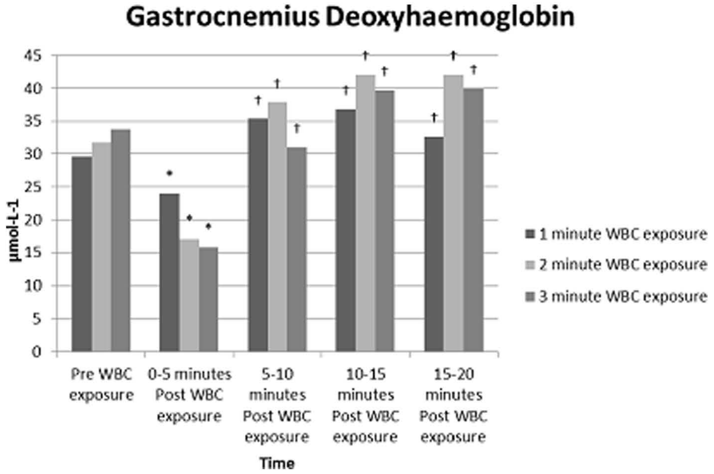

Figure 2. Tissue deoxygenation for gastrocnemius, pre and post WBC exposure for all three WBC time exposures (1, 2 and 3 minutes). Values are means (N = 9). Statistical significance (P<0.05) observed over a period of time (pre, immediately post exposure, +5 minutes, + 10 Minutes, +15 minutes and +20 minutes post exposure. * indicates significantly different to pre WBC; †indicates significantly different to 0–5 min post WBC.

doi:10.1371/journal.pone.0086420.g002

differences in perceived temperature sensation suggest that 1 minute may not be a long enough WBC exposure to initiate perceptual changes in temperature sensation.

Limitations

Although ecologically valid, with elite players participating in competitive fixtures mid-season, there was potential for players to

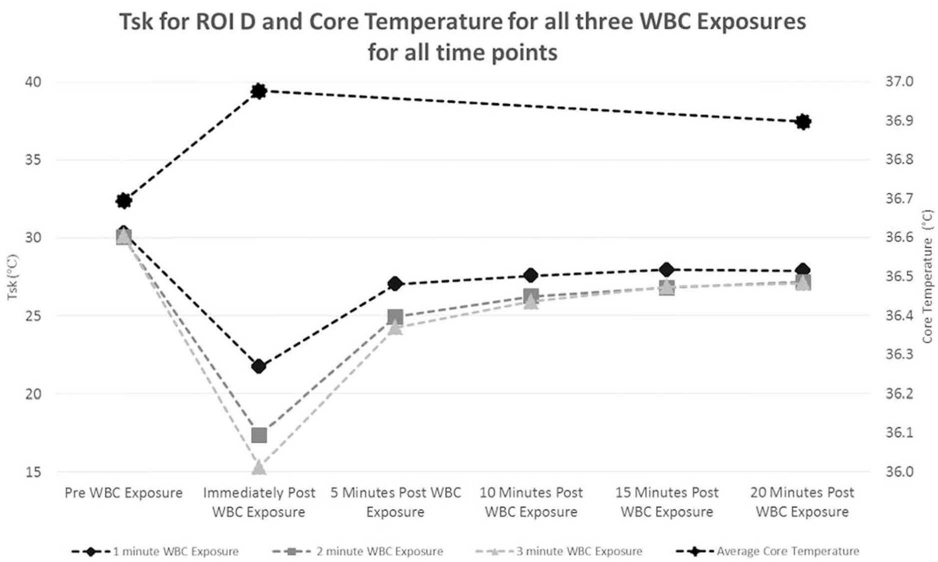

Figure 3. Core and Abdomen skin temperature before and after WBC exposure (1, 2 and 3 minutes). Y-axis on the left measures skin temperature and Y-axis on the right measures core temperature. Values are means (N = 9). for timepoints, pre, immediately post exposure, + 5 minutes, +10 Minutes, +15 minutes and +20 minutes post exposure.

