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1 *Title - Temporal patterns of knee extensor isokinetic torque strength in male and female athletes following*
2 *comparison of anterior thigh and knee cooling, over a rewarming period.*

3
4 **Introduction**

5 The therapeutic technique of cooling commonly used for the treatment of musculoskeletal conditions and
6 recovery in sport is widely debated^{1,2,3}. Deliberation around when athletes may return to activity safely,
7 following local cooling applications is recognised^{1,2}, in consideration of potential neuromuscular deficits⁴.
8 Although methodological differences reduce the strength of consensus across current studies in this area.
9 Within sporting situations, cryotherapeutic application is often associated with pitch-side or half time
10 management of injuries to induce analgesic responses². Other known physiologic effects include; reduced
11 cellular metabolism⁵, receptor firing rate⁶ nerve conduction velocity⁷ and inhibition of muscle spindles^{8,9}, are
12 well-reported^{2,3}. Reduction of tissue temperatures through local cryotherapy applications occur through contact
13 of cryotherapeutic modalities via skin surface initially, to achieve physiological responses¹⁰. A therapeutic skin
14 surface temperature (T_{sk}) target range of between 10-15°C is essential to initiate those essential responses in
15 order to aid acute injury management¹¹. Modalities of cooling differ in thermodynamic properties and therefore
16 cooling efficiency¹⁰. Efficient in phase change, modalities such as crushed or wetted ice noted numerously
17 throughout cryotherapy literature as the most efficient for inducing physiological changes^{12,13,14}. The known
18 effects of cryotherapy on performance and re-injury/further injury risk lack consensus, with methodology
19 difficult to compare outcome measures across studies. Previous studies discuss changes in muscle force
20 depending on cryotherapy location and report increases, decreases or no change^{8,15,16,17}. Emerging literature¹
21 recognised the importance of further study in muscle strength response post local cooling application,
22 applicable to sporting situations.

23 Although rate of temperature change between modalities presents fluctuations the consensus agrees on a
24 relationship existing¹²; that being, a highly significant quadratic association between T_{sk} and intramuscular

25 temperatures (T_{im}) post local cooling applications¹². The gold standard protocol to measure T_{sk} is through
26 infrared thermal imaging^{18,19}. Due to the multifactorial considerations that can affect deeper soft tissues, such
27 as duration²⁰, gender²¹, adipose tissue levels²² and location of cryotherapy applications, knowing the optimum
28 protocol for reduction in muscle temperature to induce physiological changes can be challenging. Furthermore,
29 inconsistencies in methods across studies consequently implicate the ability to compare outcomes or effects
30 accurately. This said literature clearly displays physiological changes as a result of various cryotherapy
31 applications^{20;21;22} and has indicated the importance of exploration of cryotherapy on neuromuscular function²³.

32 Literature indicates performance deficits as a result of cooling² and these have been attributed with decreases in
33 dynamic contractile force¹. These conclusions were drawn based on measures of ultrasound shear wave
34 elastography and myoelectrical activity, no output measures of strength were ascertained. It is important to
35 note that the changes in dynamic contractile force were strongly related to muscle stiffness, which resulted in
36 acute change in muscle mechanical properties after air-pulsed cryotherapy intervention¹. The authors propose
37 this may reduce the amount of stretch able to sustain by the muscle without resulting in injury. The evaluation
38 of muscle strength with isokinetic dynamometry (IKD) is commonly utilised in research due to its high test-
39 retest reliability²⁴. Measurements of peak torque (PT) and average torque (AvT) to establish muscle function
40 can determine reductions post fatigue protocols²⁵. Strength deficits can have implications on knee stability
41 during performance²⁶.

42 Significant reductions in PT and AvT quadricep strength compared to baseline measurements following a 20-
43 minute crushed ice application to the knee, which did not fully recover at 20-minutes post cooling intervention
44 in a recent study²⁷. The authors suggest reductions in concentric strength can still occur therefore, even when
45 indirectly cooled distal to the muscle belly²⁷. Due to no anterior thigh cooling in the previous study, we cannot
46 allude as to whether differences occur regarding cooling location and severity of effects on muscle concentric
47 strength in the lower limb.

48 In consideration of the available literature, a comparison between joint and direct muscle cooling over the
49 anterior thigh may further develop the evidence base in the understanding of the effects of cooling on muscle
50 strength and subsequent implications on lower limb injury risk in sporting populations. Physiological
51 differences in gender response to cooling due to levels of adipose tissue, with females generally recording higher
52 levels, causes variables in the efficiency of heat withdrawal from deeper tissues²¹. The aim therefore of the
53 current study is to compare superficial anterior thigh vs. knee cooling on concentric quadriceps muscle strength
54 in male and female athletes over a rewarming period of 30 minutes.

