Effects of Whole Body Cryotherapy and Cold Water Immersion on Knee Skin Temperature

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Key word
- cryotherapy
- skin temperature
- tissue temperature
- knee
- cryokinetics

Abstract

This study sought to a) compare and contrast the effect of 2 commonly used cryotherapy treatments, 4 min of −110 °C whole body cryotherapy and 8 °C cold water immersion, on knee skin temperature and b) establish whether either protocol was capable of achieving a skin temperature (<13 °C) believed to be required for analgesic purposes. After ethics committee approval and written informed consent was obtained, 10 healthy males (26.5 ± 4.9 yr, 183.5 ± 6.0 cm, 90.7 ± 19.9 kg, 26.8 ± 5.0 kg/m^2, 23.0 ± 9.3 % body fat; mean ± SD) participated in this randomised controlled crossover study. Skin temperature around the patellar region was assessed in both knees via non-contact, infrared thermal imaging and recorded pre-, immediately post-treatment and every 10 min thereafter for 60 min. Compared to baseline, average, minimum and maximum skin temperatures were significantly reduced ($p < 0.001$) immediately post-treatment and at 10, 20, 30, 40, 50 and 60 min after both cooling modalities. Average and minimum skin temperatures were lower ($p < 0.05$) immediately after whole body cryotherapy (19.0 ± 0.9 °C) compared to cold water immersion (20.5 ± 0.6 °C). However, from 10 to 60 min post, the average, minimum and maximum skin temperatures were lower ($p < 0.05$) following the cold water treatment. Finally, neither protocol achieved a skin temperature believed to be required to elicit an analgesic effect.

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Bibliography
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Introduction

Whole body cryotherapy (WBC) is a novel modality of cryotherapy that is currently being used in various therapeutic, medical and sporting settings [12]. WBC involves exposure to extremely cold air, usually between −100 to −130 °C (−148 to −202 °F) in a specially designed climatic chamber, for a short duration of time (2–4 min) [3, 10–12, 25]. Although the physiological effects of other cold modalities, including ice packs, cooling pads, cold water immersion and cooling spray, are relatively well established [26, 39], little is known regarding the use of this extreme cold exposure.

Physiotherapists, clinicians and practitioners alike routinely desire a reduction in a clients' skin temperature for analgesic or therapeutic purposes [15]. Although the optimal reduction in skin temperature has yet to be elucidated, it is widely believed that a skin temperature of less than 13 °C is required to induce an analgesic effect [8]. However, we have recently reviewed the effects of various modalities of cooling on skin temperature and found that ambiguity exists regarding the optimal skin temperature reductions in both a medical or sporting setting [15]. Furthermore, skin temperatures in different anatomical locations are known to respond differently to various modalities and durations of cooling [15]. Interestingly, the patellar region appears to be one location where large variations in skin temperature have been observed following various cooling modalities and protocols [4, 30, 32]. Depending on the modality used, a difference of up to 20 °C in skin temperature in the knee can be observed following various cooling protocols [15].

One of the consistent findings to emerge from previous research [15] was the long period of tissue rewarming following brief and relatively mild exposures to cold, particularly around the knee. For example, following the application of a CryoCuff for 3 min, Karki and colleagues [23] found that the skin temperature over the patella had not returned to the baseline value after 25 min (it remained 1–2ºC lower) in a group of healthy adults. Similarly, Selfe [35] found skin tempera-

