The Effects of Cryotherapy on Proprioception, Indices of Muscle Damage and on Intramuscular, Skin and Core Temperature.

A thesis submitted to the University of Limerick in fulfilment of the requirements for the Degree of Doctor of Philosophy

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Abstract

Cryotherapy, the therapeutic use of cold, has been used since the time of the ancient Greeks. In sport medicine, whole body cooling is used before and after athletic participation. Pre-cooling before exercise enables an individual to start exercise with a cooler body temperature, increase their heat storage capacity and perform more work before reaching a limiting core body temperature. Cryotherapy is also used after exercise in an attempt to alleviate the debilitating effects of exercise induced muscle damage.

Cold Water Immersion (CWI) is one of the most commonly used modalities of cooling in sports medicine. CWI involves immersing an individual in cold water to the level of the waist or sternum. Whole Body Cryotherapy (WBC) is a relatively new modality of cooling that involves exposing an individual to extremely low temperatures for a short duration of time in a specially built cryogenic chamber. The physiological effects of whole body cooling, especially WBC, are poorly understood and the potential negative effects of pre-cooling on proprioceptive acuity have not been elucidated. Furthermore, the purported benefits of using WBC as a treatment for exercise induced muscle damage have not been evaluated.

This thesis comprises 5 papers (2 reviews and 3 controlled studies) which investigate the physiological effects of whole body cooling. As it has been hypothesised that a reduction in Joint Position Sense (JPS) may reduce athletic performance or predispose injury, particular emphasis is paid to the effects of these modalities on JPS. Therefore, the primary aim was to explore the effects of CWI and WBC on proprioceptive acuity and to compare and contrast the ability of both cooling modalities to reduce muscle, skin and core temperature. A secondary aim of this thesis was to assess the effectiveness of WBC as a method of recovery following symptoms of exercise induced muscle damage.

In summary the findings of this thesis suggest that knee JPS is not reduced following CWI or WBC. In addition WBC did not reduce muscle force (maximal voluntary isometric contraction of the knee extensors) or force proprioception. The cooling potential of CWI and WBC on muscle, skin and core temperature was investigated using a randomised crossover design. A comparable reduction in muscle and core temperature was observed, however skin temperature was lower immediately after WBC compared to CWI. Finally, when administered 24 hours after eccentric exercise, WBC appears to be ineffective in alleviating muscle soreness or enhancing muscle force recovery. The results and conclusions presented in this thesis may contribute to overall understanding of whole body cooling; inform clinicians and sports people and direct future research in the area.
Declaration

My submission as a whole is not substantially the same as any that I have previously made or currently am making, whether in published or unpublished form for a degree, diploma, or similar qualification at any university or similar institution. I am the author of this thesis and the principle author of the five articles which form its core.

Signature: _______________________

Joseph T. Costello
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Many people have supported me along this long, challenging, enjoyable and sometimes frustrating journey. Although I can’t mention you all I am truly thankful for all you help. It was greatly appreciated.

For my supervisor Professor Alan Donnelly, what can I say only that I couldn’t have got here without you guidance, encouragement, advise and direction. All the time you invested in me, the meetings and the occasion beverage will never be forgotten.

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Mam, Dad, Michelle, Elissa and baby Emma ☇, who have supported me during these this marathon stay in college. Hopefully, I will now get more time to spend with you.
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For My Parents
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Journal Papers


Peer Reviewed Conference Papers


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<td>ABD</td>
<td>Abduction</td>
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<tr>
<td>ACC</td>
<td>Analogue Cryotherapy Cuff</td>
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<td>ANOVA</td>
<td>Analysis of Variance</td>
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<td>AR</td>
<td>Active Reproduction</td>
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<td>BMI</td>
<td>Body Mass Index</td>
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<td>CCTR</td>
<td>Cochrane Central Register of Controlled Trials</td>
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<td>CI</td>
<td>Crushed Ice</td>
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<td>CONC</td>
<td>Concentric</td>
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<td>CWI</td>
<td>Cold Water Immersion</td>
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<td>DF</td>
<td>Dorsiflexion</td>
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<td>DFCG</td>
<td>Deep Freeze Cooling Gel</td>
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<td>EV</td>
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<td>EXT</td>
<td>Extension</td>
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<td>GP</td>
<td>Gel Pack</td>
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<td>GRF</td>
<td>Ground Reaction Force</td>
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<td>H</td>
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<td>HWI</td>
<td>Hot Water Immersion</td>
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<td>INV</td>
<td>Inversion</td>
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<td>JPS</td>
<td>Joint Position Sense</td>
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<td>KGF</td>
<td>Kg Force</td>
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<td>MD</td>
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<td>MVC</td>
<td>Maximum Voluntary Contraction;</td>
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<td>MVIC</td>
<td>Maximal Voluntary Isometric Contraction</td>
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<td>NA</td>
<td>Not Available</td>
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<tr>
<td>Nm</td>
<td>Newton Meter</td>
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<td>NR</td>
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<tr>
<td>PCC</td>
<td>Pump Cryotherapy Cuff</td>
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<td>PEDro</td>
<td>Physiotherapy Evidence Database</td>
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<tr>
<td>PF</td>
<td>Plantar Flexion</td>
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<td>PPO</td>
<td>Peak Power Output</td>
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<td>PR</td>
<td>Passive Reproduction</td>
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<tr>
<td>PRICE</td>
<td>Protection, Rest, Ice, Compression and Elevation</td>
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<td>RCO</td>
<td>Randomized Crossover Trial</td>
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<td>RCT</td>
<td>Randomized Controlled Trial</td>
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<td>ROI</td>
<td>Region of Interest</td>
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<td>Range of Movement</td>
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<td>Rx</td>
<td>Treatment</td>
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<td>SD</td>
<td>Standard Deviation</td>
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<td>SE</td>
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<td>Ses</td>
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<td>SMD</td>
<td>Standardized Mean Differences</td>
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<td>SORT</td>
<td>Strength of Recommendation Taxonomy</td>
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<tr>
<td>SPSS</td>
<td>Statistical Package for the Social Sciences</td>
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<tr>
<td>TI</td>
<td>Thermal Imaging</td>
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<tr>
<td>Tsk</td>
<td>Skin Temperature</td>
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<td>(T_{TY})</td>
<td>Tympanic Temperature</td>
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<td>WBC</td>
<td>Whole Body Cryotherapy</td>
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Glossary of Terms

**Cold Water Immersion**

Cold Water Immersion (CWI) involves immersing an individual in a cold-water bath. These baths vary from custom built temperature controlled spas to large containers filled with water and ice. In practice there are large variations in the CWI protocols that are employed in terms of: the duration of immersion; water temperature; and the volume of body parts immersed.

**Cryotherapy**

Cryotherapy is commonly defined as the therapeutic use of cold. The use of low temperatures is used in sporting, clinical and medical settings to remove heat from the body.

**Exercise Induced Muscle Damage**

Exercise-induced muscle damage frequently occurs after unaccustomed exercise, particularly if the exercise involves a large amount of eccentric (muscle lengthening) contractions. The symptoms of EIMD manifest as a temporary reduction in muscle force, disturbed joint position sense and an increase in inflammation.

**Joint Position Sense**

Joint Position Sense (JPS) is one component of proprioception that describes one’s ability to determine exactly where a particular body part is in space.
Infrared Thermal Imaging

Infrared Thermal Imaging is a method of assessing skin temperature using a specially designed camera. It works by detecting radiation from the skin and produces images called thermograms, where the skin temperature can be calculated.

Pre-Cooling

Pre-cooling is the process of lowering the core body temperature before exercise in the heat. This is achieved through various cooling strategies including cold water immersion, icing and drinking cold fluids.

Proprioception

Proprioception is defined as the cumulative neural input to the central nervous system from mechanoreceptors. Proprioception encompasses a number of different components including kinesthesia, somatosensation, balance, reflexive joint stability, and Joint Position Sense (JPS).

Whole Body Cryotherapy

Whole Body Cryotherapy (WBC) involves repeatedly exposing an individual to very cold air, in a specially designed environmental chamber, for a short period of time (2-4 minutes).
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Chapter 1

Introduction.
1.1 Introduction

Cryotherapy is commonly defined as the therapeutic use of cold. The use of therapeutic cooling dates back to the ancient Greeks and it is currently used in several medical, clinical and rehabilitative settings. In sports medicine whole body cooling is used by athletes before exercise in the heat (Quod et al., 2006) and after intense exercise, as a treatment for Exercise Induced Muscle Damage (EIMD) (Leeder et al., 2011). Two modalities of whole body cooling, Cold Water Immersion (CWI) and -110°C Whole Body Cryotherapy (WBC), are typically used by athletes in a sporting setting. This thesis will examine the effects of these two modalities (CWI and WBC) on proprioceptive acuity, with a particular emphasis on Joint Position Sense (JPS), and on muscle, skin and core temperature. A secondary aim of this thesis is to assess the effectiveness of WBC as a method of recovery following symptoms of EIMD.

The Physiology of Cooling

In man, core temperature is normally maintained within narrow limits of 36.5-37.5°C (Guyton, 1996). Insler and Sessler (2006) have defined hyperthermia as a core temperature of more than 38°C. The detrimental effects of hyperthermia on muscle function and metabolism are well documented (Brooks et al., 1971, Gonzalez-Alonso et al., 1999). In sporting participation, a core temperature of 40°C is commonly referred to as the ‘critical core temperature’ (Marino, 2002). At this temperature participants fatigue, regardless of initial body core temperature or the rate of core temperature increase (Gonzalez-Alonso et al., 1999). In extreme cases hyperthermia can lead to heat stroke and death (Binkley et al., 2002). Conversely, Pozos et al (1996) have defined hypothermia as a core temperature of 35°C or less. As reviewed by Stocks and colleagues (2004), extreme or prolonged cold exposure can quickly overwhelm human thermoregulation with consequences ranging from impaired performance to death in extreme cases. Human homeostasis refers to the body's ability to physiologically regulate its core temperature to ensure its stability in response to fluctuations in the external environment (Canon, 1929). This thermal equilibrium is achieved through a balance between metabolic heat production and heat loss from the body (Mehnert et al., 2000).
Heat is transferred unidirectional, via conduction, convection, evaporation and radiation, from areas of high heat to low heat (Lide et al., 1994). In essence, the human body loses heat to the external environment during cold exposure. Core and skin temperature have afferent input to the thermoregulatory system that assists in triggering autonomic responses that maintain thermal homeostasis (Simon et al., 1986). The temperature regulation centre of the central nervous system is located in the hypothalamus (Brewster et al., 1995, Binkley et al., 2002). The hypothalamus regulates core temperature by receiving information from peripheral skin receptors and the circulating blood (Galaski, 1985). Lower tissue temperatures stimulate these thermoreceptors, and the resultant afferent flow elicits autonomic homeostatic responses (thermogenesis and vasoconstriction) that regulate body temperature (Simon et al., 1986). The role of vasoconstriction is to increase insulation and conserve body heat. By reducing peripheral blood flow, vasoconstriction reduces convective heat transfer between the body’s core and shell (Young and Castellani, 2007). Furthermore, although the nature of human thermogenesis in the cold is not clear, as the body loses heat to the environment a shivering response is initiated (Young and Castellani, 2007). The onset of shivering, or non-shivering thermogenesis, helps the body to replace heat lost during cold exposure. Shivering involves rapid muscular contractions and is under peripheral motor control, whereas non-shivering thermogenesis involves changes in cellular metabolism and is largely under the influences of sympathetic hormone output (Montieth and Mount, 1974).

Paradoxically, cooling has also been shown to induce vasodilatation, in what has become known as Cold Induced Vasodilatation (CIVD). CIVD is a cyclic oscillation in blood flow that occurs in the extremities 5–10 min after the start of local cold (Lewis 1930, Fox and Wyatt, 1962, Daanen, 2009). It is believed CIVD improves manual dexterity while working in the cold and reduces pain and the risk of cold injury (O’Brien, 2004).

**Local Cryotherapy**

Several methods of locally applied cryotherapy, including cryotherapy cuffs, cooling packs, ice packs and cold spray application, are used by clinicians after acute injury (Knight, 1995, Meeusen and Lievens, 1986). In the acute management of soft tissue injury local cryotherapy is also employed as part of the “I” in the PRICE protocol.
(Protection Rest Ice Compression Elevation) (Bleakley et al., 2011). Localised cooling has been shown to reduce muscle spasm (Swenson et al., 1996, Ernst and Fialka, 1994), pain (Algafly and George, 2007), local edema (Knight, 1995), swelling (Knight, 1995, Knight, 1976), blood flow (Thorsson et al., 1985, Ho et al., 1994), nerve conduction velocity (Algafly and George, 2007, Herrera et al., 2010), metabolism (Knight, 1995) and the inflammatory response in injured tissue (Knight, 1995). Furthermore, reductions in tissue temperature (muscle and skin) following local cooling are well established (Dykstra et al., 2009, Bleakley and Hopkins, 2010, Herrera et al., 2010).

Bleakley and colleagues (2011) have recently updated the existing PRICE guidelines, with a particular focus on ice (cryotherapy). Although the optimal reductions in tissues temperature (skin and muscle) are currently ambiguous, general consensus is skin temperature needs to be reduced to 12°C or below for analgesia (Bleakley et al., 2011, Bleakley and Hopkins, 2010). Furthermore, tissue temperatures of 5-15°C are believed to be required for metabolic reductions (Bleakley et al., 2011). It is less clear what reductions in muscle temperature are required to achieve the required physiological response. Providing recommendations for the optimal reduction in tissue temperature is difficult as several factors are known to affect tissue temperature including; the cryotherapy modality used (Dykstra et al., 2009), duration of application (Bleakley and Hopkins, 2010), anatomical location (Ramanathan, 1964), previous exercise (Rowell et al., 1969), levels of adiposity (Myrer et al., 2001), age (Dewhurst et al., 2010) and gender (Miggitsch et al., 2009). Furthermore, one has to consider the outcome desired after cryotherapy application (e.g. athletic recovery, pain reduction and facilitation of movement).