doi:10.1371/journal.pone.0086420.g003

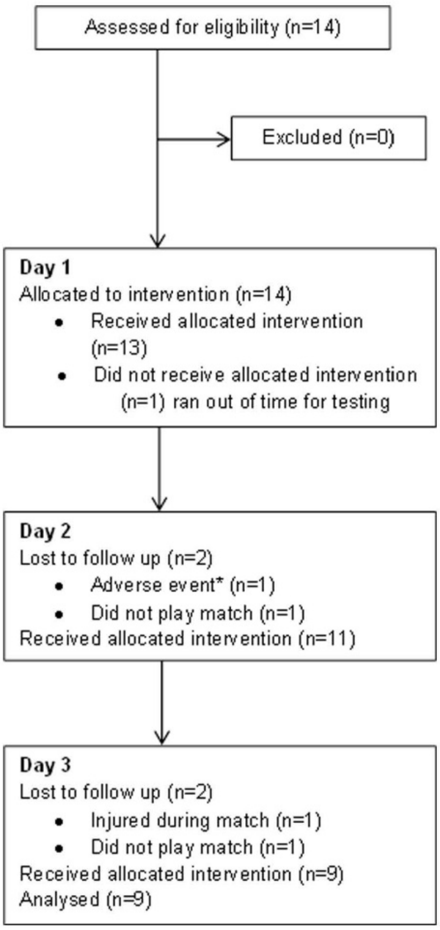

Figure 4. CONSORT diagram showing participant flow and retention.
doi:10.1371/journal.pone.0086420.g004

drop out due to injury or non-selection to play (Figure 4). The training ground environment in which the testing took place was also a limitation, as a temperature controlled room was not available. We also acknowledge that although the temperature of the cryochamber was set at −135°C, fluctuations occurred during the exposure times, which is common with prolonged use and any thermal stimulation [36]. No skin surface temperatures were measured during WBC exposure periods neither was air flow, in order to observe convective strength of WBC. This was due to the lack of equipment suitable to measure such parameters. We were unable to measure internal recommended temperature as reported by Savic et al (2013) therefore differences in actual and reported temperatures may vary. The core temperature pill should ideally be ingested approximately 6 hours prior to testing, future studies should take this into consideration.

Summary

A pattern in the results from this study emerged suggesting that a 2 minute WBC exposure at −135°C following 30 seconds pre-cooling at −60°C was the optimum WBC exposure for first team professional rugby league players. A 2 minute WBC exposure induces potentially beneficial physiological and perceptual changes, greater than those achieved following a 1 minute WBC exposure but without any of the negative effects demonstrated by a 3 minute exposure. Whilst we have not demonstrated support for a single bout of WBC, other studies have shown the potential of WBC in mediating muscular recovery by attenuating the inflammatory process [4]. Successful use of WBC to 'blunt' the inflammatory response appears to be effective when administered immediately post exercise, with repeat exposures. This supports recent literature, suggesting that physiological changes are dependent on the number of sessions of WBC [28]. It is therefore suggested that future research could follow a similar protocol to this study, using a 2 minute WBC exposure at −135°C this would facilitate the development of a stronger evidence base for WBC. These studies should focus on determining the optimum number of sessions per day/week and also over what time period exposure cycles should take place.

What are the new findings?

- 30 seconds at −60°C followed by 2 minutes WBC at around −135°C appear to be an optimum WBC exposure time.
- 2 minute WBC exposure produces physiological changes in core and skin temperature, tissue oxygenation in vastus lateralis and gastrocnemius muscles and thermal sensation responses.
- Professions working within elite sport can be advised on applying an optimal WBC exposure time of 2 minutes at around −135°C for physiological changes to occur.

How might it impact on clinical practice in the near future?