ture of the patella 2.5 °C lower than baseline 20 min after the removal of a Cryo-Cuff in a group of patellofemoral patients.
This finding is something of a paradox as the anterior knee has a superficial, well-developed vascular anastomosis of 6 major vessels forming an arterial ring, the rete patellae, encircling the patella [2, 5, 33]. Moreover, the patella is sometimes described as a 'heat shield' [32] and previous studies report that the anterior knee is, thermographically, a very cold area [27, 28]. As one of the main functions of arterial blood is to distribute heat around the body this anatomical arrangement suggests that the anterior knee should actually be quite warm. Zhang and colleagues [41] have previously highlighted the importance of the thermophysiological properties of fat in their human thermal model and the insulation properties of adipose tissue are well established [21, 22, 29]. As the anterior knee is devoid of muscle, and often has little underlying adipose tissue, the patellar region is susceptible to experiencing large reductions in skin temperature following cryotherapy. Remarkably few studies have studied the effects of cooling on the skin temperature around this region.
Both WBC and cold water immersion (CWI) are commonly used in an attempt to induce the physiological benefits of 'cold application', including analgesia. Both modalities create a significant thermal stress to the whole body as well as locally to the anterior knee. The temperature deficit between the cooling modality and the skin can be greater than 100 °C during WBC and 20 °C if a water temperature of less than 10 °C is employed during CWI. Despite the significant discrepancies between the temperature gradients, and indeed the conductivity of water and air, few authors have sought to compare and contrast the skin-cooling potential of both treatments. Consequently, limited data is available to clinicians regarding the effectiveness of the different cryotherapy treatment protocols, durations, temperatures and skin temperature rewarming. Therefore the purpose of this study was to a) compare and contrast the changes in skin temperature at the anterior knee following an identical duration of WBC and CWI and b) establish if either protocol was capable of achieving a skin temperature (< 13 °C) believed to be required for analgesic purposes.

Methods
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Design
The study design was a randomized controlled crossover, with participants randomly assigned, using a random numbers generator to start with either the WBC or CWI treatment. A minimum of 7 days later, participants repeated the remaining treatment. All trials took place at the same time of the day (± 1 h).

Participants
Ten male participants volunteered to participate in this study (**Table 1**). Participants were between the ages of 18–33 yrs and exercised at least 3 times per week. Participants were familiarized with the experimental procedures and associated risks, completed a medical questionnaire and gave their written informed consent to participate. Participants were excluded if they indicated they had any contraindication to cryotherapy including Raynaud's disease. All participants were required to refrain from smoking, consuming caffeine and alcohol for 12 h prior to each laboratory session. In addition, participants were tested at the same time of day for each trial (separated by 7–10 days), and did not undertake exercise for 24 h prior to each laboratory session. The study was conducted according to the ethical standards of the International Journal of Sports Medicine [19], and the experimental protocol was approved by the research ethics committee of the Faculty of Education and Health Sciences at the University of Limerick.

Table 1 Characteristics of the participants (n = 10).

Characteristics	Mean ± SD
age (yr)	26.5 ± 4.9
height (cm)	183.5 ± 6.0
body mass (kg)	90.7 ± 19.9
body mass index (kg/m^2)	26.8 ± 5.0
body fat (%)	23.0 ± 9.3
right patellar skinfold (mm)	7.6 ± 2.0
left patellar skinfold (mm)	7.0 ± 1.8

Treatment protocol
For the WBC treatment we utilised a protocol similar to our previous work [10–12] and participants were exposed to a treatment in a cryogenic chamber at the Shannon Cryotherapy Clinic in Ennis, County Clare, Ireland. WBC exposures were administered in a specially built, temperature-controlled unit (Zimmer Elektromedizin, Germany) consisting of 2 rooms (− 60 and − 110 °C). The temperature of the therapy room remained at a constant level (− 110 ± 3 °C [mean ± SD]), and the air in the room was dry and clear. Participants entered and stood in the first room (− 60 ± 3 °C) for 20 s before entering the second room (− 110 ± 3 °C) for 3 min and 40 s. Participants were instructed by the trained machine operator to walk slowly around the chamber and to flex and extend their elbow and fingers throughout the 3 min. In the chamber, participants wore shorts, 2 pairs of gloves and their noses and mouths were secured with a surgical mask; their ears were covered with a woollen headband and they wore their own dry shoes and ankle socks. Glasses, contact lenses and all jewellery and piercings were removed before entry to the chamber.
For the CWI treatment the water temperatures and immersion protocol were based on data frequently reported in the literature [18, 40], and a protocol similar to our previous work [11, 12, 14] was employed. Following the baseline recordings participants, wearing only shorts, were seated in a tank filled with cold water (8 °C ± 0.3 °C) and immersed to the level of the sternum for 4 min. Immediately after the CWI the participants were asked to towel-dry their body, change into dry shorts and transfer to an adjacent laboratory for the post intervention tests. The temperature of the water was measured throughout using a digital aquarium thermometer.