**Cold Water Immersion**

CWI is one modality of whole body cooling that is used in sports medicine (Wilcock et al., 2006). It typically involves immersing an individual in cold water to the level of the waist or sternum. As CWI is relatively inexpensive and does not require elaborate equipment; it is frequently used by athletes to lower their core temperature before exercise (Quod et al., 2006) and to recovery from intense exercise (Leeder et al., 2011, Wilcock et al., 2006). Whole body (head out) CWI produces a rapid and
substantial reduction in skin temperature (Peiffer et al., 2009, Marino and Booth, 1998, Young et al., 1986, Golden and Tipton, 1988). This in turn, evokes the initial responses to cold immersion, called “cold shock” (Datta and Tipton, 2006). During head out CWI there is dramatic increase in heart rate which subsides after a few minutes but remains above pre-immersion levels (Šrámek et al., 2000, Keatinge and Evans, 1961). There is an inverse relationship between the temperature of the water and heart rate; the colder the water, the higher the heart rate (Wittmers and Savage, 2000).

Other cardiovascular effects of cold induced sympathetic activation during CWI include increased systemic arterial pressure and increased total peripheral resistance (Wittmers and Savage, 2000). The initial cardiovascular responses to sympathetic activity, following CWI, will eventually subside as the core temperature falls (Wittmers and Savage, 2000) and heart rate, cardiac output, and systemic arterial pressure will decrease (Wong et al., 1983). Reductions in skin blood flow (Vaile et al., 2011, Bonde-Petersen et al., 1992), core temperature (Castle et al., 2006, Vaile et al., 2011, Young et al., 1989) and muscle temperature (Castle et al., 2006, Gregson et al., 2011) are also widely reported within the literature following CWI.

**Whole Body Cryotherapy**

WBC is another modality of cryotherapy that is being advocated in sports medicine (Hausswirth et al., 2011, Pournot et al., 2011, Banfi et al., 2010). The first WBC chamber was built in Japan in the late 1970’s, but it was only introduced to Europe in 1982 and America in the last decade (Miller et al., 2011). WBC was initially used in a clinical setting to treat patients with conditions such as multiple sclerosis (Miller et al., 2011), spine disease (Cholewka et al., 2010) and rheumatoid arthritis (Hirvonen et al., 2006). Its use in this setting is purported to allow heat-sensitive individuals exercise with greater physical comfort and to reduce pain. In sports medicine, WBC is growing increasingly popular as a treatment for muscle injuries, syndromes of overuse and to enhance recovery between training sessions (Banfi et al., 2010). A range of similar claims have been made about the benefits of WBC, but the evidence base supporting these claims is extremely limited (Banfi et al., 2010).
Existing studies examining WBC are limited in terms of quality and statistical power or else published in non-English literature. Despite the increasing popularity very few randomised controlled studies have tried to verify its efficacy (Banfi et al., 2010). Some controlled studies assessing the effects of WBC have reported a reduction in skin temperature (Westerlund et al., 2003, Cholewka et al., 2010), creatine kinase (CK) activity after training (Wozniak et al., 2007), total oxidative status in plasma (Lubkowska et al., 2008), an increase in heart rate (Westerlund et al., 2006) and the anti-inflammatory cytokines IL-10 and IL-6 (Lubkowska et al., 2010) after treatment.

**Exercise induced muscle damage (EIMD)**

EIMD was first reported in the literature in the early 1900’s (Hough, 1902) and research on this phenomenon has progressively increased in the last 50 years as elite athletes seek to enhance their training, recovery and subsequent performance. EIMD frequently occurs after unaccustomed exercise, particularly if the exercise involves a large amount of eccentric (muscle lengthening) contractions (Friden et al., 1983, Newham et al., 1987, Ebbeling and Clarkson, 1989, Stauber, 1989, Proske and Morgan, 2001, Clarkson and Hubal, 2002, Cheung et al., 2003, Howatson and van Someren, 2008). Despite substantial research addressing EIMD, the exact mechanisms responsible for damage, repair and adaptation have not been delineated. The initial disruption to skeletal muscle following exercise was attributed to progressive degeneration of certain myofibres in earlier research (Jones et al., 1986). According to Cheung and colleagues (2003) as many as six theories have been proposed as potential aetiological explanations for this muscular pathology. Howatson and van Someren (2008), who have reviewed the proposed mechanism of EIMD, have stated that a disruption to the intracellular Ca^{2+} homeostasis is believed to initiate the secondary damage. It is also thought that this secondary damage consequently leads to further myofibrillar damage in skeletal muscle (Gissel and Clausen, 2001).

The symptoms of EIMD manifest as a temporary reduction in muscle force (Mackey et al., 2008, Goodall and Howatson, 2008, Brown et al., 1997) and disturbed joint position sense (Saxton et al., 1995, Brockett et al., 1997, Paschalis et al., 2007,
Furthermore, EIMD also increases inflammatory markers both within the injured muscle and in the blood (Stupka et al., 2000, Peake et al., 2005) as well as increasing muscle soreness, stiffness and swelling (Mackey et al., 2004, Cleak and Eston, 1992, Howatson et al., 2005). The intensity of discomfort and soreness associated with EIMD increases within the first 24 hours, peaks between 24 and 72 hours, before subsiding and eventually disappearing 5-7 days after the exercise (Cleak and Eston, 1992, Howatson et al., 2009). Consequently, it is well established the EIMD negatively effects athletic performance (Burt and Twist, 2011, Twist and Eston, 2009).

Cryotherapy and Exercise Induced Muscle Damage

Several methods of cryotherapy such as ice massage (Howatson et al., 2005, Gulick et al., 1996), CWI (Sellwood et al., 2007, Howatson et al., 2009, Leeder et al., 2011) and alternating hot and cold water therapy (CWT) (Cochrane, 2004, Gill et al., 2006, Vaile et al., 2007, Bleakley et al., 2012) are being used by athletes in an attempt to recover from EIMD. Cryotherapy is speculated to help recovery from EIMD, and subsequence muscle soreness, by altering tissue temperature and blood flow (Leeder et al., 2011). Furthermore, the compressive effect of water immersion (particularly CWI or CWT) is thought to create a displacement of fluids from the periphery to the central cavity (Vaile et al., 2008). This hydrostatic pressure results in multiple physiological changes, including an increase in substrate transport and cardiac output as well as a reduction in peripheral resistance and extracellular fluid volume via intracellular-intravascular osmotic gradients (Wilcock et al. 2006). According to Vaile and colleagues (2008), a combination of such changes may; increase the removal of waste products, reduce the onset of muscle soreness and enhance recovery from EIMD. Although the use of cryotherapy in athletic recover is controversial, owing in part to the lack of physiologic data regarding underlying mechanisms (Gregson et al., 2011), a recent systematic review suggests CWI may be effective in athletic recovery (Leeder et al., 2011).

Very few studies have assessed the effect of WBC on recovery from EIMD. Banfi and colleagues (2009) have studied the effect of repeated WBC (once a day for 5
days) on EIMD in 10 players from the Italian National rugby team and concluded that WBC may be effective in treating EIMD. Furthermore, Hausswirth et al. (2011) and Pournot et al. (2011) have recently reported that repeated WBC exposures, administered 3-5 days after exercise, accelerated recovery from EIMD. Presently, the physiological effects of this extreme cold exposure or the effectiveness of this treatment as a method of athletic recovery are unclear. Furthermore, the optimal duration, temperature and number of WBC exposures required are unknown.

**Pre-Cooling**

In addition to the purported benefits of post exercise cooling, the use of pre exercise cryotherapy has been shown to improve endurance performance in hot environments in several controlled studies (Arngrimson et al., 2004, Vaile et al., 2007, Tyler and Sunderland, 2010) and review articles (Ranalli et al., 2010, Quod et al., 2006, Marino, 2002). This type of cryotherapy has become known as ‘pre-cooling’ (Ranalli et al., 2010). It is well established that exercise is prematurely terminated in the heat and that high ambient temperature and humidity have a detrimental effect on performance (Marino, 2002).

Whole body pre-cooling attempts to increases exercise endurance in the heat by delaying the attainment of a critical body core temperature (~40°C) while placing less stress on cardiovascular and metabolic systems (Lee and Haymes 1995, Gonzalez-Alonso et al., 1999). In essence, pre-cooling replicated the decrease in resting body temperature that occurs with heat acclimatization (Webster et al., 2005). A continued decrease in body core temperature is regularly observed when exercise commences following a pre-cooling intervention (Bogerd et al., 2010, Duffield et al., 2010). This has previously been attributed to the removal of blood from the warmer viscera to the cooler periphery to the body core when the peripheral circulation reopens (Kruk et al., 1990, Golden and Hervey, 1981), known as afterdrop, and is also considered partly responsible for the reduced heart rates in persons exercising after precooling (Olschewski and Bruck 1988). The concept of pre cooling before sporting performance has received considerable attention in sports medicine, particularly in the lead up to the relatively hot Olympic games in Atlanta (1996),
Athens (2004) and Beijing (2008) (Quod et al., 2006). In general pre-cooling using various strategies, such as cold water immersion (Vaile et al., 2007), cooling vests (Arngrimson et al., 2004), and cooling collars (Tyler and Sunderland, 2010), has been shown to increase time to exhaustion or increase the distance run or cycled.

The Negative Effects of Cooling on Performance

Unfortunately few authors have considered, or sought to address, the potential negative effects of pre exercise cooling on athletic performance. Little attention is given to the physiological effect of cooling at various tissue depths or to the potential adverse side effects (Macauley, 2002). Bleakley et al (2012) have recently systematically reviewed the literature, a total of 35 studies, and concluded that the current evidence base suggests that athletes will probably be at a performance disadvantage if they return to activity immediately after cooling. These conclusions were based on cooling for longer than 20 minutes, a duration commonly employed during pre-cooling (Marsh and Sleivrt, 1999, Drust et al., 2000, Quod et al., 2008, Bogerd et al., 2010). There was evidence that cooling adversely affected strength, speed, power and agility-based running tasks (Bleakley et al., 2012). This is not surprising as cooling decreases the dynamic contractile force by 4–6% for each 1°C reduction in muscle temperature (Bergh and Ekblom, 1979), alters EMG activity during submaximal leg extensions (Coulange et al., 2006) and reduces power output in humans (Sargeant, 1987). Furthermore, cooling has also been shown to negatively affect ground reaction force (Kinze, et al., 2000) and postural stability (Kernocek et al., 2008, Magnusson et al., 1990).

Proprioception

In addition to athletic performance limited research exists on the effects of cryotherapy on proprioception. The neurophysiologist Charles Scott Sherrington’s first introduced the word ‘proprioception’ to the literature at the start of the 20th century (Sherrington, 1906). The term proprioception was coined from the Latin "proprius" meaning "one's own" and described sensory information derived from neural receptors (Sherrington, 1906, Ribeiro and Oliveira, 2011). These receptors are embedded in the joint capsules, ligaments, muscles, tendons, and skin (Wassinger et al., 2007) to detect stimuli such as pain, pressure, touch, and movement. More recently Lee et al. (2003) have defined proprioception as the
cumulative neural input to the central nervous system from mechanoreceptors. Proprioception encompasses a number of different components including kinesthesia, somatosensation, balance, reflexive joint stability, and Joint Position Sense (JPS) (Riemann and Lephart, 2002). Despite describing only one component of proprioception the phrase JPS, which describes as the awareness of the position of a joint in space (Grob et al., 2002), is regularly used erroneously as a synonym for the word ‘proprioception’, within the literature (Riemann and Lephart, 2002). JPS is critically important in athletic participation for optimal performance (Wassinger et al., 2007). Furthermore, as deficits in position sense acuity may be responsible for acute joint injury (Payne et al., 1997) JPS is considered essential in injury prevention.

**Cryotherapy and Proprioception**

It has been hypothesised that cryotherapy may alter JPS by reducing muscle, skin and joint temperature, nerve conduction velocity, shivering, or cold-induced changes in neural activity (Hopper et al., 1997, Uchio et al., 2003, Surenkok et al., 2008, Oliveira et al., 2010). Although a number of factors are known to adversely affect JPS including EIMD (Saxton et al., 1995), age (Skinner et al., 1984), injury (Boyle and Negus, 1998), pain (Baker et al., 2002), neurologic disease (Wingert et al., 2009) and fatigue (Skinner et al., 1986, Ribeiro et al., 2011) the effects of cooling on JPS are ambiguous. Several authors have also found reductions in position sense acuity after cooling (Hopper et al., 1997, Uchio et al., 2003, Surenkok et al., 2008, Oliveira et al., 2010, Sekihara et al., 2007) but others have not (Wassinger et al., 2006, Dover and Powers, 2003, Thieme et al., 1996). Reductions in ankle (Hopper et al., 1997), knee (Uchio et al., 2003, Surenkok et al., 2008, Oliveira et al., 2010) and elbow (Sekihara et al., 2007) JPS have all been reported within the literature. These deficits were observed following various modalities of cryotherapy including CWI (Hopper et al., 1997), cold spray (Surenkok et al., 2008), ice packs (Surenkok et al., 2008) and cooling pads (Uchio et al., 2003) applied for between 15 and 30 minutes.

If utilising cryotherapy before or during athletic participation it is imperative that clinicians and researchers are aware of all the potential physiological changes that occur after cooling. Although, previous research has addressed the effects of local cooling on proprioception, in the form of JPS (Wassinger et al., 2007, Ribeiro and
Oliveira, 2011, Dover and Powers, 2004), the effects of whole body cooling (WBC and CWI) have not been investigated. Consequently, there is a clear need to address this paucity of research as any proprioceptive deficit may predispose injury (Wassinger et al., 2007). Furthermore, despite the extensive examination of the effects of locally applied cryotherapy on tissue and core temperature (Bleakley and Hopkins, 2010) the cooling potential of WBC on muscle, skin and core temperature needs to be established, and compared to a more established method of cooling, CWI. Finally, although WBC is commonly used in athletic recovery to treat the symptoms of EIMD, few controlled studies have focused on the efficacy of modality of cooling (Banffi et al., 2010). The research provided herein is the first to establish the following:

a) the effects of CWI on knee JPS
b) the effects of WBC on knee proprioception
c) the effects of WBC on tympanic temperature
d) the effects of WBC on muscle temperature
e) and compare the ability of CWI and WBC to reduce muscle, skin and core temperature

In summary, by addressing these questions this thesis will enable scientists, clinicians, athletic trainers, physiotherapists, coaches and athletes alike to make more informed decisions about the potential beneficial and detrimental effects of using whole body cooling.