- A duration time of 2 minutes of WBC exposure at −135°C has been established as a safe protocol for future application for male elite rugby league players.
- Clinicians should utilise the protocol from this study to compare future research which will help now determine the number of required WBC exposure sessions to initiate a larger physiological responses.
- Research investigating WBC on other elite athletes and women would be advantageous to broaden the knowledge on WBC across a variety of sports and gender.

Author Contributions

Conceived and designed the experiments: JA JS JC KM NG SA HH SD MD DP AC MB GL JR. Performed the experiments: JA JS JC KM NG SA HH SD MD DP AC MB GL JR. Analyzed the data: JA JS JC KM NG SA HH SD MD DP AC MB GL JR. Contributed reagents/materials/analysis tools: JA JS JC KM NG SA HH SD MD DP AC MB GL JR. Wrote the paper: JA JS JC KM NG SA HH SD MD DP AC MB GL JR.

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6.6 Appendix 6: List of Conference Abstracts and Personal Research Output

In addition to the peer reviewed journal papers which form this submission a list of conference abstracts and personal research are included here to illustrate a more complete picture of my academic output.

Conference Abstracts

1. **Conference Presentation Sports Kongress, Copenhagen, Denmark, 2017:**
    i. Presentation Title: *The immediate effects of a 20-minute crushed ice application on knee joint position sense during a small knee bend.*
    ii. Presentation Title: *Delayed effects of a 20-minute crushed ice application on knee joint position sense during a functional task.*

2. **Thermomed Conference, Frankfurt, Germany, 2014:**
    i. Presentation Title: *Differences in skin temperature responses during three different (-135℃) whole body cryotherapy exposure durations in elite rugby league players.*

3. **ECSS, Seville, Spain, 2020 (postponed until 2021 – COVID-19):**
    i. Presentation Title: *Recovery profiles of eccentric hamstring strength in response to cooling and compression.*
    ii. Presentation Title: *Temporal patterns of knee extensor isokinetic torque strength in athletes following comparison of anterior thigh and knee cooling over a rewarming period.*

4. **Isokinetic Conference, Lyon, France 2020 (postponed until 2022– COVID-19):**
    i. Presentation Title: *Contemporary cryo-compressive applications for post-training recovery in elite academy footballers.*
    ii. Presentation Title: *Performance markers to establish the effectiveness of cold-water immersion as a recovery modality in elite football.*

Personal Research Output

1. Allan, R., Malone, J., **Alexander, J.,** Vorajee, S., Ihsan, M., Gregson, W., Kwiecien, S., and Mawhinney, C. (2022). Cold for centuries: A brief history of cryotherapies to improve health, injury and post-exercise recovery. Eur J App Physiol. In Press.
2. Rhodes, D., Crowie, S., and **Alexander, J.** (2022). Acute effects of varying densities of foam roller on hamstring flexibility and eccentric strength. *Int J Ther Rehab.* In Press.
3. Rhodes, D., Jeffery, J., Carling, C., and **Alexander, J.** (2022). The association between grip strength and isometric mid-thigh pull performance in elite footballers. *Science and Sports.*
4. Rhodes, D., Jeffery, J., Brook-Sutton, D., **Alexander, J.** (2022). Test-retest reliability of the isometric soleus strength test in elite male academy footballers. *Int J Sports Phys Ther.* 17(2): 286-292.
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6. Greenhalgh, O., Selfe, J., Richards, J., **Alexander, J.**, and McCarthy, C. (2021). An exploration into the effectiveness of cryotherapy modalities on patients with degenerative knee conditions, through a series of single-case experiments. *Physiotherapy.* In Press.
7. Greenhalgh, O., Selfe, J., Richards, J., **Alexander, J.,** and McCarthy, C. (2021). An exploration of targeted cryotherapy protocols, using the Swellaway knee unit, on health male subjects. *Physiotherapy.* In Press.
8. Allan, R., Akin, B., Sinclair, J., Hurst, H., **Alexander, J.**, Malone, J.J., Naylor, A., Mawhinney, C., Gregson, W., and Ihsan, M. (2021). Athlete, coach and practitioner knowledge and perceptions of post-exercise cold-water immersion for recovery; a qualitative and quantitative exploration. Sports Sci Health.
9. **Alexander, J.,** Greenhalgh, O., Selfe, J., and Rhodes, D. (2021). Cryotherapy and Compression in Sports Injury Management and Rehabilitation: A Scoping Review. *Int J Ther Rehab.*
10. **Alexander, J.,** Greenhalgh, O., Selfe, J., and Rhodes, D. (2021). Exploratory evaluation of muscle strength and skin surface temperature responses to contemporary cooling modalities in sport. *Isokin Ex Sci.* In Press.
11. Richards, J., Gechev, A., **Alexander, J.,** Macedo, L., May, K., Lindley, SB. (2021). The effect of local cooling at the elbow on nerve conduction velocity and motor unit behaviour: An exploration of a novel neurological assessment. *Sensors,* 21: 6073.
12. **Alexander, J.,** Carling, C., and Rhodes, D. (2021). Utilisation of performance markers to establish the effectiveness of cold-water immersion as a recovery modality in elite football. *Biol Sport.*