Skin temperature
Skin temperature was assessed via noncontact, digital, infrared thermal imaging (TI). The protocol was similar to that of our other published research, and a ThermoVision A40M Thermal Imaging camera (Flir Systems, Danderyd, Sweden) was used in accordance with the standard protocol of infrared imaging in medicine [31]. The emissivity of the camera was set at 0.97–0.98 and connected to a personal computer (Portege A100, Toshiba, Japan) loaded with appropriate software (Thermacam Researcher Pro 2.8, Flir systems, Danderyd, Sweden). The TI camera was then mounted on a tripod 3.7–4.2 m away from the participants (subject to the height of the participant) [12]. We

Table 2 The mean average, minimum and maximum skin temperature of the right and left knee pre and post Whole Body Cryotherapy (WBC) and Cold Water Immersion (CWI) (n = 10). Values are mean ± SD.

		Pre (°C)		Post (°C)		Temperature Reduction (°C)	
		WBC	**CWI**	**WBC**	**CWI**	**WBC**	**CWI**
average	**right**	29.3 (0.7)	29.6 (0.9)	19.0 (0.9)	20.5 (0.6)	10.3 (0.6)	9.0 (0.8)
	left	29.4 (0.8)	29.5 (1.2)	19.5 (1.2)	20.6 (1.0)	9.9 (0.6)	8.9 (0.9)
minimum	**right**	27.7 (0.9)	28.1 (1.0)	16.0 (1.1)	19 (0.7)	11.7 (1.1)	9.1 (1.0)
	left	27.8 (0.7)	28.0 (1.0)	16.5 (1.4)	19.0 (0.8)	11.4 (0.0)	9.0 (0.9)
maximum	**right**	30.9 (0.8)	31.3 (0.9)	22.5 (1.1)	23.1 (0.9)	8.4 (1.0)	8.2 (1.2)
	left	31.0 (1.1)	31.1 (1.5)	23.9 (2.7)	23.6 (2.7)	7.1 (1.7)	7.5 (1.7)

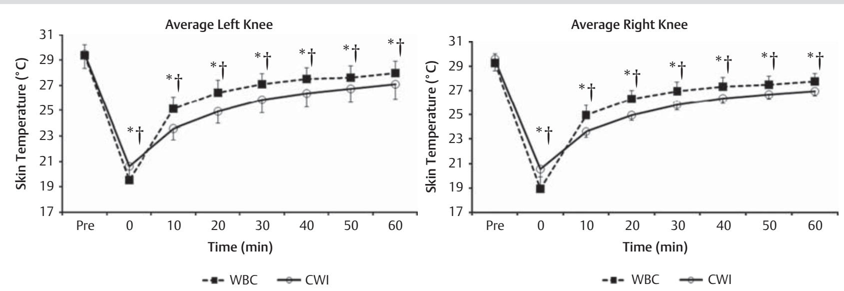

Fig. 1 Average (SD) skin temperature in the left (n = 10) and right knee (n = 10) before, immediately after and 10, 20, 30, 40, 50 and 60 min post Whole Body Cryotherapy (WBC) and Cold Water Immersion (CWI). * denotes significantly different from baseline for both modalities and † significant differences between treatments.

have previously reviewed the use and benefits of TI in the assessment of skin temperature following the application of cryotherapy [15] and concluded that the technique was a safe and non-invasive method of collecting skin temperature that offered many advantages over other commonly used techniques. Furthermore, the validity and reliability of using TI to measure skin surface temperature has previously been established [17, 20, 34]. A quadrilateral Region of Interest (ROI) around the knee was created using inert markers placed 5 cm above and below the most superior and inferior aspect of the patella on both knees [15, 34]. These markers allowed post-process analysis of a quadrilateral ROI around the patellar region [12, 15]. The minimum, maximum and average skin temperatures within this ROI on both knees were manually recorded before, immediately post-treatment and 10 min thereafter for 60 min after the CWI and WBC treatments. The subjects wore shorts, stood for the duration of the testing period and were asked to remain in the anatomical position while images were being recorded. The temperature and humidity of the laboratory during each testing session (WBC and CWI) was 22.0 ± 0.5 °C and 50 ± 5 %, respectively, and subjects spent 20 min acclimatising to the room before the commencement of testing.