1.2 Aims & Hypothesis

The aims of this Ph.D. were to:

1. Systematically review the literature addressing the effects of cryotherapy on joint position sense (Chapter 2)

2. Investigate the effects of CWI on knee JPS (Chapter 3)

H₀: Cold water immersion will not alter knee joint position sense
\( H_1 \): Cold water immersion will alter knee joint position sense

3. Establish the effects of Whole Body Cryotherapy on knee JPS and force proprioception (Chapter 4)

   \( H_0 \): Whole body cryotherapy will not alter knee joint position sense or force proprioception

   \( H_1 \): Whole body cryotherapy will alter knee joint position sense or force proprioception

4. Examine the use of WBC as a method of recovery from symptoms of EIMD (Chapter 4)

   \( H_0 \): Whole body cryotherapy will not reduce the symptoms of exercise induced muscle damage

   \( H_1 \): Whole body cryotherapy will reduce the symptoms of exercise induced muscle damage

5. Critically review the use of infrared thermal imaging as a method of assessing skin temperature after cryotherapy (Chapter 5)

6. Establish the effects of WBC on muscle, skin and core temperature (Chapter 6)

   \( H_0 \): Whole body cryotherapy will not reduce muscle, skin or core temperature

   \( H_1 \): Whole body cryotherapy will reduce muscle, skin and core temperature

7. Compare the reductions observed in muscle, skin and core temperature after WBC to a more commonly used method of cryotherapy, CWI (Chapter 6)

   \( H_0 \): Cold water immersion will not have the same effect on muscle, skin and core temperature as whole body cryotherapy

   \( H_1 \): Cold water immersion will have the same effect on muscle, skin and core temperature as whole body cryotherapy
1.3 Thesis Outline

This thesis is presented in a research publication format (Table 1). Four of the chapters have been peer reviewed and accepted for publication in international journals and one is currently in review. Throughout the thesis some formatting changes to the articles have been made in order to aid presentation and readability of the thesis but in the main the text appears as in the published articles. Figures and tables are presented in the papers and are numbered according to the papers. References will appear at the end of each chapter and are presented according to requirements of the specific journal.

This work is divided into two sections: Part 1 investigates the effect of cryotherapy on proprioception, with a particular focus on JPS and Part 2 establishes the effect of WBC on muscle, skin and core temperature and compares it to a similar duration of CWI.

Table 1. Journal of publication, target audience and ISI Impact Factor for each chapter presented in this thesis.

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<th>Chapter</th>
<th>Journal</th>
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<tr>
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<td>Scandinavian Journal of Medicine and Science in Sports</td>
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<td>Scandinavian Journal of Medicine and Science in Sports</td>
<td>Sport Medicine</td>
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<tr>
<td>5</td>
<td>Journal of Thermal Biology</td>
<td>Biomedical Scientists</td>
<td>1.273</td>
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<td>6</td>
<td>Medicine &amp; Science in Sports &amp; Exercise</td>
<td>Sport Medicine</td>
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In **Part 1, Chapter 2** systematically reviews the relevant literature on the effects of different modalities of cryotherapy on joint position sense. This review identifies the existing research in the area, appraises the methodological and statistical analysis used in the individual studies, synthesizes the results using effects size and establishes the clinical and sporting significance of the topic. In addition Chapter 2, in the section titled “Recommendation for Future Research”, proposes a number of areas that warranted further investigation. Two of these recommendations highlight the need for an examination into the effects of CWI (**Chapter 3**) and WBC (**Chapter 4**) on knee JPS.

**Chapter 3** is a randomised controlled cross over trial that investigates the effects of both CWI and a tepid immersion on knee JPS (n = 14). This chapter, which was the first published study to assess the effects of CWI on knee JPS, was heavily based on the methodological and statistical recommendations outlined in the previous study (Chapter 2). The methodology includes a highly reliable method of recording JPS (3D motion analysis), the use of; a control treatment, open and closed chain JPS outcome measures, a range of test angles and the analysis of absolute, relative and variable error.

**Chapter 4** develops the area further and examines the effect of WBC on knee JPS, force proprioception and maximal voluntary isometric contraction of the knee extensors (n = 36). Again this chapter is heavily influenced by the findings of chapter 2 and expands the work completed in chapter 3. All these outcome measures were assessed on the right limb before, immediately after exposure and again 15 minutes later. Furthermore, a convenience sample of these subjects (n = 18) also
underwent an eccentric exercise protocol on their contralateral left leg 24 hours before exposure to induce EIMD. As a result of the paucity of research in the area of WBC this is the first study to date that has sought to examine the effects of WBC on proprioception and EIMD. During the publication process Chapters 3 and 4 were in review at the same time and as a result Chapter 4 does not reference or refer to chapter three.

Part 2 of this thesis addresses the limitations of the previous chapter(s). Chapter 2 addressed the need to report the reductions in tissues temperature observed, in research examining the effects of various methods of cooling on JPS. Due to methodological and financial restraints this was not feasible in the previous chapters.

Chapter 5 is a critical review that aims to determine (a) the effectiveness of Thermal Imaging (TI) in assessing skin temperature following cryotherapy and (b) the effectiveness of different modalities of cryotherapy in reducing skin temperature. Skin thermistors and thermocouples are currently the most popular method of assessing skin temperature in the literature. However, these devices often consist of a thin metallic foil which serves as a heat spreader backed by a foam insulation pad. This has the potential of creating a layer of insulation over the area of skin being assessed and therefore significantly degrades the accuracy of the measured temperature (Boetcher et al., 2009). This artefact of testing, recording, and reporting erroneous skin temperature data is therefore troublesome, especially if the temperature of the skin is being assessed during (or after) a cryotherapy treatment. This review explores the benefits and limitation of using TI in cryotherapy research.

Chapter 6 addresses a significant gap in the existing literature regarding the effects of WBC on muscle, skin and core temperature as outlined in the previous chapters. One of the limitations of Part 1 of this thesis was that reductions in muscle, skin and core temperature following the cryotherapy treatment were not measured. Although tympanic temperature was reported in Chapter 4, it is not regarded as an accurate measure of core temperature, especially in extremely cold environmental conditions. As mentioned in Chapters’ 2, 3, and 4 one of the purported mechanism by which
cryotherapy may alter proprioception is by a reduction nerve conduction velocity (NCV). The linear relationship between NCV and skin temperature has been explained earlier in the introduction (1.1). Furthermore, Riemann and Lephart (2002) suggested that muscle spindles play a more significant role in JPS acuity compared to cutaneous afferents. Consequently, any alteration in tissue temperature needs to be fully elucidated after cryotherapy. Therefore, the aim of chapter five was to evaluate the effects of WBC on muscle (deep and superficial), skin and core temperature and to compare these reductions to those observed after a more established method of cooling, CWI.

1.4 Information on Publications

Part 1

Chapter 1

The text in Chapter 1 (Introduction) has not been submitted, or published, in any conference proceeding or academic journal.

Chapter 2


Status of Paper: Accepted and published

Peer Review Process: This article underwent a double blind peer review process with 3 external referees in accordance with the rules and regulation of the Journal of Athletic Training.

ISI Journal Impact Factor in 2011: 1.993 (28/80; Sport Sciences Category)

Copyright Declaration: The Journal of Athletic Training have kindly given permission (see appendix J) to include this article in the current thesis.
Chapter 3


Status of Paper: Accepted and published

Peer Review Process: This article underwent a double blind peer review process with 2 external referees in accordance with the rules and regulation of the Journal of Sports Sciences.

ISI Journal Impact Factor in 2011: 1.870 (31/80; Sport Sciences Category)

Copyright Declaration: Taylor and Francis (the publishers of the Journal of Sports Sciences) have kindly given permission (see appendix K) to include this article in the current thesis.

Chapter 4


Status of Paper: Accepted and published

Peer Review Process: This article underwent a double blind peer review process with 2 external referees in accordance with the rules and regulation of the Scandinavian Journal of Medicine and Science in Sports.

ISI Journal Impact Factor in 2011: 2.794 (8/80; Sport Sciences Category)

Copyright Declaration: John Wiley and Sons (the publishers of the Scandinavian Journal of Medicine and Science in Sports) have kindly given permission (see appendix L) to include this article in the current thesis.

Part 2
Chapter 5


Status of Paper: Accepted and published.

Peer Review Process: This article underwent a double blind peer review process with 2 external referees in accordance with the rules and regulation of the Journal of Thermal Biology.

ISI Journal Impact Factor in 2011: 1.3273 (47/86; Sport Sciences Category)

Copyright Declaration: Elsevier (the publishers of the Journal of Thermal Biology) have kindly given permission (see appendix M) to include this article in the current thesis.

Chapter 6


Status of Paper: Currently under review

Peer Review Process: This article will undergo a double blind peer review process with 2 external referees in accordance with the rules and regulation of European Journal of Applied Physiology.

ISI Journal Impact Factor in 2011: 2.214

Chapter 7

The text in Chapter 7 “Discussion & Main Conclusions” has not be submitted or publish in any conference proceeding or academic journal.
Other Journal Papers

Appendix A


Status of Paper: Accepted and published

Peer Review Process: This article underwent a double blind peer review process with 3 referees in accordance with the rules and regulation of Sports Medicine.

ISI Journal Impact Factor in 2011: 5.072 (1/80; Sport Sciences Category)

Copyright Declaration: Sports Medicine have kindly given permission (see appendix E) to include this article in the current thesis.

Appendix B

Reference: Bleakley, C. M., Costello, J. T. Does cooling alter the mechanical properties of soft tissue? A systematic review, Archives of Physical Medicine and Rehabilitation.

Status of Paper: Currently under review

Peer Review Process: This article will undergo a double blind peer review process with 2 external referees in accordance with the rules and regulation of Archives of Physical Medicine and Rehabilitation.

ISI Journal Impact Factor in 2011: 2.254 (18/80; Sport Sciences Category)
1.5 References


Venerologica - International Journal for Skin Research, Clinical Dermatology and Sexually Transmitted Diseases, 89 (5), 586-98


Part 1
Chapter 2

Cryotherapy and Joint Position Sense in Healthy Participants: A Systematic Review.
Cryotherapy and Joint Position Sense in Healthy Participants: A Systematic Review.

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Conception and design of the systematic review: JC, AD
Systematic acquisition of data: JC
Data analysis: JC
Interpretation of data: JC
Writing the article: JC
Critical revision of article: JC, AD
Final approval: JC, AD
2.1 Abstract

Objective: To (1) search the English-language literature for original research addressing the effect of cryotherapy on Joint Position Sense (JPS) and (2) to make recommendations regarding how soon healthy athletes can safely return to participation after cryotherapy. Data Sources: We performed an exhaustive search for original research using the AMED, CINAHL, MEDLINE, and SPORTDiscus databases from 1973 to 2009 to gather information on cryotherapy and JPS. Key words used were cryotherapy and proprioception, cryotherapy and joint position sense, cryotherapy, and proprioception. Study Selection: The inclusion criteria were (1) the literature was written in English, (2) participants were human, (3) an outcome measure included JPS, (4) participants were healthy and (5) participants were tested immediately after a cryotherapy application to a joint. Data Extraction: The means and SDs of the JPS outcome measures were extracted and used to estimate the effect size (Cohen d) and associated 95% confidence intervals for comparisons of JPS before and after a cryotherapy treatment. The numbers, ages and sexes of participants in all 7 selected studies were also extracted. Data Synthesis: The JPS was assessed in 3 joints; ankle (n=2), knee (n = 3), and shoulder (n = 2). The average effect size for the 7 included studies was modest, with effect sizes ranging from - 0.08 to 1.17, with a positive number representing an increase in JPS error. The average methodologic score of the included studies was 5.4/10 (range 5-6) on the Physiotherapy Evidence Database scale. Conclusion: Limited and equivocal evidence is available to addresses 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.

Key Words: Cryotherapy, somatosensory system, proprioception, therapeutic modalities.
2.2 Introduction

Cold, in the form of cryotherapy, has been used since the time of the ancient Greeks, as an analgesic to reduce inflammation after acute musculoskeletal injury or trauma.\(^1\) Cryotherapy is commonly used to reduce tissue temperature, metabolism, inflammation, pain, circulation, tissue stiffness, muscle spasm, and symptoms of delayed-onset of muscle soreness.\(^2\) Cryotherapy protocols, including ice application, water immersion and commercially available cooling pads, are being used by athletic trainers despite the lack of conclusive scientific research regarding the potential risks facing athletes or patients.\(^3\) Although the potential negative effects of cryotherapy itself and its possible influence on proprioception are unknown, and despite equivocal evidence supporting its effectiveness, some clinicians continue to use cryotherapy in the treatment of acute soft-tissue injury\(^4\) and to alleviate the symptoms of delayed-onset muscle soreness.\(^3\)

The effect of cryotherapy on proprioception, which is a component of the somatosensory system, is poorly understood. Proprioceptive acuity has previously been defined as an individual’s ability to sense joint position, movement and force to discriminate movements of their limbs.\(^5,6\) Consequently, proprioceptive acuity is an essential component of injury prevention and rehabilitation, but it is often ignored with devastating consequences, because proprioceptive deficits may be responsible for many acute ankle and knee injuries.\(^4,7-9\) The term proprioception, developed as a result of Sherrington’s\(^10\) landmark work in the early 1900’s, is commonly defined as the cumulative neural input to the central nervous system from mechanoreceptors.\(^11\) These receptors are located in the joint capsules, ligaments, muscles, tendons and skin\(^12\) to detect stimuli such as pain, pressure, touch, and movement. Therefore, their function is critical to both sporting performance and activities of daily living.