13. **Alexander J,** Allan, R., and Rhodes D. (2021) Short Communication. Cryotherapy in Sport: A Warm Reception for the Translation of Evidence into Applied Practice. *Res Sports Med.*
14. Rhodes D, **Alexander** J, and Greig M. 2021. The temporal pattern of recovery in Directional Dynamic Stability post football specific fatigue. *J Sports Rehab.*
15. **Alexander, J.,** Keegan, J., Reedy, A., and Rhodes, D. (2021). Effects of contemporary cryo-compression on post-training performance in elite academy footballers. *Biol Sport.*
16. **Alexander, J.,** Jeffery, J., and Rhodes, D. (2021). Recovery Profiles of Eccentric Hamstring Strength in Response to Cooling and Compression. *J Bodywork Movement Therapies.*
17. Selfe, J., Thorpe, C., May, K., and **Alexander, J.** (2021). Cryotherapy: Physiology and New Approaches (in: A Comprehensive Guide to Sports Physiology and Injury Management). Elsevier Publications.
18. **Alexander, J.,** and Rhodes, D. (2020). Editorial Commentary - Thermography for defining efficiency of cryotherapy modalities in sport. *Temperature.*
19. Rhodes, D., Jeffery, J., and **Alexander, J.** (2020). The Influence of Grip Strength on Isometric Mid-Thigh Pull Performance in Elite Footballers. *J Sports Rehab.* In Press.
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24. **Alexander, J.,** Rhodes, D., Birdsall, D., Selfe, J. (2020). Comparison of cryotherapy modality application over the anterior thigh across rugby union positions; A Crossover Randomized Controlled Trial. *Int J Sports Phys Ther.* 15(2): 210-220.
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27. Rhodes, D., **Alexander, J.,** and Greig, M. (2020). The temporal pattern of recovery in eccentric hamstring strength post-localised fatigue. *J Health.*