Reliability

The test-retest reliability of the current methodology (using mean differences and 95 % limits of agreement) was established using the value of the pre-WBC subtracted from the pre-CWI trials in the 10 subjects (i. e., 10 pairs of knees). The mean difference (SD) for average, minimum and maximum skin temperature between the 2 trials was −0.3 (0.9), −0.3 (1.0) and −0.4 (0.7) °C and −0.1 (1.1), −0.2 (1.0) and −0.1 (1.1) °C in the right and left knee respectively. Limits of agreement (mean difference ± 1.96 times the standard deviation) for average, minimum and maximum skin temperature in the right knee ranged from −2.0 to 1.4, −2.3 to 1.7 and −1.7 to 0.9 °C. Limits of agreement in the left knee ranged from −2.3 to 2.1, −2.2 to 1.9, −2.2 to 2.1 °C for average, minimum and maximum skin temperature.

Statistical analysis

All data are presented as group means and SD. To compare the baseline skin (minimum, maximum and average) temperature before WBC and CWI, a paired sample t-test was performed. A *priori* analysis where the final baseline (°C) recording of skin temperature was compared to that of the post treatment temperature at 0, 10, 20, 30, 40, 50 and 60 min following both cryotherapy modalities was performed. A repeated measures analysis of variance (ANOVA) (knee × treatment × time) was used to investigate changes in time with one inter-subject variable, treatment, with 2 levels (WBC and CWI) and 2 intra-subject variables, *knee*, with 2 levels (left and right) and time with 8 levels (baseline, 0, 10, 20, 30, 40, 50 and 60 min post). The effect of time, treatment and treatment by time interactions were tested. When the effect was significant, a Bonferroni post-hoc test was used to investigate intra-group differences. All variables were tested for normal distribution with the Shapiro-Wilk test. When the assumption of sphericity was violated, significance was adjusted using the Greenhouse-Geisser method. The current study had an 80 % power to detect a difference of 1 °C in skin temperature between conditions.

Results

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Average, minimum and maximum knee skin temperatures were similar before both treatments ($P > 0.05$, [paired sample t-test], ▶ **Table 2**). There was no significant difference between the left and right knees on average ($F_{1,9} = 0.139$, $P = 0.718$, $1-\beta = 0.063$), minimum ($F_{1,9} = 0.564$, $P = 0.472$, $1-\beta = 0.103$) or maximum ($F_{1,9} = 0.314$, $P = 0.589$, $1-\beta = 0.079$) skin temperature at any time point.

Average ($F_{7,63} = 1101.914$, $P < 0.001$, $1-\beta = 1.0$; ▶ **Fig. 1**), minimum ($F_{7,63} = 747.539$, $P < 0.001$, $1-\beta = 1.0$; ▶ **Fig. 2**) and maximum ($F_{7,63} = 359.474$, $P < 0.001$, $1-\beta = 1.0$; ▶ **Fig. 3**) skin temperatures were significantly reduced following both WBC and CWI. 60 min after both treatments, the temperature of the skin (average, maximum and minimum) had yet to return to

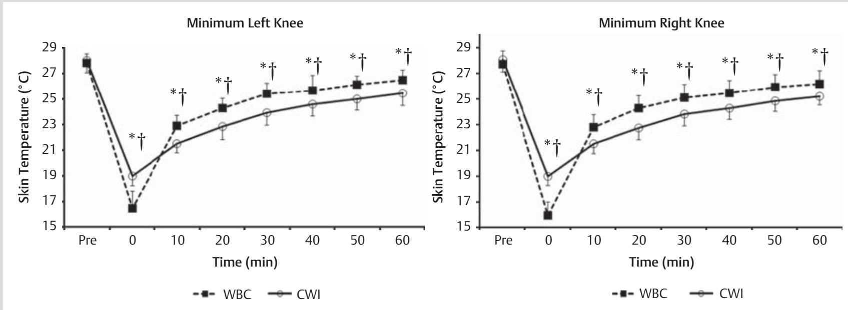

Fig. 2 Minimum (SD) skin temperature in the left (n=10) and right knee (n=10) before, immediately after and 10, 20, 30, 40, 50 and 60 min post Whole Body Cryotherapy (WBC) and Cold Water Immersion (CWI). * denotes significantly different from baseline for both modalities and † significant differences between treatments.

