

Title

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

Journal

International Journal of Sports Medicine

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Abstract

This study sought to a) compare and contrast the effect of two commonly used cryotherapy treatments, four minutes 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 ($<13^{\circ}\text{C}$) believed to be required for analgesic purposes. With ethics committee approval and written informed consent 10 healthy males (26.5 ± 4.9 yr, 183.5 ± 6.0 cm, 90.7 ± 19.9 kg, 26.8 ± 5.0 kg/m², $23.0\pm 9.3\%$ body fat; mean \pm 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 temperature was significantly reduced ($p<0.001$) immediately post and at 10, 20, 30, 40, 50 and 60 min after both cooling modalities. Average and minimum skin temperature was lower ($p<0.05$) immediately after whole body cryotherapy ($19.0\pm 0.9^{\circ}\text{C}$) compared to cold water immersion ($20.5\pm 0.6^{\circ}\text{C}$). However, from 10 to 60 min post, the average, minimum and maximum skin temperature was 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.

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 minutes) [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, after various cooling modalities and protocols, have been observed [4,30,32]. Depending on the modality used, a difference of up to 20°C in skin temperature in the knee can be observed after various cooling protocols [15].

One of the consistent findings to emerge from previous research [15] was the long period of tissue rewarming following short duration and relatively mild exposures to cold, particularly around the knee. For example following the application of a CryoCuff for 3 minutes, Karki

and colleagues [23] found the skin temperature over the patella had not returned to the baseline value after 25 minutes (it remained 1 to 2°C lower) in a group of healthy adults. Similarly, Selfe [35] found skin temperature of the patella 2.5°C lower than baseline 20 minutes 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 six 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 ($<13^{\circ}\text{C}$) believed to be required for analgesic purposes.

Methods

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 seven 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 18-35 who exercised at least three 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 hours 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 hours 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.

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), which consists of two rooms (-60 and -110 °C). The temperature of the therapy room remained at a constant level ($-110 \pm 3^{\circ}\text{C}$ [mean \pm SD]), and the air in the room was dry and clear. Participants entered and stood in the first room ($-60 \pm 3^{\circ}\text{C}$) for twenty seconds before entering the second room ($-110 \pm 3^{\circ}\text{C}$) for three minutes and forty seconds. 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 three minutes. In the chamber, participants wore shorts, two 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 ($8^{\circ}\text{C} \pm 0.3^{\circ}\text{C}$) and immersed to the level of the sternum for 4 minutes. 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) 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 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 commonly used other 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 5cm 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 temperature within this ROI on both knees was manually recorded before, immediately post 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 $22.0 \pm 0.5^{\circ}\text{C}$ and $50 \pm 5\%$

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 two 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 \pm 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 x treatment x time) was used to investigate changes in time with one between-subjects variable, *treatment*, with two levels (WBC and CWI) and two within-subject variables, *knee*, with two levels (left and right) and *time* with eight 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 within-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

Average, minimum and maximum knee skin temperature was similar before both treatments ($P > 0.05$, [paired sample t-test], **Table 2**). There was no significant difference between the left and right knees in 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 temperature were significantly reduced following both WBC and CWI. Sixty minutes after both treatments the temperature of the skin (average, maximum and minimum) had yet to return to baseline. A significant difference between treatments was observed in average ($F_{1,9} = 9.422$, $P = 0.013$, $1-\beta = 0.78$), minimum ($F_{1,9} = 5.716$, $P = 0.04$, $1-\beta = 0.569$) and maximum ($F_{1,9} = 6.454$, $P = 0.032$, $1-\beta = 0.62$) skin temperature. Post-hoc analysis showed these differences occurred at 0, 10, 20, 30, 40, 50 and 60 min post treatment in average and minimum (**Fig. 1 and 2**) and at 10 to 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 and 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 cross over study which sought to compare and contrast the effects of WBC and CWI on anterior knee temperature in healthy participants. The finding of this study suggest that although WBC caused a greater reduction in skin temperature, participants' skin temperature tended to recover quicker 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 induce an analgesic effect.

Between 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 minutes 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 minutes 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 considered 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 12°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 other studies results 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 cold air at -30°C to the knee for 5 minutes 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°C to 30°C. Oosterveldt [30] compared local application of ice chips to the anterior knee for 30 minutes with cold air at -160°C for 6.5 minutes. 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 two 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°C to 11.5°C and a 9.4°C reduction of intra-articular temperature to 22.5°C. Although not recorded in the current study, based on these data, it would appear that brief exposures to WBC, and possibly CWI, may potentially reduce intra-articular temperature at the knee.

The two 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 minutes 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 minutes local cooling (administered via a cooling pad) and found an increased 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 practise and reported elsewhere in the literature and in order 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 ($\sim 0.5^{\circ}\text{C}$) and deep muscle ($\sim 2^{\circ}\text{C}$) temperature in a similar group of participants.

In summary, this randomised controlled cross over study, was the first to examine the effect of CWI and WBC on knee skin temperature. WBC was shown to elicited 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 of tissue temperature.