55 **Methods**

56 Approved by the Science, Technology, Engineering, Medicine and Health (STEMH) ethical committee, the
57 process of this study commenced according to the Declaration of Helsinki²⁸. All participants provided written
58 informed consent to take part in the study. Physiological gender differences reported in literature²¹ detail that
59 females have larger adipose tissue however the effects cooling has on biomechanical function between males
60 and females is limited. Twelve participants, 6 males (Height 179.0±4.4cm; Weight 65.4±6.4kg; age 19.2±1.3
61 years and BMI 20.4±1.3 kg/m²) and 6 females (Height 163.1±8.7cm; Weight 59.7±6.0kg; age 19.2±0.9 years and
62 BMI 22.4±1.4 kg/m²) volunteered to take part in the study, based on a priori power calculation to determine
63 optimum sample size (statistical power >0.7; $p < 0.05$). Participants adhered to the inclusion criteria; healthy,
64 aged between 18-40 years old, no history of lower limb musculoskeletal injury in the past six months, no
65 neurological disease, and no known contraindications to cryotherapy or cold, such as Raynauds¹³. Advice
66 against the consumption of caffeine/alcohol or partake in physical activity¹¹, minimised external factors that
67 may affect local cooling intervention and standardised protocol prior to data collection. All data took place in a
68 movement analysis laboratory.

69 Participants were randomly allocated (randomisation.com) to receiving either anterior thigh or knee cooling,
70 returning one week later for exposure to the opposite intervention location. Both groups followed a clinically

71 relevant cooling dosage of 10-minutes wetted ice, supporting earlier suggestions for investigation into dosages
72 of cooling in line with pitch-side or half time applications of cryotherapy in sport². On arrival, participants
73 underwent a 15-minute acclimatisation period supporting previous study methods²⁷, to ensure a steady thermal
74 state. Room temperature recorded at hourly intervals throughout testing monitored fluctuations as closely as
75 possible. During the acclimatisation period, anthropometric measurements and dominant leg were established.
76 The dominant limb for testing chosen due to regularly being the limb used to kick in land-based sports and
77 determined by which leg the participant naturally chose to kick a football with²⁹.

78 Following gold-standard recommendations in current literature^{18,19}, T_{sk} data using an infrared thermal imaging
79 camera (ThermoVision A40M, Flir Systems, Danderyd, Sweden) gathered at baseline, immediately post and at
80 10-minute intervals up to 30 minutes post of either the anterior thigh or knee, dependent on group allocation
81 was facilitated by determining a region of interest (ROI). To create an anatomical region of interest over the
82 anterior thigh, application of thermally inert skin surface markers formed a framework¹². Location of markers
83 consisted of superior marker placement, 1/3 way between ASIS and Base of Patella; Inferior marker placement
84 2/3 way between ASIS and Base of Patella. Central thigh was determined by the measure of thigh circumference
85 at centre of thigh (COT), located at 50% between ASIS and Base of Patella. Markers then placed at 10% of this
86 distance in medial and lateral directions from COT completed the ROI for anterior thigh¹². Markers also placed
87 at the base of patella, medial and lateral border of patella tendon margin at tibiofemoral joint line level and tibial
88 tubercle determined a ROI for local knee cooling³⁰. The thermal imaging camera situated at a height of 134cm
89 from the ground, positioned perpendicular to the anterior lower limb, with participants laying supine on a
90 plinth followed standard clinical set up with an emissivity setting of 0.97-0.98.

91 Following baseline T_{sk} data collection, a measure of concentric quadriceps muscle strength determined baseline
92 strength data using an isokinetic dynamometer (IKD) (Cybex, division of Lumex Inc., Ronkonkoma, NY, USA)
93 chosen due to high reliability (0.9-0.98)²⁴. A 10-minute wetted ice application either to the anterior thigh or

94 knee region followed², depending on allocation of group. Previous research surrounding cooling techniques
95 recommends use of wetted ice^{12,13,14}. Therefore, the protocol for wetted ice intervention consisted of 800ml of
96 cubed ice and 800ml of room-temperature water; then placed into a clear polythene bag size of 22x40cm, with
97 the excess air removed and secured with a knot¹³. The bag of wetted ice held in place securely to the limb with
98 a cling-film wrap, and between skin and the wetted ice bag, a placement of a thin, damp microfiber towel for 10
99 minutes at either anterior thigh or knee^{11,30}.