A number of techniques for clinically examining proprioceptive acuity are described in the literature, including threshold detection of passive movement, the absolute method\(^13\) and Joint Position Sense (JPS). An individuals’ JPS primarily determines his or her ability to perceive a target joint angle or limb position and then, after the
limb has been returned to its starting position, to reproduce the predetermined angle.\textsuperscript{14,15} The conscious ability to position a limb is a highly specialised proprioceptive function and is a vitally important clinical outcome measure, involving both the control of movement and stability.\textsuperscript{16} The JPS tests are routinely administered by clinicians to assess any proprioceptive deficits in the knee joint after anterior cruciate ligament injury,\textsuperscript{7,17-19} stretching,\textsuperscript{20} fatigue,\textsuperscript{14,21,22} pain,\textsuperscript{16} patellar taping\textsuperscript{23,24} and cooling.\textsuperscript{12,25-30} The primary reason JPS is assessed by clinicians is to identify any reduction that may potentially predispose an individual to proprioception-related injury.\textsuperscript{4,7-9,12,25-30}

A systematic review is necessary to evaluate the effects of locally applied cryotherapy to a joint, specifically in relation to JPS. The brevity of quality research addressing the potential for cryotherapy, when applied to a joint, to reduce JPS and hence to potentially predispose an individual to injury needs to be addressed through further research. Similarly, no authors have systematically evaluated the available literature regarding the effect of cryotherapy on proprioception or JPS. A comprehensive summary of the available literature is needed, so that both the health care profession and the sporting community alike can make educated clinical decisions as to how soon healthy athletes can train or compete after cryotherapy. Our purpose was to search the English-language literature for original research addressing the effect of cryotherapy on JPS and to recommend how soon healthy athletes can safely return to participation after a cryotherapy treatment.

2.3 Methods

Search Strategy

We performed an exhaustive search for original research using AMED (1986-May 2009), CINAHL (1981-May 2009), MEDLINE (1973-May 2009), and SPORT Discus (1982-May 2009) to gather information on cryotherapy, proprioception and JPS. Searches were performed using the key terms \textit{cryotherapy and proprioception}, \textit{cryotherapy and joint position sense}, \textit{cryotherapy}, and \textit{proprioception}. Potentially relevant articles were also obtained by physically searching the bibliographies of
included studies to identify any study that may have escaped the original search. A total of 74 articles were identified (Figure 1).

**Study Selection**

The criteria for study selection were (1) the literature was written in English, (2) participants were human, (3) JPS was included as an outcome measure, (4) participants were healthy, and (5) participants were tested immediately after a cryotherapy application to a joint. Articles were excluded if the title or abstract did not meet the inclusion criteria. We then obtained the full text of each of the relevant studies to see if the study could be included in this systematic review. Ultimately, the article had to address at least 1 outcome measure of JPS before and after a cryotherapy application.

**Assessment of Methodological Quality**

A total of 7 studies, which provided at least 1 outcome measure of JPS before and after a cryotherapy treatment were included. The Physiotherapy Evidence Database (PEDro) scale was used to rate the quality of the selected articles. The PEDro scale is an 11-item scale designed for rating the methodologic quality of randomised controlled trials. Each satisfied item (except for the first item which relates to external validity) contributes 1 point to the total PEDro score. The items include random allocation, concealment of allocation, comparability of groups at baseline; blinding of patients; therapists and assessors; analysis by intention to treat; and adequacy of follow up. The PEDro scale gives a potential scoring range of 0-10, where 0 points (the worst possible score) are awarded to a study that fails to satisfy any of the included items and 10 points (the best possible score) are awarded to a study that satisfies all included items. Studies scoring 9 or 10 on the PEDro scale are considered to have methodologically excellent internal validity, those scoring 6 to 8 are considered good, those scoring 4 or 5 are considered fair, and those scoring less than 4 are poor. Two evaluators who had previous experience with the PEDro scale, first scored each study individually. Together, the reviewers then discussed the
methodologic quality of each study before both agreeing on the final score. All studies graded using the PEDro scale were included.

**Data Extraction and Statistical Analysis**

In order to calculate effect sizes and associated 95% confidence intervals for the change in JPS before and after the cryotherapy treatment, we computed the Cohen d by the following method: \( \frac{[\text{mean of posttest} - \text{mean of pretest}]}{(\text{pooled SD of pretest and posttest})} \).\(^{34}\) To interpret the strength of the effect sizes, values from 0 to 0.2 were considered as being weak; 0.21 to 0.5, modest; 0.51 to 1, moderate and greater than 1, strong.\(^{35}\) Figures 2 through 4 illustrate the point estimates for the effects sizes and associated 95% confidence intervals for the studies conducted on the shoulder, knee and ankle, respectively.

The quality of the evidence was then assessed using the Strength of Recommendation Taxonomy (SORT).\(^{36}\) The SORT gives a recommendation level to individual studies of 1 through 3, where 1 indicates good-quality patient-orientated evidence, 2 indicates limited-quality patient-orientated evidence, and 3 indicates non-patient orientated evidence or other evidence.\(^{36,37}\) The SORT also included a strength of recommendation that ranges from A to C.\(^{36}\) A indicates a recommendation based on consistent and good-quality patient-oriented evidence, B indicates a recommendation based on inconsistent or limited-quality patient-oriented evidence, and C indicates a recommendation based on consensus, usual practice, opinion, disease-oriented evidence, or case series for studies of diagnosis, treatment, prevention, or screening.\(^{36}\)

**2.4 Data Synthesis**

**Study Quality**

The average PEDro score for the 7 articles was 5.4/10 (range = 5-6; mode = 5; median = 5, Table).
The Effects of Cryotherapy on JPS in Healthy Participants

Seven articles met the inclusion criteria for this review (Table). In the 7 studies, 204 participants (77 men, 112 women; the sex of 15 participants was unknown\textsuperscript{28}) were tested. The mean number of participants per study was 29.1±11.5, with a mean age of 22 ± 1.6 years.

The 7 studies reviewed herein assessed 3 specific joints after a cryotherapy intervention: the ankle,\textsuperscript{26,29} knee\textsuperscript{27,28,30} and shoulder.\textsuperscript{12,25} The modality for assessing JPS was primarily unilateral active joint repositioning,\textsuperscript{12,25,27,29,30} with only Surenkok et al\textsuperscript{28} using a passive reproduction test. Active joint repositioning was selected primarily because active testing is believed to be more functional than passive testing.\textsuperscript{16} Two methods of limb positioning or placement at the target angle were reported in the literature, namely passive\textsuperscript{12,20,27,28,30} and active.\textsuperscript{29} Three groups\textsuperscript{12,25,28} assessed individuals’ self reported dominant limb, classified as one’s kicking leg or throwing shoulder arm; 1 group\textsuperscript{30} chose the left limb only; 2 groups\textsuperscript{26,29} randomly chose the tested limb; and only 1 group\textsuperscript{27} assessed both limbs.
Figure 1. Flow chart describing the selection and exclusion of articles. PEDro indicates Physiotherapy Evidence Database.

Cryotherapy was judged to have negatively affected JPS if the degree of positional error was greater post treatment when compared with baseline or control results. The Alpha level was set at 0.05 for all 7 studies. Cryotherapy had a negative effect on JPS in 3 studies, whereas cryotherapy had no effect on JPS in 4 studies. All investigators included used a pre-test post-test within-subject design with a cryotherapy application.
Three of the groups\textsuperscript{12,26,29} that administered a superficial ice application reported no change in JPS post treatment. Dover and Powers\textsuperscript{25} and Wassinger et al\textsuperscript{12} both applied cubed ice, contained in a bag, for a duration of 30 minutes and 20 minutes respectively, to the shoulder. Although Wassinger et al\textsuperscript{12} reported no differences in positional error after the ice application, they noted a decrease in movement patterns and throwing accuracy after treatment. Similarly, applied an ice pack to the knee for 20 minutes, but they did not state if their ice pack was commercially available or constructed by themselves specifically for this purpose. Also, the focus of Thieme et al\textsuperscript{30} appeared to be on movement reproduction pattern and not joint angle reproduction. All the researchers\textsuperscript{25-30} reported their result in degrees, except Wassinger et al\textsuperscript{12} who reported positional error in centimetres of vertical displacement. As a result, although Wassinger et al\textsuperscript{12} had a substantial interclass correlation coefficient of 0.61 to 0.8 between trials for the assessment of proprioception on the electromagnetic tracking device, the findings of this study\textsuperscript{12} are hard to interpret and correlate with the literature. Nonetheless all 3 authors\textsuperscript{12,25,30} using an ice application concluded that cryotherapy did not adversely affect JPS at the location measured. The point estimates of effect sizes for these 3 studies, ranged from -0.08 to 0.28 (Figures 2 and 3) with a positive effect size reflecting an increase in JPS error. Most of the 95\% confidence intervals around these points crossed zero, which indicates that a reduction in JPS was unlikely. Therefore, a superficial ice application appeared to have little effect on JPS.

Two groups\textsuperscript{27,28} employing a cooling pad to the knee for a period of 15 minutes and 30 minutes, respectively, between tests, found that knee joint repositioning was affected post treatment (p<0.05). Unfortunately, the results of these studies (Table) are difficult to compare because Surenkok et al\textsuperscript{28} failed to state the temperature of their cooling pad and used passive joint reposition, compared with Uchio et al\textsuperscript{27} who employed active testing after using a cooling pad maintained at 4°C. Despite the methodologic differences Uchio et al\textsuperscript{27} found a reduction in their participants’ level of accuracy in matching knee joint placement immediately post treatment of 1.7±2.1° post cooling (p<0.05), although the reduction was not significant 15 minutes later (0.9±1.7°, p>0.05). This reduction was reported by the authors\textsuperscript{28} as similar to that of an individual with a cruciate ligament injury who is receiving
potentially inadequate position sense feedback for athletic activity. Similarly, Surenkok et al.\textsuperscript{28} reported inaccuracies in JPS post treatment of 1.05±1.09° and 0.4±2.66° using 2 separate movement protocols (extension to flexion and flexion to extension, respectively). The results of the effect size analysis (Figure 3) for the studies utilizing a cooling pad are less consistent, with point estimates ranging from 0.09 to 0.9 (weak to moderate); positive effects sizes indicate an increase in joint repositioning sense error. Even though Surenkok et al.\textsuperscript{28} reported a reduction in JPS error, the 95% confidence intervals for both trials using the cooling pad crossed zero. However, the study conducted by Uchio et al\textsuperscript{27} had a moderate effect size and the 95% confidence intervals did not cross zero. These findings suggest that using a cooling pad may be more effective in achieving greater reductions in joint, skin and intramuscular temperatures, but as temperature changes were not reported by Surenkok et al,\textsuperscript{28} this possibility is difficult to confirm.

The 2 groups\textsuperscript{26,29} using a water immersion cryotherapy protocol found different results for ankle JPS. Both Hopper et al\textsuperscript{26} and LaRiviere and Osternig\textsuperscript{29} used similar immersion durations, (15 and 20 minutes, respectively), water temperatures (4°C and 5°C, respectively) and neither group immersed the knee joint (Table). Hopper et al\textsuperscript{26} found JPS in the ankle reduced by 0.5±0.75° after an ice water immersion at 4° for 15 minutes. However they concluded that a decrease in 0.5°, although statistically significant, would not be deemed clinically significant. These results are in contrast to those of LaRiviere and Osternig\textsuperscript{29} who found ankle JPS unaffected after a water immersion. This difference is also recognizable in relation to effect size (Figure 4). Hopper et al\textsuperscript{26} unanimously showed a reduction in JPS after immersion, with a modest effect size for 40° of inversion and a strong effect for 80° of inversion; neither 95% confidence interval crossed or came close to crossing zero, indicating a significant effect. Conversely both tests conducted by LaRiviere and Osternig\textsuperscript{29} have weak effect sizes, and both 95% confidence intervals crossed zero. Two possible explanations could account for the disparity in the studies;\textsuperscript{26,29} the different predetermined test angles and participant positioning during testing. Hopper et al\textsuperscript{26} assessed each volunteers’ ability to match a predetermined angle of 40% and 80% of the individuals’ full range of ankle inversion while seated, whereas LaRiviere and Osternig\textsuperscript{29} assessed 30° and 40° of ankle flexion in a supine position. Because both
used similar treatment protocols, but found different results, the effect of cold may be angle dependent.