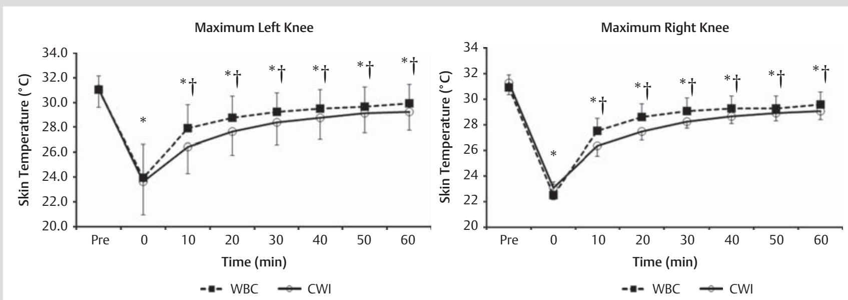

Fig. 3 Maximum (SD) skin temperature in the left (n=10) and right knee (n=10) before, immediately after and 10, 20, 30, 40, 50 and 60 min post Whole Body Cryotherapy (WBC) and Cold Water Immersion (CWI). * denotes significantly different from baseline for both modalities and † significant differences between treatments.

baseline. A significant difference between treatments was observed on average ($F_{1,9}$=9.422, P=0.013, 1−β=0.78), minimum ($F_{1,9}$=5.716, P=0.04, 1−β=0.569) and maximum ($F_{1,9}$=6.454, P=0.032, 1−β=0.62) skin temperature. Post-hoc analysis showed these differences occurred at 0, 10, 20, 30, 40, 50 and 60 min post-treatment on average and at minimum (**Fig. 1, 2**) and at 10–60 min in maximum skin temperature (**Fig. 3**). Immediately after WBC, average and minimum knee skin temperature (in both knees) were lower compared to CWI (**Table 2**, **Fig. 1, 2**). However, the pattern of skin temperature recovery was different between treatment, and participant knee temperature tended to remain cooler for longer after CWI (**Fig. 1–3**).

Discussion

To our knowledge, this is the first randomised controlled crossover study which sought to compare and contrast the effects of WBC and CWI on anterior knee temperature in healthy participants. The findings of this study suggest that although WBC caused a greater reduction in skin temperature, participants' skin temperature tended to recover faster following this modality compared to CWI. Moreover, despite their popularity in clinical, sporting and rehabilitative settings, neither protocol induced skin temperatures sufficiently cold enough to elicit an analgesic effect.

Inter-limb skin temperature was similar at baseline before exposure to both treatments (**Table 2**). Baseline knee skin temperature ranged from 29.3–29.6 °C, across both knees and testing conditions, and this is comparable to what others have reported [1,4,20,38]. As expected, the temperature at the anterior knee was bilaterally reduced following 4 min of exposure to each of the cryotherapy conditions (**Fig. 1–3**). Following CWI there was a 9.1 °C reduction from the baseline temperature of 29.6 °C to 20.5 °C (**Table 2**). Following WBC there was a 10.3 °C reduction from the baseline temperature of 29.4 °C to 19.0 °C (**Table 2**). These data are consistent with the findings of Cholewka [9], who reported a mean reduction of skin temperature over the tibias of 8.7 °C following a similar WBC exposure. The differential response between CWI and WBC conditions was statistically significant and exceeded the suggested minimum clinically important difference of 0.5 °C proposed by Selfe and colleagues [36].

As previously highlighted [15,23–25,35] there was an extended period of rewarming that took place following brief exposures to cold. Both CWI and WBC displayed significantly lower skin temperatures 60 min after exposure (**Fig. 1–3**). It is interesting that brief systemic exposure to cooling results in a rewarming profile very similar to local cooling at the knee, which is often applied for much longer periods of time [15]. As both modalities are typically repeated over the course of the same day, these rewarming patterns are worth considering for clinicians administering these treatments.