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List of Figures & Tables

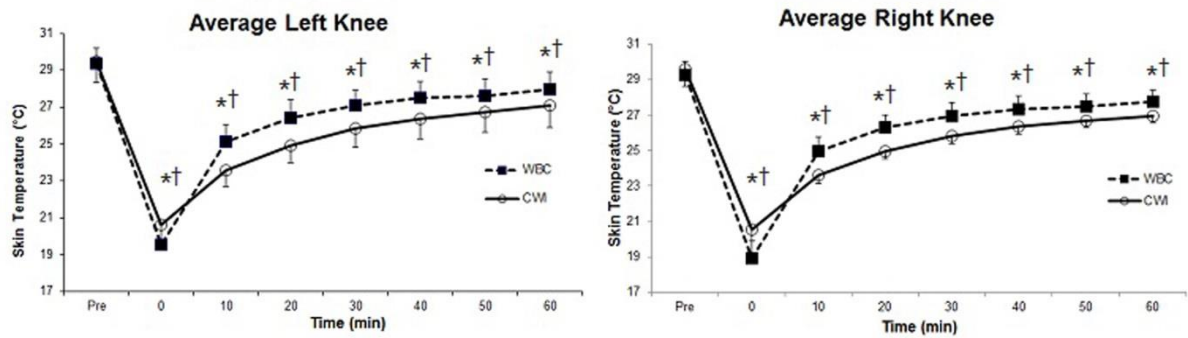


Figure 1 Average (SD) skin temperature in the left (n=10) and right knee (n=10) before, immediately after and 10, 20, 30, 40, 50 and 60 min post Whole Body Cryotherapy (WBC) and Cold Water Immersion (CWI). * denotes significant different from baseline for both modalities and † significant differences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

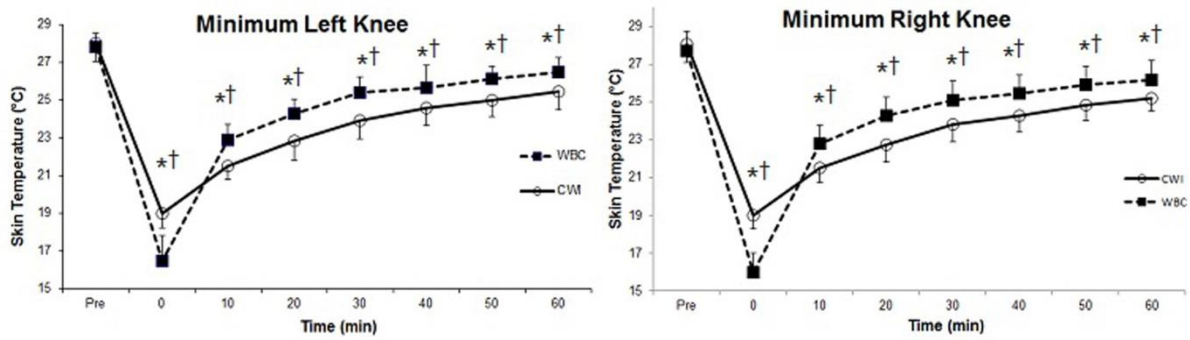


Figure 2 Minimum (SD) skin temperature in the left (n=10) and right knee (n=10) before, immediately after and 10, 20, 30, 40, 50 and 60 min post Whole Body Cryotherapy (WBC) and Cold Water Immersion (CWI). * denotes significant different from baseline for both modalities and † significant differences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

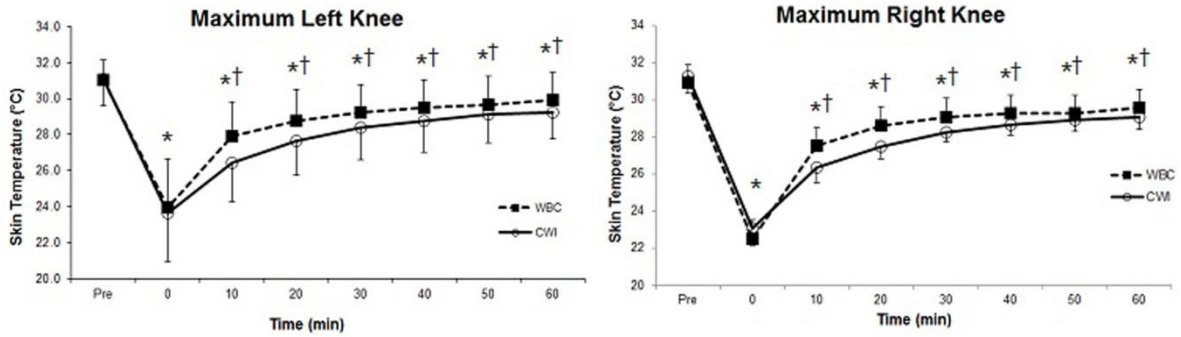


Figure 3 Maximum (SD) skin temperature in the left (n=10) and right knee (n=10) before, immediately after and 10, 20, 30, 40, 50 and 60 min post Whole Body Cryotherapy (WBC) and Cold Water Immersion (CWI). * denotes significant different from baseline for both modalities and † significant differences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

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

Table 1 Characteristics of the participants (n = 10)

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 \pm 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)