Based on this evidence, it appears that some cryotherapy modalities may adversely affect components of JPS. We have awarded the current evidence a level of 2, with a grade of recommendation B on the SORT scale, as a result of methodologic design variations and inconsistencies in the findings of the reviewed studies.
### Table 1. Details of Included Articles

<table>
<thead>
<tr>
<th>Authors</th>
<th>PEDro Score/ Missing Items</th>
<th>Cryotherapyy Protocol</th>
<th>Joint</th>
<th>N</th>
<th>Proprioceptive Test</th>
<th>Instrument Used</th>
<th>No. of Trials</th>
<th>P- Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wassinger et al¹⁶</td>
<td>5; no random allocation, no concealed allocation, no blinding</td>
<td>Ice bag, filled with 1500g of cubed ice, applied to the acromion and secured by elastic bandage for 20 mins.</td>
<td>Shoulder</td>
<td>22</td>
<td>AR while standing after passive placement in 2 target positions. 90° of shoulder flexion to 20° flexion and 20° of flexion to 90° of flexion</td>
<td>Biodex</td>
<td>3 in each direction</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>Dower and Powers¹⁹</td>
<td>6; no concealed allocation, no blinding</td>
<td>1kg of cubed ice applied to the tip of the acromin covering the deltoids and lateral scapula for 30 mins</td>
<td>Shoulder</td>
<td>30</td>
<td>AR while standing after an actively assisted placement in 2 target positions. 90% of total external rotation (ER) and internal rotation (IR).</td>
<td>Inclinometer</td>
<td>3 in each direction</td>
<td>0.181</td>
</tr>
<tr>
<td>Hopper et al²⁰</td>
<td>5; no random allocation, no concealed allocation, no blinding</td>
<td>Ice water immersion of the ankle for 15 mins at 5°C to a depth of 5cm above the medial malleolus.</td>
<td>Ankle</td>
<td>49</td>
<td>AR after passive placement at 40% and 80% of active full range of inversion.</td>
<td>Pedal Goniometer</td>
<td>3 in each section</td>
<td>0.049*</td>
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<td>Study</td>
<td>Methodology</td>
<td>Parameter(s)</td>
<td>Measurements</td>
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<tr>
<td>Uchio et al&lt;sup&gt;21&lt;/sup&gt;</td>
<td>Icing system 2000 cooling pad applied to 1 knee for 15 mins. Temperature</td>
<td>Knee</td>
<td>AR after passive placement. Ten different angle used between 5° and 25° knee flexion.</td>
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<td></td>
<td>= 4°C.</td>
<td></td>
<td>Cybex Dynamometer</td>
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<tr>
<td>Surenkok et al&lt;sup&gt;22&lt;/sup&gt;</td>
<td>Cold pack applied to cover the knee joint and secured by an elastic bandage</td>
<td>Knee</td>
<td>PR after passive Placement. Extension to flexion and flexion to extension measured. Angle measured = 45°</td>
<td></td>
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<td></td>
<td>for 30 mins. Temperature = NA. Cold spray (Ethyl Chloride) applied to the</td>
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<td>Cybex Dynamometer</td>
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<td></td>
<td>knee until participants reported a feeling of cold. Temperature = NA</td>
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<td>For all trials</td>
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<tr>
<td>LaRiviere and Osternig&lt;sup&gt;21&lt;/sup&gt;</td>
<td>Ice immersion of the ankle to 4cm distal from the knee joint line for 5</td>
<td>Ankle</td>
<td>AR after a predetermined angle was actively located. 2 joint angles assessed 30/40° ankle flexion.</td>
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<td></td>
<td>and 20 mins at 4°C</td>
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<td>Orthotron II Isokinetic Dynamometer</td>
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</tbody>
</table>

For all trials.
<table>
<thead>
<tr>
<th>Study</th>
<th>Participants</th>
<th>Intervention</th>
<th>Outcome</th>
<th>Measurement</th>
<th>Device</th>
<th>Trials</th>
<th>Significance</th>
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</thead>
<tbody>
<tr>
<td>Thieme et al.</td>
<td>6; no concealed allocation, no blinding</td>
<td>2 Ice packs applied to the left knee for 20mins. One covered 10cm above and below the patella and the other the popliteal space.</td>
<td>Knee 37 AR after passive placement. Angles measured between 90°-60°, 60°-30° and 30°- full extension.</td>
<td>Kin-Com Dynamometer</td>
<td>2 trials in each sector</td>
<td>&gt;0.05 For all trials</td>
<td></td>
</tr>
</tbody>
</table>

* Reported statistical significance

PEDro indicates Physiotherapy Evidence Database

NA indicates not available

PR indicates passive reproduction

AR indicates active reproduction
Figure 2. Effect sizes and 95% confidence intervals compare those who experienced an increase in Joint Position Sense (JPS) error in the shoulder post cryotherapy and those who did not.
Figure 3. Effect sizes and 95% confidence intervals compare those who experienced an increase in Joint Position Sense (JPS) error in the knee post cryotherapy and those who did not. E-F indicates extension to flexion; F-E, flexion to extension.
Figure 4. Effect sizes and 95% confidence intervals compare those who experienced an increase in Joint Position Sense (JPS) error in the ankle post cryotherapy and those who did not.

2.5 Discussion

Joint Position Sense has been defined as the awareness of the position of a joint in space,\(^{38}\) and the term is used erroneously as a synonym for proprioception\(^ {39}\) within the literature. This is primarily because ‘proprioception’ encompasses a number of different components including kinesthesia, somatosensation, balance, reflexive joint stability and JPS.\(^ {28,30,39}\) To date, 7 studies\(^ {12,25-30}\) have addressed the effect of cryotherapy on JPS with conflicting results. Four groups of authors\(^ {12,25,29,30}\) found cryotherapy to have no effect on JPS, whereas 3 others\(^ {26-28}\) found JPS was reduced after cryotherapy. Given the pressure on athletes to maximise their availability and possible performance in endurance events after cryotherapy, individuals may sometimes be required to either train or return to competition after a cryotherapy.
treatment.\textsuperscript{26} Despite the general consensus that cryotherapy is an effective analgesic, clinicians are concerned about the potential effects of cryotherapy on an individual’s neuromuscular functioning.\textsuperscript{12,27,40}

Absolute mean error proved the most common measurement in the analysis of JPS throughout the reviewed studies.\textsuperscript{12,25-29} This method has been defined by Olsson et al,\textsuperscript{41} as the average actual errors of a number of trials, ignoring the direction. Two groups\textsuperscript{25,29} measured variable error, defined as the SD of a number of trials.\textsuperscript{41} In addition, only 2 groups\textsuperscript{25,26} assessed constant error, which is similar to absolute mean except that it takes directional error into account.\textsuperscript{41} Thieme et al\textsuperscript{30} used the most accurate trial, determined as the most accurate reproduction of the predetermined angle, for statistical analysis. We believe that this may be a factor in the authors’ finding that an ice application to had no effect on JPS. However, the authors\textsuperscript{30} still reported an average 2° error across all 3 trial angles after cryotherapy when compared with control. If the authors had analyzed mean error, they might have found a statistically significant reduction in knee JPS after cryotherapy. Using the most (or the least) accurate trial has potential to increase the risk of an unbalanced method of data recording when trials that produced either a greater or lower degree of angle error are disregarded. Using the mean of a number of trials would, therefore, give a better indication of an individual’s joint position accuracy.

**Cryotherapy Modalities and Degrees of Muscle and Joint Cooling**

The disparity in findings reported in the literature is likely to result from the methodologic differences in individual studies. Cryotherapy modalities varied from ice pack application to water immersion and durations from 5 to 30 minutes. Also, the outcome measures assessed varied from active to passive reproduction, and incorporated different anatomical locations, including the shoulder, knee and ankle.

Surenkok et al\textsuperscript{28} were the only investigators to employ proprioceptive tests (JPS and static balance) after 2 separate cryotherapy interventions in a crossover study design. The tests were completed after the application of cold spray (ethyl chloride applied
to the knee until volunteers reported a feeling of cold) and after 1 week the same testing procedures were repeated after the application of a cooling pad. These procedures were conducted to compare and contrast the effects of different cryotherapy modalities on neuromuscular functioning. The authors\textsuperscript{28} found similar results using these techniques; both methods negatively affected JPS after treatment. The JPS acuity was reduced by an average of more than 1° during 2 testing procedures (flexion to extension and extension to flexion) after cold spray application. However, applying spray until volunteers reported a feeling of cold is a subjective measurement. Because neither application duration nor skin temperature was reported, the findings should be treated with caution.

The impairment in JPS reported by 3 groups\textsuperscript{26-28} post treatment may be associated with a greater reduction in intramuscular or joint cooling, reduced nerve conduction velocity, shivering or cold-induced change in proprioceptive sensitivity. This possibility is pertinent when the findings are compared with those of other authors\textsuperscript{12,25,29,30} who used more superficial applications and reported no post treatment effect. However, only 3 of these groups\textsuperscript{25-27} recorded skin temperature and none reported intramuscular temperatures so this theory is difficult to establish. Riemann and Lephart\textsuperscript{39} suggested that, even though all 3 groups who measured skin temperature reported reductions in skin temperature, cutaneous afferents play only a minor role in joint proprioception, whereas muscle spindles and joint receptors have a much more significant role. Therefore, whether superficial applications of cryotherapy, such as cold spray or ice, can cool deep tissue sufficiently to elicit a reduction in proprioceptive or joint position acuity is questionable. More research, regarding the effects of cryotherapy on intramuscular and joint cooling, reduced nerve conduction velocity, shivering and cold-induced change in proprioceptive sensitivity, is required before conclusions can be reached as to why JPS error was increased post cryotherapy in these studies.\textsuperscript{26-28}

Previous investigations however, have also suggested that nerve conduction velocity decreases in a linear fashion with tissue cooling\textsuperscript{42} and not skin cooling,\textsuperscript{43} and the rate of decrease in muscle tissue temperature is depends on the cooling temperature.\textsuperscript{44}
Yet, skin temperature is a good indicator of intramuscular temperature. Furthermore, ice massage reduces muscle temperature more than an ice bag application and a cool whirlpool treatment is better than crushed-ice packs in maintaining muscle temperature reductions. Different cooling techniques may produce different degrees of joint cooling so we believe that the modality of cooling, (ice water immersion, a cooling pad or ice application) may be critical in governing the effect on JPS.

Although it has caused much debate, the cryotherapy modality applied appears to be an important factor affecting ground reaction force (GRF). According to Hart et al., any alteration in the neuromuscular or biomechanical adaptations during landing in the aftermath of a cryotherapy intervention, might place an individual at risk of injury. This alteration may result from a reduction in the usually quick and efficient communication of sensory information after cryotherapy. Two groups using an ice application found no effects on peak vertical GRF at landing post treatment when compared to baseline or control measurements. In contrast Kinzey et al., using cold water immersion, found that peak vertical GRF was negatively affected post treatment.

A number of authors have noted similar findings in relation to closed kinetic chain proprioception (balance) or postural sway after cryotherapy. The detection and response to sway during quiet standing or indeed dynamic balance is vital in preventing injury, such as lateral ankle sprain. Cryotherapy, in the form of an ice application or cold spray, had no effect on balance post treatment when compared with baseline or control measurements. The results of these studies contrast with those of researchers, who used cold-water immersion and found balance was negatively affected immediately after treatment. Therefore, because of the increased area of surface contact, water immersion is likely to cause more joint and muscle cooling than other, more superficial applications such as ice. However, although this theory is plausible, it is refuted by those who found balance unaffected after immersing participants in cold water. This topic will continue to be the subject of further debate until a conclusive answer is established.


**Study Quality**

The average PEDro score for the 7 articles was 5.4/10 (low-high range = 5-6, mode = 5, median = 5, Table). Overall, the quality of the studies was fair to good.\(^{33}\) Disguising a cryotherapy application from the participants or therapists was difficult, so the two criteria relating to blinding of volunteers and therapists were not met in any of the included studies. All authors used a single group pre-cryotherapy and post-cryotherapy testing design and, as a result, no study was awarded a point for between-group statistical comparisons. In terms of statistical power only Dover and Powers\(^{25}\) performed a priori power analysis to identify the required number of volunteers needed to establish statistical differences between error scores. Similarly, none of the authors\(^{12,25-30}\) reported giving sham or a placebo treatment to a control group.

**Effect Size**

The relatively small sample sizes of many of the studies reviewed, along with the discrepancies in both the joint assessed and the modality of cryotherapy have also made comparisons difficult. The number of participants in each study was low, with 3 of the groups testing fewer than 22 volunteers\(^{12,27,28}\) and no group examining more than 50. This is one factor that may influence the strength of the effect size. To interpret the strength of the effect sizes, values from 0 to 0.2 were interpreted as weak, 0.21 to 0.5 as modest, 0.51 to 1 as moderate and greater than 1 as strong; with the terms *weak, modest, moderate* and *large* describing the difference in JPS between pretest and posttest.\(^{35}\) The average point estimate of the effect size of the include studies was modest, with a weak to modest effect size reported in many studies.

Many of the 95% confidence intervals derived from the studies cross zero. This observation leads us to question how significant an effect, if any, cryotherapy has on JPS. As a result, we cannot report a significant effect on JPS after cryotherapy. In the 3 studies that showed a decrease in JPS,\(^{26-28}\) the magnitude to which cryotherapy modalities influenced JPS appears minimal. However, subtle proprioceptive deficits
can both predispose an individual to a greater risk for injury and impair sport performances.\textsuperscript{12}

\textbf{Recommendations for Future Research}

For researchers who intend to study the effects of cryotherapy on JPS further, we have made a number of recommendations. First, research is required to address how much of a reduction in nerve conduction velocity, skin, core, or intramuscular or joint temperature is required before the decline in limb reproduction acuity become apparent. Once this is identified, investigators can then establish whether various modalities of cryotherapy, including climatic chambers, ice application, cooling vests, water immersion or cold spray, are capable of achieving this reduction.

Second, reliable and validated proprioceptive measurements (e.g. threshold detection of passive movement, force acuity, and static and dynamic balance) must be administered in conjunction with joint repositioning tests after a cryotherapy intervention to give a balanced account of the effect of cryotherapy on proprioception and neuromuscular functioning. When assessing proprioceptive acuity, administering the correct number of trials is essential, because a single proprioceptive assessment may provide erroneous data post cryotherapy.\textsuperscript{57} Also, these outcome measures need to be repeated until researchers are satisfied that proprioception acuity has returned to baseline measurements after a deficit has occurred.

Investigators should also recruit sufficient numbers of participants before undertaking future clinical trials involving cryotherapy and JPS. To assist this process, we recommend a priori analysis be conducted before any testing is undertaken. Within this review only 1 group\textsuperscript{25} reported completing such analysis, and the relatively low sample sizes of fewer than 30 participants\textsuperscript{12,25-30} are troublesome.
To our knowledge, no authors have addressed JPS in the wrist or elbow after cryotherapy, JPS after exposure to cold climatic chambers, knee JPS after water immersion, JPS after cryotherapy in an injured population or JPS after the use of cooling vests. Further researchers should target these areas.