Interestingly, and despite the frequent use of both WBC and CWI in a clinical/rehabilitative setting, neither protocol induced skin temperatures sufficient to induce an analgesic effect. Bleakley and Hopkins [8] have highlighted the need to reduce skin temperature below 13 °C for analgesic purposes. Both protocols were approximately 8 °C above this mark, and these findings are similar to data we have previously presented on thigh skin temperature after the same protocols [12]. Based on these findings, the therapeutic and physiological benefits of employing the temperatures and durations as those described here is questionable, and further research is warranted to improve or indeed standardise current cooling protocols.

The decreases in skin temperature reported in this study are, however, interesting to consider in light of the results of other studies investigating intra-articular knee temperature during experimental cooling. Dahlstedt [16] reported that knee skin surface temperature had to be 20 °C or less to produce any demonstrable decrease in knee joint intra-articular temperature. Kim [24] investigated a local application of cold air at −30 °C to the knee for 5 min and reported a 22.1 °C reduction of skin temperature to 9.7 °C. Simultaneous intra-articular temperature measurement of the knee joint demonstrated a drop of

3.9 °–30 °C. Oosterveldt [30] compared local application of ice chips to the anterior knee for 30 min with cold air at −160 °C for 6.5 min. They reported that cold air caused a 15 °C reduction of skin temperature to 13.8 °C and a 4.1 °C reduction in knee joint intra-articular temperature to 28.8 °C. Despite the different magnitude of skin cooling achieved in these 2 studies, the intra-articular cooling reported was very similar (~4 °C). In contrast to this, Oosterveldt [30] reported that ice chips produced a reduction in skin temperature of 16.4 °–11.5 °C and a 9.4 °C reduction of intra-articular temperature to 22.5 °C. Although not recorded in the current study it would appear, based on these data, that brief exposures to WBC, and possibly CWI, may potentially reduce intra-articular temperature at the knee.

The 2 different dry air methods described above [24, 30] produced very similar joint temperatures but quite different skin temperatures. The wet ice method described also resulted in similar reductions in skin surface temperatures, but resulted in a much lower joint temperature. It is likely this difference could be related to the length of exposure, as both the cold dry air methods consisted of brief exposures, whereas the wet ice method at 30 min was considerably longer. Being cognisant of this we eliminated this variable by standardising the exposure duration in the current study. Consequently, it appears that dry cold and wet cold do have slightly different effects on skin temperature reduction and subsequent rewarming (▶ **Fig. 1–3**). This theory warrants further investigation as it may have important physiological and clinical implications.

Following brief CWI and WBC exposures, skin temperature at the anterior knee was 20.5 °C and 19 °C, respectively, which are both lower than the figure reported by Uchio and colleagues [37]. These authors reported skin temperature reduced to 21.6 ± 3 °C following 15 min local cooling (administered via a cooling pad) and found an increase in knee joint stiffness and decreased proprioceptive acuity. If a cooling protocol that is similar to either of those described in this study is to be incorporated into a rehabilitative or training programme, it may be advisable to adopt caution in any subsequent weight-bearing or dynamic movements. It is possible that joint stiffness and proprioceptive acuity would be affected across the lower limb joints in both limbs [6, 7, 13].

The results of this study are limited to a group of young healthy male participants. Due to the higher level of adiposity in females, and the subsequent effect of insulation, future research incorporating a female population is warranted. We acknowledge that consensus has yet to be reached regarding optimal (and indeed practical) temperatures and duration of different cooling protocols. However, the cooling protocols employed in this study are typical of those utilised in practice and reported elsewhere in the literature. Furthermore, to compare and contrast both modalities (WBC and CWI) we used a similar duration of cooling. Additional research is required in order to optimise and regulate different cryotherapy protocols. Finally, although not reported in the current study, we have previously described [12] the effects of both modalities on core (~0.5 °C) and deep muscle (~2 °C) temperature in a similar group of participants.

In summary, this randomised controlled crossover study was the first to examine the effect of CWI and WBC on knee skin temperature. WBC was shown to elicite a greater decrease in knee skin temperature compared to CWI immediately after treatment. However, both modalities display different recovery patterns and average and minimum skin temperature after CWI was significantly lower than WBC at 10, 20, 30, 40, 50 and 60 min after treatment. Finally, as neither protocol achieved a skin temperature sufficient to elicit an analgesic effect around the patellar region, the current study highlights the need to establish optimal cooling protocols (in terms of modality, temperature and duration) based on tissue temperature.