100 In the same format at T_{sk} , IKD data was collected immediately post intervention and at 10 minute intervals up
101 to 30 minutes post for each group as recommended in a previous study²⁷. Between isokinetic measures
102 participants were asked to long sit on a plinth. Previous research within isokinetic testing advocates the use of
103 a range of testing speeds²⁵. The gravity corrected torque-angle curve was analysed for each testing speed, with
104 analysis restricted to the isokinetic phase. PT, the corresponding angle (Θ), and AvT across the isokinetic phase
105 were identified for each player, at each testing speed²⁵. Concentric isokinetic torque measurements for the
106 quadriceps performed at three repetitions per time point, into knee extension at $60^{\circ}.s^{-1}$ and at $150^{\circ}.s^{-1}$, with
107 passive movement into flexion at $10^{\circ}.s^{-1}$ between repetitions²⁷. The two repetitions eliciting the highest PT value
108 were identified for each time point and utilised for subsequent analysis. Observation of each repetition
109 completed by the same researcher ensured consistent and smooth effort exerted by each participant throughout
110 testing²⁷. To minimise participants' extraneous body movement's standard positional setup using chest, pelvis
111 and mid-thigh straps were applied²⁷ with the tibial strap placed three-quarters distally on the tibia, and
112 rotational axis of the dynamometer aligned to the lateral femoral epicondyle. To isolate torque production at
113 the quadriceps participants crossed their upper limbs across the chest²⁷.

114

115 *Statistical Analysis*

116 A univariate repeated measures general linear model quantified main effects for recovery duration post-ice
117 application and isokinetic testing speed. Significant main effects in recovery duration were explored using post
118 hoc pairwise comparisons with a Bonferonni correction factor. The assumptions associated with the statistical
119 model were assessed and met to ensure model adequacy. To assess residual normality for each dependant
120 variable, q-q plots were generated using stacked standardised residuals. Scatterplots of the stacked
121 unstandardized and standardised residuals were also utilised to assess the error of variance associated with the
122 residuals. Mauchly's test of sphericity was also completed for all dependent variables, with a Greenhouse
123 Geisser correction applied if the test was significant. Partial eta squared (η^2) values were calculated to estimate
124 effect sizes for all significant main effects³¹. Partial eta squared was classified as small (0.01–0.059), moderate
125 (0.06-0.137), and large (>0.138). Interactions within the general linear model were also identified within the
126 analysis of data. All statistical analysis was completed using PASW Statistics Editor 24.0 for windows (SPSS Inc,
127 Chicago, USA). Statistical significance was set at $P \leq 0.05$, and all data are presented as mean \pm standard
128 deviation.

129

130 **Results**

131 *Skin Surface Temperature (T_{sk}) ($^{\circ}C$)*

132 Whole group T_{sk} data demonstrated statistical significant decreases at the knee for all timepoints compared to
133 pre application temperatures, IP ($p \leq 0.001$), 10 minutes ($p \leq 0.001$), 20 minutes ($p \leq 0.001$), and 30 minutes
134 post intervention ($p = 0.03$) (Figure 1). Post cryotherapy application to the quadriceps noted statistically
135 significant decreases in T_{sk} at IP ($p \leq 0.001$), 10 ($p \leq 0.001$), and 20 minutes post intervention ($p = 0.04$). No
136 statistically significant changes in T_{sk} were reported at post 30 minutes intervention for the anterior thigh ($p =$
137 0.11), however T_{sk} did not return to baseline temperatures for whole group (Figure 1).

138 Statistically significant decreases in T_{sk} were also noted when comparing male and female groups separately
139 across all time points for the knee ($p \leq 0.05$) (Table 1). Comparatively, statistically significant decreases for
140 quadricep T_{sk} were noted in males at each time point up to 20 minutes post ($p \leq 0.05$), however no significant
141 decreases in T_{sk} were noted for males ($p = 0.41$), or females ($p = 0.19$) at the anterior thigh at 30 minutes post
142 (Table 1). Throughout the entire investigation, ambient room temperature was constant ($21.1 \pm 0.5^\circ\text{C}$).