Finally, we advocate that investigators assessing an individual’s ability to reproduce a predetermined joint angle should use absolute mean error as the outcome measure. This method is the most reliable and validated\textsuperscript{41,57} method of reporting joint error and should be used instead of the most or least accurate trial. Reporting constant error, in conjunction with absolute mean, may also prove beneficial in determining the trend of directional error during repositioning trials.

**Recommendations for Clinicians**

We have highlighted a number of concerns for clinicians with regards to the effect of cryotherapy on JPS. First, little is known about the potential of cryotherapy to deteriorate JPS, primarily due to the small number of relevant publications. Second, because clinicians administer cryotherapy using different modalities, durations and application areas it is possible that duration and application areas, the variability of these factors may result in different effects on proprioceptive acuity. Finally, with 3 of the 7 reviewed studies\textsuperscript{26-28} showing an increase in JPS error post cryotherapy, we recommend that clinicians consider that proprioceptive functioning may be altered and increase risk of injury. In light of this review, we would therefore suggest caution, when the athlete must perform dynamic activities (such as twisting, turning, landing or running), immediately after a cryotherapy treatment.

**2.6 Conclusion**

Based on the limited and ambiguous evidence addressing the effect of cryotherapy on JPS, we are unable to support or discourage its use before athletic participation. In the 7 studies we reviewed three joints were assessed (shoulder, knee, and ankle) in a combined 204 healthy participants after a cryotherapy intervention. Four groups
found cryotherapy to have no effect on JPS, whereas 3 others found JPS reduced after a cryotherapy treatment. Because of the differences in the joints being assessed, the modality of cooling, measurement techniques and quality of the reviewed studies, further research is needed before a conclusive answer as to whether cryotherapy reduces JPS can be determined. Given this brevity of research we are also unable to make a recommendation as to when athletes can safely return to participation after treatment. Despite the suggested benefits of cryotherapy, until further evidence is provided, athletic trainers and clinicians should be cautious when returning individuals to physically demanding or dynamic tasks after cryotherapy.
2.7 References


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Chapter 3

Effects of Cold Water Immersion on Knee Joint Position Sense in Healthy Volunteers.
Effects of Cold Water Immersion on Knee Joint Position Sense in Healthy Volunteers.

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Conception and design: JC, AD

Data Collection: JC

Data analysis: JC

Interpretation of data: JC

Writing the article: JC

Critical revision of article: JC, AD

Final approval: JC, AD
3.1 Abstract

The purpose of this study was to determine the effects of cryotherapy, in the form of cold water immersion, on knee joint position sense. Fourteen healthy volunteers, with no previous knee injury or pre-existing clinical condition, participated in this randomised cross-over trial. The intervention consisted of a 30 minute immersion, to the level of the umbilicus, in either cold (14 ± 1°C) or tepid water (28 ± 1°C). Approximately one week later, in a randomised fashion, the volunteers completed the remaining immersion. Active ipsilateral limb repositioning sense of the right knee was measured, using weight-bearing and non-weight-bearing assessments, employing video-recorded 3D motion analysis. These assessments were conducted immediately before and after a cold and tepid water immersion. No significant differences were found between treatments for the absolute (p = 0.29), relative (p = 0.21) or variable error (p = 0.86). The average effect size of the outcome measures was modest (range -0.49 to 0.9) and all the associated 95% confidence intervals for these effect sizes crossed zero. These results indicate that there is no evidence of an enhanced risk of injury following a return to sporting activity, after cold water immersion.

Key words: Cryotherapy, Joint Position Sense, Proprioception, Pre-Cooling, Knee Injury
3.2 Introduction

Cryotherapy or “cold therapy” is widely used by physiotherapists, clinicians, athletes and others for various clinical purposes. Cryotherapy has been used for decades by sports people to decrease pain, swelling, secondary hypoxic injury, arterio/venous constriction, relieve muscle spasm, facilitate movement and to reduce core and skin temperature (Knight, 1995). More recently, cryotherapy before exercise, or pre-cooling, has been reported to improve endurance activities in humid conditions (for a review, see Quod et al 2006). Similarly, a number of authors have suggested that pre-cooling may allow individuals with multiple sclerosis to exercise with greater physical comfort (White et al 2000, Kinnman et al 2000). However, cryotherapy users should also consider the potential negative effects of pre-exercise cryotherapy on proprioception and neuromuscular functioning.

Decreases in muscle temperature, following cryotherapy, have been shown to reduce muscle force and muscle power (Sargeant 1987), possibly due to a reduction of myosin ATPase activity. Similarly, reductions in tissue temperature have been shown to decrease nerve conduction velocity (Algafty & George 2007), by reducing action potential propagation. Limited research is available on the potential of cryotherapy, especially in the form of cold water immersion, to reduce proprioceptive acuity. Proprioceptive acuity, which is a component of the sensorimotor system (Riemann and Lephart 2002a, 2002b), has previously been defined as an individual’s ability to sense joint position, movement, and force to discriminate movements of their limbs (Gandevia et al 2002). Muscle spindles and skin stretch receptors play a major role in position sense (Proske and Gandevia 2009). As cold water decreases skin, intramuscular and rectal temperatures (Peiffer et al 2009a, 2009b), where the muscle spindles and skin stretch receptors are located, it is possible that knee joint position sense may be altered. The resultant abnormal proprioception could potentially predispose musculoskeletal pathology by altering movement control, hence leading to abnormal stresses being exerted on tissues (Baker et al 2002).
To date, no study has addressed the effects of cold water immersion on knee joint position sense. Several studies have suggested that cryotherapy before exercise may change the biomechanical properties of the joint, resulting in inadequate peripheral feedback and potentially leading to injury when rehabilitation or exercise is resumed (Uchio et al 2003, Hopper et al 1997, Surenkok et al 2008, Oliveira et al 2010). As cold exposure has previously been shown to reduce nerve conduction velocity (Algafly and George 2007, Ochs and Smith 2004), balance (Makinen et al 2005) and alter neuromuscular transmission in muscles (Coulange et al 2006), it is possible that cold water immersion could also reduce knee joint position sense. Five studies (Surenkok et al 2008, Uchio et al 2003, Hopper et al 1997, Sekihara et al 2007, Oliveira et al 2010) have previously reported a reduction in joint position sense acuity after cryotherapy treatment, while four others (Thieme et al 1996, LaRiviere and Osternig 2004, Dover and Powers 2004, Wassinger et al 2007) reported no effect. The joints assessed by these studies included; the shoulder (Dover and Powers 2004, Wassinger et al 2007), knee (Thieme et al 1996, Uchio et al 2003, Surenkok et al 2008, Oliveira et al 2010), elbow (Sekihara et al 2007) and ankle (Hopper et al 1997, LaRiviere and Osternig 1994).

Thus, the aim of the present study was to determine if cold water altered healthy individuals’ knee joint position sense following immersion. Both weight-bearing and non-weight-bearing clinical assessment of knee joint position sense, using three-dimensional motion analysis, were used before and after a water immersion to determine if cold water immersion reduces knee joint position sense.

3.3 Methods

Design

This was a prospective, randomised, cross-over design where volunteers acted as their own controls. The volunteers were immersed at two temperatures (detailed below) and these sessions were separated by six to ten days. The order of the testing was randomly assigned using a random number generator. Ethical approval of the design was gained from the University of Limerick’s Research Ethics Committee,
and signed informed consent was obtained from each participant before any data collection took place.

**Volunteers**

Fifteen participants (9 males, 6 females) aged 21.9 - 25.1 years (mean 23.2 years) agreed to participate in this study. One male participant dropped out as he was unable to attend the second testing session due to personal commitments. The anthropometric data of the 14 participants who completed the study are displayed in Table 1. Individuals were excluded from the study if they had Reynaud’s disease, ankle or knee injuries in the previous twelve months, a history of ear or vestibular conditions. Individuals were also excluded if they were not between the ages of 18 and 40 years or if they were not comfortable with being blind-folded during testing.

**Table 1** Characteristics of the fourteen subjects who completed the study (mean ± SD)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Female (n = 6)</th>
<th>Male (n = 8)</th>
<th>Total (n = 14)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>23.1 ± 0.7</td>
<td>23.4 ± 1.2</td>
<td>23.3 ± 1.0</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>169.1 ± 6.5</td>
<td>181.4 ± 7.1</td>
<td>175.7 ± 9.1</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>63.9 ± 9.4</td>
<td>78.9 ± 6.0</td>
<td>72.0 ± 10.8</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>22.4 ± 3.3</td>
<td>24.0 ± 1.5</td>
<td>23.2 ± 2.6</td>
</tr>
<tr>
<td>Limb Dominance</td>
<td>Right (n = 6)</td>
<td>Right (n = 8)</td>
<td>Right (n = 14)</td>
</tr>
</tbody>
</table>

**Intervention**

All participants reported to the test location on two separate occasions, once for cold water (14°C ± 1°C) immersion treatment and once for tepid water (28°C ± 1°C) immersion (control). The temperature of the water immersions was measured using a
digital aquarium thermometer. In both the cryotherapy and the control session, participants were seated in a water tank and immersed to the level of the umbilicus for thirty minutes. The water was stirred at regular intervals by the experimenter. Male participants wore only shorts, while females were allowed to wear shorts and a t-shirt. Immediately after the water immersion the participants were asked to towel dry their body, change into dry shorts and t-shirts, and transfer to the laboratory. On both occasions, the participants completed the joint position sense tests immediately before and after the water immersion (approximately 5 minutes post immersion). During the initial visit, demographic variables (age, height, weight, lower limb dominance) were ascertained and recorded (Table 1). Limb dominance was determined by asking the participants which leg they would normally use to kick a ball.

*Outcome measure*

Knee joint position sense was assessed under both weight-bearing and non-weight-bearing test conditions. All of the measurements were performed in a controlled environment, as this has previously been shown to improve reliability (Piriyaprasarth and Morris 2007). Before the testing began, all participants were familiarised with the procedures through explanation, demonstration, and at least two practise repetitions. All test procedures were performed in an isolated room, by the same experimenter who was not blinded to the experimental design. To eliminate vestibular and visual information, the participants wore blindfolds (Olsson et al 2004) and wore headphones over which white noise was played during testing. Active ipsilateral matching was chosen because it is a commonly used and validated method of assessing knee joint position sense (Olsson et al 2004).

For all the trials described below, three reflective markers were attached to 2cm cloth adhesive and then positioned on the greater trochanter, the lateral epicondyle of the femur, and the lateral malleolus of the right limb (Harato et al 2008). These markers were used to facilitate the recording of the internal joint angle throughout the trials. During the immersion period, these markers were removed from the participant.
However, the cloth adhesive backing was not removed so that the three markers could be placed at the same locations following the immersion. Knee joint angle was recorded using an Eagle five-camera system (Motion Analysis Corporation, Santa Rosa, CA, USA) sampling at 400 Hz. The cameras were placed 3-5 metres around the participant at various heights of 0.5-1.5 metres to facilitate the recording of the movement of the markers during the trials. The system was calibrated each morning before testing with an L-frame and a wand, as described in the manufacturers’ guidelines. This system has previously been shown to have excellent reliability for reporting knee motion (Ford et al. 2003). A default Butterworth fourth order zero-phase-shift filter (20 Hz cut-off) was used to smooth the data before exporting it into Microsoft Excel 2000 to calculate error scores.

For the non-weight-bearing assessment, each participant was positioned in a seated position with the leg resting at approximately 90° of flexion and the popliteal fossa not touching the edge of the seat (Panics et al. 2008). The limb was then extended by the examiner at a slow steady speed (~10°/s) to a randomly assigned index angle of approximately ~35°, ~55° or ~70° of flexion (Aydog et al. 2005). The examiner asked the participant to hold this position for ~5 seconds, which the participant was asked to remember with particular emphasis on the knee joint, and then the examiner returned the leg to its starting position at the same angular velocity. This time period, which has been used previously (Mohammadi et al. 2008), enables the participant to become aware of the position of their limb. The participants were then asked to actively reproduce the predetermined target angle with the ipsilateral limb. Participants attempted to replicate the predetermined angle three times (Olsson et al. 2004) and the average was taken. Taking the average of several trials has previously been shown to be more reliable than taking a single measurement (Piriyanprasarth and Morris 2007). After the assessment of each angle, the participants were asked to leave the chair and walk around briefly, which helped them to concentrate on the new test angle and not the previous angle.

For the weight bearing assessment of knee joint position sense, we used a similar protocol that has previously been described (Mir et al. 2008, Stillman and McMeeken...
The weight bearing assessment included two unique movements; (a) flexion to extension and (b) extension to flexion. For both movements, the participants wore a blindfold and were allowed to place their left hand on a flat table for balance. This table stood at a height of 0.5 metres. The participants were instructed to stand with approximately 95% of their body weight directed through their right foot, and with the back foot touch-weight-bearing (Hopper et al 2003). The starting position of flexion to extension movement was a semi-squat (~ 60°), with the right hand placed across the chest so not to obscure the markers. Participants extended the weight-bearing right leg, at a slow angular velocity, until instructed to stop (~45°). They were asked to “remember” this position while focusing on the knee joint position as they held the test position for approximately 5 seconds, before returning to the normal erect stance (~ 7 seconds). Finally, the participants reproduced the unilateral flexed position while concentrating on the knee. For the extension to flexion movement, the starting position was a normal erect stance. While wearing a blindfold and with their right hand across their chest, participants were instructed to place approximately 5% of their weight on their left foot. They then flexed their right limb until instructed to stop (~45°). The participants were instructed by the experimenter to “remember” this position while focusing on the knee as they held the position isometrically (~ 5 seconds). After this, the participants returned to an erect stance (~ 7 seconds) before attempting to reproduce the unilateral flexed position, while concentrating on the knee. The holding times used in this study have previously been used in other published work (Mir et al 2008).