References

1 *Ammer K*. Temperature of the human knee – A review. Therm Int 2012; 22: 137–151
2 *Arnoldi C*. The Patellar Pain Syndrome. Acta Orthop Scand 1991; 62: 1–29
3 *Banfi G*, *Lombardi G*, *Colombini A*, *Melegati G*. Whole-body cryotherapy in athletes. Sports Med 2010; 40: 509–517
4 *Becher C*, *Springer J*, *Feil S*, *Cerulli G*, *Paessler H*. Intra-articular temperatures of the knee in sports – An in-vivo study of jogging and alpine skiing. BMC Musculoskelet Disord 2008; 9: 46
5 *Bjorkstrom S*, *Goldie I*. A study of the arterial supply of the patella in the normal state, in chondromalacia patellae and in osteoarthrosis. Acta Orthop Scand 1980; 51: 63–70
6 *Bleakley CM*, *Costello JT*. Do thermal agents affect range of movement and mechanical properties in soft tissues? A systematic review. Arch Phys Med Rehabil 2013; 94: 149–163
7 *Bleakley CM*, *Costello JT*, *Glasgow PD*. Should athletes return to sport after applying ice? A systematic review of the effect of local cooling on functional performance. Sports Med 2012; 42: 69–87
8 *Bleakley CM*, *Hopkins TJ*. Is it possible to achieve optimal levels of tissue cooling in cryotherapy? Phys Ther Rev 2010; 15: 344–351
9 *Cholewka A*, *Stanek A*, *Sieron A*, *Drzazga Z*. Thermography study of skin response due to whole-body cryotherapy. Skin Res Technol 2012; 18: 180–187
10 *Costello JT*, *Algar LA*, *Donnelly AE*. Effects of whole body cryotherapy (−110 °C) on proprioception and indices of muscle damage. Scand J Med Sci Sports 2012; 22: 190–198
11 *Costello JT*, *McNamara P*, *O'Connell M*, *Algar LA*, *Leahy M*, *Donnelly AE*. Tissue viability imaging of skin microcirculation following exposure to cold Air (−110 °C) and cold water (8 °C). Arch Exerc Health Dis 2012 in press
12 *Costello JT*, *Culligan K*, *Selfe J*, *Donnelly AE*. Muscle, skin and core temperature after −110 °C cold air and 8 °C water treatment. PLoS ONE 2012; 7: e48190 doi:48110.41371/journal.pone.0048190
13 *Costello JT*, *Donnelly AE*. Cryotherapy and joint position sense in healthy participants: A systematic review. J Athl Train 2010; 45: 306–316
14 *Costello JT*, *Donnelly AE*. Effects of cold water immersion on knee joint position sense in healthy volunteers. J Sports Sci 2011; 29: 449–456
15 *Costello JT*, *McInerney CD*, *Bleakley CM*, *Selfe J*, *Donnelly AE*. The use of thermal imaging in assessing skin temperature following cryotherapy: a review. J Therm Biol 2012; 37: 103–110
16 *Dahlstedt L*, *Samuelson P*, *Dalen N*. Cryotherapy after cruciate knee surgery – Skin, subcutaneous and articular temperatures in 8 patients. Acta Orthop Scand 1996; 67: 255–257
17 *Denoble AE*, *Hall N*, *Pieper CF*, *Kraus VB*. Patellar skin surface temperature by thermography reflects knee osteoarthritis severity. Clin Med Insights Arthritis Musuloskelet Disord 2010; 3: 69–75
18 *Gregson W*, *Black MA*, *Jones H*, *Milson J*, *Morton J*, *Dawson B*, *Atkinson G*, *Green D*. Influence of cold water immersion on limb and cutaneous blood flow at rest. Am J Sports Med 2011; 39: 1316–1323
19 *Harriss DJ*, *Atkinson G*. Update – ethical standards in sport and exercise science research. Int J Sports Med 2011; 32: 819–821
20 *Hildebrandt C*, *Raschner C*. An intra-examiner reliability study of knee temperature patterns with medical infrared thermal imaging. Therm Int 2009; 19: 73–77
21 *Jutte L*, *Hawkins J*, *Miller K*, *Long B*, *Knight K*. Skinfold thickness at 8 common cryotherapy sites in various athletic populations. J Athl Train 2012; 47: 170–177
22 *Jutte L*, *Merrick M*, *Ingersoll C*, *Edwards J*. The relationship between intramuscular temperature, skin temperature, and adipose thickness during cryotherapy and rewarming. Arch Phys Med Rehabil 2001; 82: 845–850
23 *Karki A*, *Karppi P*, *Ekberg J*, *Selfe J*. A thermographic investigation of skin temperature changes in response to a thermal washout of the knee in healthy young adults. Therm Int 2004; 14: 137–141
24 *Kim Y*, *Baek S*, *Choi K*, *Lee S*, *Park S*. The effect of cold air application on intra-articular and skin temperatures in the knee. Yonsei Med J 2002; 43: 621–626