28. Buran, MP., **Alexander, J.,** Roddam, H., Leather, M., and Rhodes, D. (2019). An Exploratory Study into the Development of a multidisciplinary Team in Elite Level Cricket: A Thematic Analysis. *ARC J Res Sports Med.* 4(2): 1-10.
29. Supplementary Football Medical and Performance Association (FMPA) Article. This article published in 2018 for the Football Medical Association Magazine, taken from the publication: *Selfe, J., Alexander, J., et al., (2014). The Effect of Three Different (-135°C) Whole Body Cryotherapy Exposure Durations on Elite Rugby League Players. PLoS ONE*, 9(1);1-9.
30. **Alexander, J.,** and Rhodes, D. (2019). Temporal Patterns of Knee Extensor Isokinetic Torque Strength in Male and Female Athletes Following Comparison of Anterior Thigh and Knee Cooling, over a Rewarming Period. *J Sports Rehab.*
31. **Alexander, J.,** et al. (2019). Mapping of knee skin sensitivity and temperature at the knee following Cryotherapy. *PRM+*. 2(1): 1-5.
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36. **Alexander, J.** (2017). WBC exposures and changes in inflammatory blood markers, tissue oxygenation, core and skin surface temperature alongside thermal comfort and sensation. Feature Article - *Football Medicine and Performance Association.*
37. Selfe, J., **Alexander, J.,** et al. (2014). The Effect of Three Different (-135°C) Whole Body Cryotherapy Exposure Durations on Elite Rugby League Players. *PLoS ONE*. 9(1): 1-11.
38. **Alexander, J.,** et al. (2014). Postural characteristics of female dressage riders using 3D motion analysis and the effects of an athletic taping technique: A randomised control trial. *Phys Ther Sport*.
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6.7 Appendix 7: Programme of Related Studies

Relevant courses / training completed:

Course	Date(s) Completed
PRINCE 2® Project Management Course + Certification	2015
Epigeum (Introduction to Research Skills) - Introduction to Research Skills	2020
Epigeum (Research Methods) - Research Methods in Literature Review - Research Methods in the Sciences	2020
Epigeum (Ethical Research) **Becoming an Ethical researcher** - Ethical Decision Making - Underpinning values for ethical research - Ethical concerns associated with different forms of research - Ethical concerns associated with different research methods and activities **Research Ethics in Practice** - Working with human participants - Understanding research ethics approval - Working ethically in challenging circumstances - Working ethically in a global environment	2020
Epigeum (Entrepreneurship in the Research Context - Academic Entrepreneurship: An introduction - Entrepreneurial Opportunities: Recognition and Evaluation - Entrepreneurial Resources: People, teams and finance.	2020
Epigeum (Transferable Skills) - Getting published in the arts - Getting published in the sciences - Intellectual property in the research context - Career planning in the Sciences - Working with your supervisor - Managing your research Project - Conferences, presenting and networking	2020

6.8 Appendix 8: Collaborative letters of support from co-authored publications

Publication 1: Alexander, J., Alexander, J., Selfe, J., Oliver, B., Mee, D., Carter, A., Scott, M., Richards, J., and May, K. (2016). An exploratory study into the effects of a 20-minute crushed ice application on knee joint position sense during a small knee bend. *Physical Therapy in Sport*. 18(1); 21-26.

This is to declare on behalf of all associated authors, as first author of the above scientific publication, Jill Alexander formulated the study rationale, experimental design and aim, compiled data, wrote the manuscript taking into account feedback, collaborative comments and suggestions from the co-authors, prepared the manuscript for submission and revised the manuscript as per the reviewers comments.

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Professor James Selfe

Publication 2: Alexander, J., Richards, J., Attah, O., Cheema, S., Snook, J., Wisdell, C., May, K and Selfe, J. (2018). Delayed effects of a 20-minute crushed ice application on knee joint position sense assessed by a functional task during a re-warming period. *Gait and Posture.* 62: 173-178.

This is to declare on behalf of all associated authors, as first author of the above scientific publication, Jill Alexander formulated the study rationale, experimental design and aim, compiled data, wrote the manuscript taking into account feedback, collaborative comments and suggestions from the co-authors, prepared the manuscript for submission and revised the manuscript as per the reviewer's comments.

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Professor James Selfe

Publication 3: Rhodes, D and Alexander J. (2018). The effect of knee joint cooling on isokinetic torque production of the knee extensors; considerations for application. *International Journal of Sports Physical Therapy.* 13(6); 6-8.

This is to declare that as dual author of the above scientific publication, Jill Alexander formulated the study rationale, experimental design and aim, compiled data, write the manuscript considering feedback collaborative comments and suggestions from the co-authors, prepared the manuscript for submission and revised the manuscript as per reviewer comments.