For both these procedures, the participants repeated the movements three times (Mir et al 2008) after the predetermined angle was established. Similar to the study of Stillman and McMeeken (2001) the target angle was subjectively judged by the experimenter for both movements (flexion to extension approximately 43.4° and extension to flexion approximately 44.3°). For the purpose of this study, the absolute mean error (the average error in the three trials ignoring the direction of the error), relative error (the average of the errors in the three trials taking into account the direction of the error), and variable error (the standard deviation of the three relative error measurements) were analysed (Olsson et al 2004). The reliability of the chosen method (using mean differences and 95 % limits of agreement) was established in
our 14 participants using the pre-experimental and pre-control results. The mean
difference for absolute error between the first and second test was 0.037°, with a
standard deviation of 3.1°, and limits of agreement (mean difference ± 1.96 times the
standard deviation) ranging from -6.039° to 6.113°.

Data analysis

The Statistical Package for the Social Sciences (SPSS) for windows (version 15.0,
SPSS Inc, Chicago, IL, US) was used for statistical analysis. For each trial the
absolute error was calculated by subtracting the reproduced angle for the target
angle. A positive angle represents an overestimation and a negative value represents
an underestimation. The middle 3 seconds of the reproduced angle, correct to three
decimal places, was used to analyse the data. Data are presented as means and 95%
confidence intervals (95% CI). Three scores were calculated for the absolute, relative
and variable error. Variables were tested for normal distribution with the Shapiro-
Wilk test. The results were the normalised and analyzed using a 2x2x5 (ice/control x
pre/post x 5 angles) mixed-design, repeated-measures analysis of variance
(ANOVA) to determine if differences existed between control and cold application
sessions, pre and post treatment, and the five sectors of movement. The current study
had an 80% power to detect a 1.6° difference between experimental and control
conditions. For all analysis, statistical significance was set at p < 0.05. To calculate
effect sizes (Cohen’s d) and associated 95% confidence intervals for the change in
joint position sense before and after the cryotherapy treatment, Cohen’s d was
calculated using the following method: (mean of post-test – mean of pre-test) /
(pooled standard deviation of pre-test and post-test) (Morris 2008). To interpret the
strength of the effect sizes, values from 0-0.2 were interpreted as being weak, 0.21-
0.5 as modest, 0.51-1 as moderate and values that were greater than 1 were
interpreted as being a strong effect (Cohen et al 2007).
3.4 Results
No significant differences, between pre and post-tests with both the cold and tepid water using a repeated-measures ANOVA, were found for absolute error (p = 0.29), relative error (p = 0.21) or variable error (p = 0.86) scores (Table 2). In addition, no other main effects or interactions were found to be significant. Figure 1 illustrate the point estimates for the effects sizes (Cohen’s d) and associated 95% confidence intervals for the five angles on the day of the cold water immersion and the five angles on the day of the tepid water immersion. The average effect size of the cold water immersion was modest, with effect sizes ranging from -0.1 to 0.9, with a positive number representing an increase in joint position sense error. For the tepid water treatment, the average effect size was weak, with point estimates ranging from -0.49 to 0.6 (Figure 1).
Figure 1: Effect sizes (Cohen’s d ± 95% confidence intervals) showing the influence of both the cold and tepid water on knee Joint Position Sense (JPS). E-F denotes extension to flexion and F-E denotes flexion to extension.
Table 2. Mean (SD) for absolute, relative and variable error scores at each of the five right knee repositioning trials (n = 14).

<table>
<thead>
<tr>
<th>Outcome</th>
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<th>Relative error</th>
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<th>Variable error</th>
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<tr>
<td></td>
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<td>Pre-test</td>
<td>Post-test</td>
<td>Pre-test</td>
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<tr>
<td></td>
<td>Exp</td>
<td>Con</td>
<td>Exp</td>
<td>Con</td>
<td>Exp</td>
</tr>
<tr>
<td>~35°</td>
<td>4.5</td>
<td>5.5</td>
<td>5.4</td>
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<td>(3.1)</td>
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<td>~75°</td>
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</tr>
<tr>
<td></td>
<td>(1.9)</td>
<td>(2.5)</td>
<td>(2.9)</td>
<td>(1.2)</td>
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</tr>
<tr>
<td>Extension-</td>
<td>4.3</td>
<td>3.3</td>
<td>4.4</td>
<td>5.5</td>
<td>2.2</td>
</tr>
<tr>
<td>Flexion</td>
<td>(2.7)</td>
<td>(3.0)</td>
<td>(3.3)</td>
<td>(3.9)</td>
<td>(4.6)</td>
</tr>
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<td>Flexion-</td>
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<td>5.9</td>
<td>6.7</td>
<td>4.8</td>
<td>7.8</td>
</tr>
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<td>Extension</td>
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<td>(3.6)</td>
<td>(3.2)</td>
<td>(7.5)</td>
</tr>
<tr>
<td>-----------</td>
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</tr>
</tbody>
</table>

Exp = Cold water immersion, Con = Tepid water immersion
3.5 Discussion
The aim of this study was to determine whether cold water immersion reduced knee joint position sense in healthy participants. No significant difference in knee joint position sense was detected following cold water immersion for thirty minutes. Our findings are similar to that of other published work using different cryotherapy protocols and joint position sense assessments (Thieme et al 1996, Uchio et al 2003, LaRiviere and Osternig 2004, Dover and Powers 2004, Wassinger et al 2007, Sekihara et al 2007). Despite previous research showing changes in thixotropy of the forearm muscles following cold water immersion (Lakie et al 1986), to date no published study has elucidated the biomechanical and neurophysiological effects on the healthy knee joint and this study is the first to address the potential decrease in joint position sense acuity after cold water immersion.

In relation to the methodological design of this study, we used a temperature of 14°C for thirty minutes, as similar protocols have been adopted by other researchers using pre-exercise cryotherapy (White et al 2000, Marsh and Sleivert 1999). Similarly, this duration has been noted as the minimum necessary for clinicians and physiotherapists to use in order to suppress the metabolism of the knee and reduce inflammation (Knight 1995). During the five minute delay between leaving the water tank and commencing joint position sense testing, it is possible that skin and muscle temperature increased in the experimental group (cold water immersion) and this may also be a factor in the findings of the present study. This point is supported by Surenkok et al (2008) and Uchio et al (2003), who indicated that joint position sense is normalized at 5 and 15 minutes following the application of a cold pack/spray and a cooling pad respectively. However, after cold water immersion, it is more likely that individuals would take time to dry off and change into dry clothing before exercise. The rationale behind this protocol was also to prevent the participants experiencing any effect of wearing wet clothing. Similarly, having the control group performing the assessments in wet clothing was not desirable, as this may have altered their results. The current study emulated a pre-exercise cryotherapy protocol by Marsh and Sleivert (1999), who reported improvements in short term cycling performance following treatment, and a delay of 10 minutes between the end of the cold water immersion and the start of a warm up (Marsh and Sleivert 1999). This
time delay, similar to the current study, was necessary for each participant to dry off, dress, and transfer to the assessment area (Marsh and Sleivert 1999). Consequently, we think that our results are valuable to those concerned about the increased risk of proprioceptive-related injury following cold water immersion, as they emulate a protocol supporting the use of pre-exercise cryotherapy.

We include both weight-bearing and non-weight-bearing assessments because it has been suggested that weight bearing assessments have more clinical relevance for assessing proprioceptive function in relation to injury (Waddington et al 1999). On the other hand, non-weight-bearing assessments replicate other movement patterns including the swing phase in gait (Stillman and McMeeken 2001) and limb position before heel strike (Co et al 1993). Combining the two types of assessment allowed a better evaluation of proprioceptive acuity in the form of knee joint position sense following cryotherapy. The error in knee joint position sense reported in this study is similar to that of a number of other studies, in both the weight-bearing (Mir et al 2007) and non-weight-bearing assessment (Panics et al 2008, Stillman 2000, Olsson et al 2004).

Previous work has attributed a reduction in joint position sense following cryotherapy to reduced skin temperatures, a reduction in nerve conduction velocity, the eventual blocking of conduction, and alterations in motor output (Uchio et al 2003, Surenkok et al 2008). A potential reason why Hopper at al (1997) found a significant reduction in ankle inversion reproduction is the temperature of the water. These authors used a water immersion of 9°C lower than the present study (i.e. 5°C) and this may explain the reduction due to increased skin and intramuscular temperature. Using water immersion of 5°C elicited a 14°C drop in skin temperature, measured at the antero-lateral aspect of the ankle. The reporting of skin, muscle and core temperature would allow for a more comprehensive comparison of this study to other published work. However, significant reduction in skin and intramuscular temperature have recently been reported following similar immersion protocols (14.3°C for 20 minutes to the level of the mid-sternum) to the current study (Peiffer et al 2009a, 2009b). Peiffer et al (2009a, 2009b) reported reductions in skin (right
calf, right quadriceps, right biceps, and chest) and muscle temperature (rectus femoris) to 21°C and 32°C respectively after 20 minutes of immersion. Approximately five minutes after immersion, the time the current study started the assessments, these values only deviated minimally. This reduction is approximately 4°C less than that reported by Hopper et al (1997) and may explain the disparity in the findings.

The degree of skin, muscle and joint cooling experienced is important in the assessment of joint position sense, as nerve conduction velocity has been shown to decrease linearly with tissue cooling (Ruiz et al 1993). It has previously been reported that to reduce nerve conduction velocity by approximately 10%, a skin temperature of 12.5-13.5°C is required (McMeeken and Cocks 1984). Similarly, Alqafly and George (2007) reported that a skin temperature of 15°C was required for a 17% reduction of nerve conduction velocity and 10°C for a reduction of 33%. Despite not measuring nerve conduction velocity or skin temperature, from the information derived from similar studies (Peiffer et al 2009a, Peiffer et al 2009b, McMeeken and Cocks 1984, Alqafly and George 2007) we can deduce that participants experience a reduction in nerve conduction velocity of less than 10%.

The results of this study, recorded 5 minutes after cold water immersion, indicate that the ability to derive knee joint position sense helps to withstand the muscle, joint and skin cooling experienced during the immersion, and that for a reduction in knee joint position sense, tissue temperature together with nerve conduction velocity has to be reduced further. As we used a protocol commonly employed by sports people in the current study, it does not exclude the possibility that a different protocol, using a different duration, temperature, or modality, would reduce knee joint position sense. Despite the use of a mixed-design, repeated-measures analysis of variance, some of the variables in the current study were not normally distributed and this is a statistical limitation. In addition, the current study was only powered to detect large discrepancies in knee joint position sense and smaller increases in joint position sense error would have been outside the scope of the study.
Physiotherapists, coaches, athletic trainers and clinicians all administer cryotherapy, in the form of cold water immersion, for a number of reasons, including the reduction of pain and swelling, to relieve muscle spasm, and to facilitate movement. The benefits of using cold water immersion for athletes (Quod et al 2006), injured individuals (Cochrane 2004) and people with multiple sclerosis (White et al 2000) has been well publicised. However, Thieme et al (1996), Uchio et al (2003), and Surenkok et al (2008), as recently reviewed by Costello and Donnelly (2010) have all highlighted the potential of various modalities of cryotherapy to reduce proprioceptive acuity and hence predispose injury. The change in joint position sense accuracy following this protocol proved statistically insignificant (Table 2). The evaluation of effect sizes (Cohen’s d) and associated 95% confidence intervals supports these findings (Figure 1).

Further research is required to determine whether different durations and locations of application of ice-packs, cooling pads, whole body cryotherapy or spray have a negative effect on joint position sense. Similarly, no published study has assessed the potential of any of the modalities of cryotherapy, listed above, to alter joint position sense acuity in elite athletes, patients with multiple sclerosis or an injured population. Joint position sense is not the only component of proprioception that has the potential to be altered following a cold application. Further research could also assess other aspects of proprioception, including balance, touch acuity, and force reproduction in the immediate aftermath of a cryotherapy application.

3.6 Conclusion
In conclusion, we found no evidence of impaired knee joint position sense in healthy individuals following a cryotherapy protocol commonly employed in athletic training. These results were obtained using an accurate technique (3D motion analysis) of measuring knee joint position sense. Furthermore, our study provides no evidence of an enhanced risk of injury, due to a detriment in angle proprioception, following this specific cryotherapy protocol. However, further research is required to
address the equivocal evidence that exists regarding the effects of different durations and temperatures of cryotherapy applications on proprioceptive acuity.
3.7 References


Chapter 4

Effects of Whole Body Cryotherapy (-110°C) on Proprioception and indices of Muscle Damage.
Effects of Whole Body Cryotherapy (-110°C) on Proprioception and indices of Muscle Damage.

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Conception and design: JC, LA, AD

Data collection: JC

Data analysis: JC

Interpretation of data: JC

Writing the article: JC

Critical revision of article: JC, LA, AD

Final approval: JC, LA, AD
4.1 Abstract

The purpose of this study was to investigate the effects of Whole Body Cryotherapy (WBC) on proprioceptive function, muscle force recovery following eccentric muscle contractions and tympanic temperature ($T_{TY}$). Thirty-six subjects were randomly assigned to a group receiving two 3-minute treatments of $-110 \pm 3^\circ C$ or $15 \pm 3^\circ C$. Knee Joint Position Sense (JPS), maximal voluntary isometric contraction (MVIC) of the knee extensors, force proprioception and $T_{TY}$ were recorded before, immediately after the exposure and again 15 minutes later. A convenience sample of 18 subjects also underwent an eccentric exercise protocol on their contralateral left leg 24 h before exposure. MVIC (left knee), peak power output (PPO) during a repeated sprint on a cycle ergometer and muscles soreness were measured pre-, 24, 48 and 72 h post-treatment. WBC reduced $T_{TY}$ by 0.3°C, when compared with the control group ($p < 0.001$). However, JPS, MVIC or force proprioception was not affected. Similarly, WBC did not effect MVIC, PPO or muscle soreness following eccentric exercise. WBC, administered 24 h after eccentric exercise, is ineffective in alleviating muscle soreness or enhancing muscle force recovery. The results of this study also indicate no increased risk of proprioceptive-related injury following WBC.