143 **Peak Torque (PT)**

144 Table 1 summarises the effects of wetted ice application and the temporal pattern recovery on PT. There was a
145 significant main effect for time ($p \leq 0.001$, $\eta^2 = 0.126$), with pre ice application higher than all other time points
146 ($p \leq 0.05$). With the data set collapsed to consider each speed in isolation, PT displayed a significant main effect
147 for time at all speeds (PT_{60} : $p = 0.03$, $\eta^2 = 0.98$; PT_{150} : $p = 0.001$, $\eta^2 = 0.177$) (Table 1). There was also significant
148 main effects for isokinetic testing speed ($p \leq 0.001$, $\eta^2 = 0.264$), sex of the participant ($p \leq 0.001$, $\eta^2 = 0.269$)
149 and position of the ice application ($p \leq 0.001$, $\eta^2 = 0.151$) (Table 1). There were no significant interactions found
150 between speed, time, position and gender for PT ($p \geq 0.05$).

151 **Average Peak Torque (AvT)**

152 Table 1 further summarise the effects of wetted ice application and the temporal pattern recovery on AvT. There
153 was a significant main effect for time ($p \leq 0.001$, $\eta^2 = 0.159$), with pre ice application higher than all other time
154 points ($p \leq 0.02$) except at 30 minutes post ($p = > 0.05$). With the data set collapsed to consider each speed in
155 isolation, AvT displayed a significant main effect for time at all speeds (AvT_{60} : $p = 0.009$, $\eta^2 = 0.126$; $AvPT_{150}$: p
156 < 0.001 , $\eta^2 = 0.234$) (Table 1). There was also significant main effects for isokinetic testing speed ($p \leq 0.001$, η^2
157 $= 0.301$), sex of the participant ($p \leq 0.001$, $\eta^2 = 0.246$) and position of the ice application ($p \leq 0.001$, $\eta^2 = 0.085$)
158 (Table 1). There was a speed \times position interaction ($p = 0.023$, $\eta^2 = 0.028$), no other significant interactions
159 were found ($p \geq 0.05$).

160 **Discussion**

161 The current study reports the effects of anterior thigh and knee cooling on PT and AvT isotonic strength of the
162 quadriceps in males and females over a rewarming period. Previous studies have traditionally cooled over the
163 exercising muscle¹³ and others only the distal joint³² or simultaneously⁴, to our knowledge no study compares
164 both. It is unclear however as to the extent of positive or deleterious effects of local cooling at different locations
165 over the peripheral lower limb on the mechanical properties of muscle strength, with literature failing to reach
166 a strong consensus. Results demonstrate reductions in PT and AvT concentric quadriceps strength in males and
167 females, of which did not fully recover to baseline at 30 minutes post cryotherapy intervention. Findings from
168 the current study agree with ^{1,2,27}, but also refute^{16,17} some evidence. It is problematic however to copiously
169 compare results directly, because of the variability in testing protocols across available literature. Notably,
170 current findings report the need for further enquiry into the immediate and latent effects of common
171 cryotherapeutic applications used pitch side in sport with varied dosage applications on muscle strength.

172 To mimic closely common applications of cold applied pitch-side or at half time during competitive sport,
173 duration of wetted ice followed a 10-minute dosage in the current study³⁴. Although contrasting to longer
174 dosage protocols^{3,8,9}, the decision supports the recommendation for investigations in cryotherapy to replicate
175 simulated play and helps understand the extent of effects induced by cryotherapy applications in sporting
176 scenarios². A 10-minute wetted ice exposure initiated whole group average T_{sk} recorded at $9.6 \pm 1.6^{\circ}\text{C}$ (knee) and
177 $12.1 \pm 1.4^{\circ}\text{C}$ (anterior thigh), immediately post intervention in the current study. These results establish a T_{sk}
178 response to within the desired therapeutic range of cooling ($10\text{-}15^{\circ}\text{C}$)¹¹, expected for physiological response
179 occurred after a 10-minute application (Figure 1). Whole group T_{sk} did not return to baseline levels at 30
180 minutes over the knee ($24.0 \pm 1.0^{\circ}\text{C}$), or at 20 minutes post over the anterior thigh ($29.1 \pm 0.6^{\circ}\text{C}$) for whole group
181 data (Figure 1), supporting previous literature²⁷. In addition, regardless of cooling location, reductions in
182 strength were reported in both male and female groups, for both speeds ($PT_{60/150}$, $AvPT_{60/150}$) (Table 1). The