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Dr David Rhodes

Publication 4: Alexander J, and Rhodes, D. (2019). Temporal patterns of knee extensor isokinetic torque strength in male and female athletes following comparison of anterior thigh and knee cooling, over a rewarming period. *Journal of Sports Rehabilitation.* 29(6): 723-729.

This is to declare that as first author of the above scientific publication, Jill Alexander formulated the study rationale, experimental design and aim, compiled data, write the manuscript taking into account feedback collaborative comments and suggestions from the co-authors, prepared the manuscript for submission and revised the manuscript as per reviewer comments.

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Dr David Rhodes

Publication 5: Alexander, J., Selfe, J., Greenhalgh, O., and Rhodes, D. (2021). Exploratory evaluation of muscle strength and skin surface temperature responses to contemporary cryotherapy modalities in sport. *Isokinetics and Exercise Science.* In Press.

This is to declare that as first author of the above scientific publication, Jill Alexander formulated the study rationale, experimental design and aim, compiled data, write the manuscript taking into account feedback collaborative comments and suggestions from the co-authors, prepared the manuscript for submission and revised the manuscript as per reviewer comments.

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Dr David Rhodes

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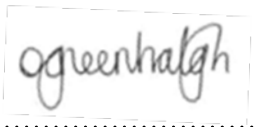
Professor James Selfe



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Olivia Greenhalgh

Publication 6: Alexander, J., Rhodes, D., Fowler, E., May, K., Richards, R., and Selfe, J. (2019). Mapping of skin surface sensitivity and skin surface temperature at the knee over a re-warming period, following cryotherapy. *PRM+ Journal of Quantitative Research in Rehabilitative Medicine*. 2(1): 1-5.

This is to declare on behalf of all associated authors as first author of the above scientific publication, Jill Alexander formulated the study rationale, experimental design and aim, compiled data, write the manuscript taking into account feedback collaborative comments and suggestions from the co-authors, prepared the manuscript for submission and revised the manuscript as per reviewer comments.

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Professor James Selfe

Publication 7: Alexander, J., Selfe, J., Birdsall, D., and Rhodes, D. (2019). Comparison of cryotherapy modality application over the anterior thigh across rugby union positions; A crossover randomized controlled trial. *International Journal of Sports Physical Therapy.* 15(2): 210-220.

This is to declare that as first author of the above scientific publication, Jill Alexander formulated the study rationale, experimental design and aim, compiled data, wrote the manuscript taking into account feedback collaborative comments and suggestions from the co-authors, prepared the manuscript for submission and revised the manuscript as per reviewer comments.

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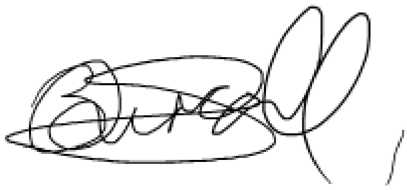
Dr David Rhodes



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Daniel Birdsall

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Professor James Selfe

Publication 8: Alexander, J. and Rhodes, D. (2020). Thermography for defining efficiency of cryotherapy modalities in sport. *Temperature.* 30(8): 105-107.

This is to declare that as first author of the above scientific publication, Jill Alexander formulated the study rationale, experimental design and aim, compiled data, write the manuscript taking into account feedback collaborative comments and suggestions from the co-authors, prepared the manuscript for submission and revised the manuscript as per reviewer comments.

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Dr David Rhodes

Publication 9: Alexander, J., Allan, R., and Rhodes, D. (2021). Cryotherapy in Sport: a warm reception for the translation of evidence into applied practice. *Research in Sports Medicine. 10:1-4.*

This is to declare that as first author of the above scientific publication, Jill Alexander formulated the editorial rationale, research question, compiled the manuscript taking into account feedback collaborative comments and suggestions from the co-authors, prepared the manuscript for submission and revised the manuscript as per reviewer comments.