25 *Klimek AT*, *Lubkowska A*, *Szyguła Z*, *Frączek B*, *Chudecka M*. The influence of single whole body cryostimulation treatment on the dynamics and the level of maximal anaerobic power. Int J Occup Med Environ Health 2011; 24: 184–191
26 *Knight KL*. Cryotherapy in sport injury management. Champaign, IL: Human Kinetics, 1995
27 *Lovisatti L*, *Mora L*, *Pistolesi G*. Thermographic patterns of lower limb arterial disease. Bibl Radiol 1975; 6: 107–114
28 *Mayr H*. Thermographic evaluation after knee surgery. In: Ammer K, Ring E (eds.). The Thermal Image in Medicine and Biology. Uhlen-Verlag, Wien: Uhlen, 1995
29 *Myrer JW*, *Myrer KA*, *Measom GJ*, *Fellingham GW*, *Evers SL*. Muscle temperature is affected by overlying adipose when cryotherapy is administered. J Athl Train 2001; 36: 32–36
30 *Oosterveld F*, *Rasker J*. Effects of local heat and cold treatment on surface and articular temperature of arthritic knees. Arthritis Rheum 1994; 37: 1578–1582
31 *Ring E*, *Ammer K*. The technique of infrared imaging in medicine. Thermol Int 2000; 10: 7–14
32 *Salisbury RS*, *Parr G*, *De Silva M*, *Hazleman BL*, *Page-Thomas DP*. Heat distribution over normal and abnormal joints: thermal pattern and quantification. Ann Rheum Dis 1983; 42: 494–499
33 *Scapinelli R*. Studies on the vasculature of the human knee joint. Acta Anat 1986; 70: 305–331
34 *Selfe J*, *Hardaker N*, *Thewlis D*, *Karki A*. A valid and reliable method of data analysis in thermal imaging of the anterior knee. Arch Phys Med Rehabil 2006; 87: 1630–1635
35 *Selfe J*, *Sutton C*, *Hardaker NJ*, *Greenhalgh S*, *Karki A*, *Dey P*. Anterior knee pain and cold knees: a possible association in women. Knee 2010; 17: 319–323
36 *Selfe J*, *Whitaker J*, *Hardaker N*. A narrative literature review identifying the minimum clinically important difference for skin temperature asymmetry at the knee. Thermol Int 2008; 18: 41–44
37 *Uchio Y*, *Ochi M*, *Fujihara A*, *Adachi N*, *Iwasa J*, *Sakai Y*. Cryotherapy influences joint laxity and position sense of the healthy knee joint. Arch Phys Med Rehabil 2003; 84: 131–135
38 *Warren TA*, *McCarty EC*, *Richardson AL*, *Michener T*, *Spindler KP*. Intra-articular knee temperature changes – Ice versus cryotherapy device. Am J Sports Med 2004; 32: 441–445
39 *Webb P*. Heat storage and body temperature during cooling and rewarming. Eur J Appl Physiol Occup Physiol 1993; 66: 18–24
40 *Wilcock IM*, *Cronin JB*, *Hing WA*. Water immersion: Does it enhance recovery from exercise? Int J Sports Physiol Perform 2006; 1: 195–206
41 *Zhang H*, *Huizinga C*, *Arens E*, *Yu T*. Considering individual physiological differences in a human thermal model. J Therm Biol 2001; 26: 401–408