183 noted reductions in strength coincide with reductions in T_{sk} over the rewarming period and demonstrate a
184 relative incline over 30 minutes post removal (Table 1). Observation of percentage difference in concentric
185 quadriceps strength data between cooling locations noted no definitive pattern when comparing all post data
186 to baseline. Although, a trend is suggestive that concentric strength data immediately post demonstrated greater
187 reductions noted subsequently following knee joint cooling than the anterior thigh in males for both speeds
188 (PT/AvPT: $60^{\circ}.s^{-1}/150^{\circ}.s^{-1}$), but not in females. Accordingly at all other timepoints (10, 20 and 30 minutes), data
189 recorded greater reductions for anterior thigh cooling compared to knee for both gender groups, and speeds.
190 Unsurprisingly this supports previously reported quadratic relationship mechanisms between T_{sk} and deeper
191 musculature response to cooling following removal of local cooling¹²; that being that as skin rewarms, muscle
192 continues to cool pertinent to cooling ability of the cryotherapy modality applied. This also supports the
193 findings that strength following cooling at either locations, across both gender groups and speeds does not
194 return to pre-intervention levels at 30 minutes. Although largely data reports different percentages of strength
195 deficit noted following anterior thigh compared to knee cooling; both cooling locations demonstrated
196 statistically significant reductions in concentric strength over the rewarming period (Table 1) regardless of
197 gender or speed compared to baseline measures. Due to the relatively small sample size utilised in the present
198 study, caution when comparing findings between genders may be noted. This may also contribute to the
199 interactions between variables highlighted in the complex study design. Significant interactions were
200 highlighted for speed \times position in AvT, with a small effect size reported. Consideration must be given to this
201 in future work.

202 Local cryotherapy in athletic practice, particularly prior to returning to activities that expose muscle tissue to
203 exercise induced damage should consider the findings from the current investigation. Results agree with those
204 conclusions of previous authors, that ≥ 10 -minutes of cooling reduces muscle contractility and subsequently,
205 performance⁸. Furthermore the authors agree that desensitization of deep joint mechanoreceptors following

206 knee joint cooling may affect neuromuscular response, proposing a change in proprioceptive feedback³³, but
207 importantly reaffirm the detrimental effects distal cooling has on the strength of musculature as much as that
208 of direct cooling over the anterior thigh. Reductions in torque production ability of the quadriceps, are formerly
209 reported immediately following a 20-minute cooling application over the anterior knee joint, and highlighted
210 the importance of investigating rewarming periods prior to returning to sport²⁷. The implications of reduced
211 muscle strength of the quadriceps or surrounding musculature may predispose an increased risk of non-contact
212 injury at the knee complex³⁴. Investigations report acute changes in the mechanical properties of muscle
213 following cryotherapy consequently lowers the amount of stretch that muscle tissue is able to sustain without
214 subsequent injury¹. Cooling over regions susceptible to strain injury, such as myotendinous junction, may
215 present an increased risk of injury by returning to activity soon after cryotherapy applications. Point et al (2018)
216 considers this heightened risk is due to the reduced capacity of the muscle tendon unit to sustain external strain
217 following cooling caused by increased stiffness in the cooled tissues³⁵. Muscle fibres therefore more prone to
218 damage¹ due to known mechanisms predisposing to soft-tissue injury, such as reductions in available range of
219 motion³⁷ and increases in contractile tissue stiffness³⁷. Assumed putative changes in global viscoelastic and
220 myoelectrical activity initiated by lower temperatures may be factors that contribute to the reduction noted in
221 isotonic PK and AvPK in the current study, supporting previous suggestions^{1,7}. Reduced muscle deformation,
222 passively, have been reported in cold muscles, prior to rupture, following exposure to cold-water immersion³⁸.
223 Although consideration that cold-water immersion is more likely to alter properties of multiple structures that
224 cross over the joint including agonists and antagonist muscles, tendons and articular structures¹. It is difficult
225 therefore to compare directly current results to CWI or air-pulsed cryotherapy modalities directly, on that basis.

226 **Conclusion**

227 Local cooling over superficial joint or muscles in males and females may result in performance deficits due to
228 reductions in concentric muscle strength. Future studies are essential, in order to establish margins whereby

229 safe return to sport following cooling exposures to the lower limb. Sports medicine practitioners should
230 consider reductions in strength ability of the quadriceps even after shorter application durations (<20') of
231 wetted ice, and regardless cooling location (joint/muscle) or gender. To advance safe rationale for pitch-side
232 cryotherapy applications, comparison of other commonly applied cryotherapy modalities are necessary and
233 observation of multiple variables that may affect the development of optimum dose duration and return to
234 activity panaceas.

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