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Dr Robert Allan

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Dr David Rhodes

Publication 10: Alexander, J., Greenhalgh, O., Selfe, J., and Rhodes, D. (2021). Cryotherapy and Compression in Sports Injury Management: A Scoping Review. *International Journal of Therapy and Rehabilitation.* In Press.

This is to declare that as first author of the above scientific publication, Jill Alexander formulated the study rationale, experimental design and aim, compiled data, write the manuscript taking into account feedback collaborative comments and suggestions from the co-authors, prepared the manuscript for submission and revised the manuscript as per reviewer comments.

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Dr David Rhodes

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Professor James Selfe

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Olivia Greenhalgh

Publication 11: Alexander, J., Greenhalgh, O., Rhodes, D. (2020). Physiological Parameters in Response to Levels of Pressure during Contemporary Cryo-Compressive Applications: Implications for Protocol Development. *Journal of Athletic Enhancement.* 9(1): 1-6.

This is to declare that as first author of the above scientific publication, Jill Alexander formulated the study rationale, experimental design and aim, compiled and analysed data, wrote the manuscript taking into account feedback collaborative comments and suggestions from the co-authors, prepared the manuscript for submission and revised the manuscript as per reviewer comments.

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Dr David Rhodes

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Olivia Greenhalgh

Publication 12: Alexander, J. Jeffery, J, Rhodes, D. (2021). Recovery Profiles of Eccentric Hamstring Strength in Response to Cooling and Compression. *Journal of Bodywork and Movement Therapies.* 27: 9-15.

This is to declare that as first author of the above scientific publication, Jill Alexander formulated the study rationale, experimental design and aim, compiled and analysed data, wrote the manuscript taking into account feedback collaborative comments and suggestions from the co-authors, prepared the manuscript for submission and revised the manuscript as per reviewer comments.

Dr David Rhodes

Josh Jeffery

Publication 13: Alexander, J., Keegan, J., Reedy, A., and Rhodes, D. (2021). Effects of contemporary cryo-compression on post-training performance in elite academy footballers. *Biology of Sport.* 39(1): 11-17.

This is to declare that as first author of the above scientific publication, Jill Alexander formulated the study rationale, experimental design and aim, compiled and analysed data, wrote the manuscript taking into account feedback collaborative comments and suggestions from the co-authors, prepared the manuscript for submission and revised the manuscript as per reviewer comments.

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Dr David Rhodes

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Jane Keegan

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Antony Reedy

Publication 14: Alexander, J., Carling, C and Rhodes, D. (2021). Utilisation of performance markers to establish the effectiveness of cold-water immersion as a recovery modality in elite football. *Biology of Sport.* 39(1): 19-29.

This is to declare that as first author of the above scientific publication, Jill Alexander formulated the study rationale, experimental design and aim, compiled and analysed data, wrote the manuscript taking into account feedback collaborative comments and suggestions from the co-authors, prepared the manuscript for submission and revised the manuscript as per reviewer comments.

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Dr David Rhodes

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Dr Chis Carling

Publication 15: Selfe, J., Alexander, J., Costello, JT., May, K., Garratt, N., Atkins, S., Dillon, S., Hurst, H., Davison M., Przybyla, D., Coley, A., Bitcon, M., Littler, G., and Richards, J. (2014). The Effect of Three Different (-135°C) Whole Body Cryotherapy Exposure Durations on Elite Rugby League Players. *PLoS ONE,* 9(1); 1-9.

This is to declare on behalf of all associated authors, that as second author of the above scientific publication, Jill Alexander provided a significant contribution to the study rationale, experimental design and aim, compiled data, wrote the manuscript taking into account feedback collaborative comments and suggestions from the co-authors, prepared the manuscript for submission, submitted the manuscript and revised the manuscript as per reviewer comments.

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Professor James Selfe