**Key Words:** eccentric exercise, joint position sense, maximal voluntary contraction, muscle soreness.
4.2 Introduction

Cryotherapy, in the form of cold water immersion and ice packs, has been used for decades as a post-exercise recovery strategy in a variety of sports. The application of cold is believed to work by decreasing muscle temperature levels, diminishing pain and muscle spasm and reducing the inflammatory process; thus aiding the recovery process after trauma (Knight, 1995; Banfi et al., 2010). Cold water immersion has also been used before exercise (pre-cooling) or during exercise to improve endurance activities in humid conditions (Duffield et al., 2010). A new modality of cryotherapy, called Whole Body Cryotherapy (WBC), is currently being offered by clinicians as an alternative to cold water immersion or ice packs. WBC involves repeatedly exposing participants to very cold air (-110 °C) while dressed in minimal clothing for a short period of time (Westerlund et al., 2009). WBC is used in a clinical setting to treat the pain, edema and inflammation of various rheumatic diseases, so patients can do therapeutic exercises after WBC (Westerlund et al., 2003). In sports medicine, WBC is promoted as a treatment for muscle injuries, syndromes of overuse, and to enhance recovery between training sessions (Banfi et al., 2010). WBC has previously been shown to reduce skin (Westerlund et al., 2003) and oral (Taghawinejad et al., 1989) temperature, lower total oxidative status in plasma (Lubkowska et al., 2008), increase anaerobic capacity (Klimek et al., 2010), lower creatine kinase activity (Wozniak et al., 2007; Banffi et al., 2008) and alter the concentration of cortisol (Wozniak et al., 2007). As a result Klimek and colleagues (2010) suggest that this type of treatment should therefore be recommended during the recovery process due to the recognized benefits of cryostimulation/cryotherapy in athletes. However, despite the extreme temperatures utilised by this treatment, little is known about the potential of WBC to reduce proprioceptive function or enhance recovery from delayed onset of muscle soreness.

Proprioceptive acuity, which is a component of the sensorimotor system, has been defined previously as an individual’s ability to sense joint position, movement and force to discriminate movements of their limbs (Riemann & Lephart, 2002). A decrease in proprioception acuity and/or diminished knee joint proprioception has previously been linked to rendering the knee less sensitive to potentially damaging
forces and possibly at an increased risk for ligament injury (Baker et al., 2002). Despite a number of authors suggesting no detriment in joint position sense following cryotherapy (LaRiviere & Osternig, 1994; Thieme et al., 1996; Uchio et al., 2003; Dover & Powers, 2004; Wassinger et al., 2007), it is possible that the application of cold may decrease proprioception and predispose an individual to injury due to decreases in nerve conduction velocity, muscle force production, proprioceptive afferent information, or a combination of these factors (Hopper et al., 1997; Surenkok et al., 2008; Oliveira et al., 2010). The importance, for clinicians and sportspeople alike, of increasing the awareness of the potential effects of cryotherapy on proprioceptive acuity in healthy individuals has been highlighted previously (Oliveira et al., 2010). Several studies (Uchio et al., 2003; Dover & Powers, 2004; Wassinger et al., 2007; Surenkok et al., 2008; Oliveira et al., 2010) and a systematic review (Costello & Donnelly, 2010) have highlighted previously the limited research available on the effects of locally applied cryotherapy (the application of an ice pack to a joint or muscle group or the immersion of a joint(s) in cold water) on proprioceptive acuity. Further controlled and empirical studies are required to address this brevity of research, and also in the area of WBC.

Many sporting organisations, clinicians, coaches and athletes are currently using WBC, despite the limited number of publications in the area, and the current study aimed to address this deficit in the literature. To our knowledge, the effects of WBC on knee JPS, muscle force reproduction, recovery after muscle damaging exercise, or tympanic temperature ($T_{TY}$) have yet to be investigated. There were two distinct aspects to the current study, Experiment 1 focused on proprioceptive function and $T_{TY}$, while Experiment 2 on recovery from eccentric muscle damage. Therefore, the purpose of this study was (1) to evaluate the immediate effects of WBC on proprioception and $T_{TY}$ and (2) to evaluate the effectiveness of WBC in the treatment of muscle soreness and function following eccentric exercise damage.
4.3 Methods

Subjects

The study population, for Experiment 1, consisted of 36 healthy participants (age, mean ± standard deviation (SD), 20.8 ± 1.2 years, height 177.0 ± 4.8 cm, and body mass 76.0 ± 7.9 kg). Subjects were recruited from the University of Limerick’s student population. The study was conducted in accordance with the Declaration of Helsinki and approved by The University of Limerick’s Research Ethics Committee (ULREC: 09/47). After providing informed written consent, participants were randomly assigned, using a random number generator, to a cold group (WBC; 6 women and 12 men) or control group (6 women and 12 men). Participants completed a pre test questionnaire and were excluded if they had a history of lower limb injuries in the past twelve months, ear or vestibular conditions or if they had any contradiction to cryotherapy including Reynaud’s disease. They were also excluded if they were not between the ages of 18 and 40, not physically active for an average of 3 days a week or not comfortable with being blind-folded during testing. Subjects were also instructed to refrain from consuming alcohol or caffeine 24 hours before testing commenced.

Experimental overview

The current study was a single-blinded randomized controlled trial with two independent variables. In Experiment 1 of the study (proprioceptive acuity following WBC), these variables including time (baseline, immediately post and 15 minutes post-intervention application) and treatment groups (3 minutes of WBC and a control). Concealed, random allocation was used to assign participant treatment group after baseline measurements. In Experiment 2 of this study (the effects of WBC on muscle force recovery following eccentric exercise) a convenience sample of 18 volunteers (9 in each group) were recruited from the original 36 participants. Similarly, there were two independent variables for this component of the study including time (baseline, 24, 48 and 72 hours post-treatment) and treatment group (3 minutes of WBC and a control). The main outcome measures of the Experiment 1, based on the right limb, were knee JPS, maximal voluntary isometric contraction
(MVIC), muscle force reproduction of the right knee extensors and TTY. The main outcome measures of Experiment 2, where 18 subjects underwent an eccentric muscle damaging protocol on their contralateral left limb 24hr before treatment, were MVIC (on the left knee extensors), muscle soreness and peak power output (PPO) recorded during repeated sprints on a cycle ergometer.

Whole body cryotherapy protocol.

Participants were exposed, in pairs, to either a cold or a control treatment in a cryogenic chamber at the Shannon Cryotherapy Clinic in Ennis, County Clare, Ireland. For the cold group, WBC exposures were administered in a specially built, temperature-controlled unit (Zimmer Elektromedizin, Germany), which consists of two rooms (-60 °C 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. Subjects entered and stood in the first room (-60 ± 3°C) for 20 seconds before entering the second room (-110 °C ± 3°C) for three minutes. The duration and temperature of the cold chamber were similar to that utilised elsewhere (Westerlund et al., 2003; Westerlund et al., 2006; Westerlund et al., 2009; Klimek et al., 2010). Subjects were instructed by the trained machine operator to walk slowly around the chamber and to flex and extend their elbows and fingers throughout the 3 minutes. For the control group, subjects followed the very same procedures as the cold group except both chambers were set at a temperature of 15 ± 3°C. In the chamber, both groups wore 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 had their own dry shoes and socks. All participants wore shorts, male participant wore nothing above the waist during the exposure and females wore crop tops or sports bras. Glasses, contact lenses and all jewellery and piercings were removed before entry to the chamber.

All subjects repeated the treatment (either -110 ± 3°C or 15 ± 3°C), after a lapse of 2 hours. After the first visit to the chamber, the subjects were randomly chosen to complete either knee JPS or MVIC and force-reproduction assessments. The
remaining tests (either knee JPS or MVIC and force-reproduction) were completed after the second visit to the chamber. The order of the testing for each subject was randomised. Baseline tests (knee JPS or MVIC and force reproduction) were completed immediately before exposure to the chamber and post-tests followed immediately after each exposure (within 2-3 minutes) and again 15 minutes later. Approximately two hour after the first exposure, participants completed the remaining pre-tests and again entered the chamber. This time lag of two hours between treatments has been recommended by the manufactures and used extensively by the operators of the chamber in Ennis.

**Experiment 1**

**Knee Joint Position Sense.**

Active ipsilateral limb repositioning of the right knee was assessed after passive positioning, using an electrogoniometer placed at the lateral aspect of knee joint (Panics et al., 2008). This measurement has been validated as reliable in the clinical setting and has been suggested as the most appropriate test for determination of JPS in clinical studies (Olsson et al., 2004). This device used was a Biometrics™ electrogoniometer with an ADU301 angle display unit. This device has been validated previously with accuracy of ± 0.5 degrees (Rowe et al., 2001). To reduce the contribution of vestibular and visual input, participants wore blind-folds and headphones, over which white noise was played during the testing procedures. Before commencing testing, all participants were familiarised with the procedures by explanation, demonstration and at least three practise repetitions a minimum of 24 hours pre-testing and again on the day of testing, immediately before the pre-testing. Subjects were positioned in a seated position where the leg was resting at approximately 90° of flexion and the popliteal fossa did not touch the edge of the seat (Panics et al., 2008). The limb was then extended by the examiner at a slow steady speed (~10°/s) to a randomly assigned index angle between 10° and 30°, 30° and 60° or 60° and 90° of flexion. The examiner asked the subjects to hold this position for ~ 5 seconds (Olsson et al., 2004), which the subject was asked to remember with particular emphasis on the knee joint, and then the examiner returned the leg to its starting position at the same angular velocity. This 5 second time period
enables the subject to become aware of the position of their limb. Subjects were then
asked to actively reproduce the predetermined target angle with the ipsilateral limb. Subjects attempted to actively replicate the predetermined angle three times and the average was recorded. After the assessment of each angle, subjects were asked to leave the chair and walk around briefly. This assisted the subjects to concentrate on the new test angle and not the previous angle.

Maximal Voluntary Isometric Contraction (MVIC).

MVIC of the right knee extensors was recorded in a seated position using a Tornvall Chair. The subject was seated in an upright position with their right knee flexed at 90 degrees. A strap placed around the ankle was connected to a pre-calibrated load cell (Novatech, Hastings, UK), attached by an inextensible bolt to the chair. An analogue signal from the load cell was digitised using a recording system (Powerlab 4/25T, ADInstruments, Oxfordshire, UK) and recorded on a PC running Chart™ 5 software (ADInstruments, Oxfordshire, UK). Participants were seated with arms crossed against the chest, and the hips were tied down to isolate the knee extensors. Participants were counted down from 3 and then asked to maximally contract their right leg for 3 seconds. The subjects performed the test 3 times with a minimum of 1 minute rest between each repetition. The maximum value of the 3 trials was recorded as the result. The subjects were given constant verbal encouragement and received visual feedback from a monitor throughout all MVIC tests. All participants were familiarised with these procedures as described previously.

Force-reproduction.

Force-reproduction testing was performed with the subject seated and positioned in the same position as for MVIC testing immediately before entering the chamber, after the cryotherapy treatment (within 3 minutes) and again 15 minutes later. A modified procedure based on that used by Dover & Powers (2003) was used in the current study. A target force equivalent to 25% and 50% of the MVIC was used for all subjects. To begin the force reproduction measurement, the subject attempted to extend their knee with sufficient force, while receiving visual and verbal feedback,
until the target force being produced (either 25% or 50% randomly assigned) was reached. A computer screen was positioned on the desk in front of the subjects so that they could easily see the screen and the forces they produced during the entire length of the trial (Rubley et al., 2003). Each volunteer's individual target force (25% or 50% of their MVIC) was displayed as a horizontal line (in black). A second line (in red) represented the instant output of the volunteer's isometric force. Volunteers were instructed to match the force output line with the target line. Visual feedback was then removed and the subjects were instructed to reproduce the force after 10 seconds. When the subject verbally indicated that he or she had achieved the target force, $T1$ was recorded for 3 seconds. The measurement was repeated 2 more times for a total of 3 trials at both angles. The error score for each trial was calculated as the mean absolute difference between the target force and the reproduced force (Dover & Powers, 2003). All participants were again familiarised with this procedure as described previously.

**Tympanic Temperature.**

A Braun ThermoScan ear thermometer, (model PRO 4000, Braun, Kronberg, Germany), was used to measure tympanic temperature. The ear was tugged and the probe placed snugly into the external auditory canal of the right ear (Dzarr et al., 2009). The probe remained in this position briefly (1–2 seconds) until the machine bleeped to signal a recording had been taken. Tympanic temperature was recorded before entry to the chamber and 3, 8, 15 and 20 minutes after exiting the chamber. The same experimenter recorded all tympanic temperatures.

**Experiment 2**

**Subjects**

In addition to participating in Experiment 1 a convenience group of 18 subjects (age, mean ± (SD), 21.2 ± 2.1 years, height 177.5 ± 5.1 cm and body mass 77.2 ± 9.6 kg), sourced from the original 36 subjects, voluntarily agreed to participate in the second component of the study. Nine subjects participated from both the cold (2
women and 7 men) and control groups (2 women and 7 men). For these 18 subjects who participated in Experiment 2, the exposure commenced 24 hours following eccentric exercise.

**Eccentric exercise protocol.**

Immediately after the pre-tests on day one, the volunteers completed an eccentric exercise bout consisting of 100 high-force maximal eccentric contractions of the left knee extensors. We used an eccentric muscle damaging protocol used previously in a similar study (Mackey et al., 2004). These contractions were performed on an isokinetic dynamometer (Con-Trex MJ; CMV AG, Dubendorf, Switzerland) set at an angular velocity of 1.57 rads.s$^{-1}$. The 100 contractions were divided into 20 sets of 5 repetitions, with a minimum rest period of 1 minute between sets. Participants were in a seated position with strapping isolating movement of the knee joint around the chest and opposite leg. The left leg in all subjects was tested and was strapped securely to the lever arm of the isokinetic system. The volunteers were required to maximally resist the forced lengthening of their quadriceps through a range of motion, from almost full extension to almost full flexion (Mackey et al., 2004). The subjects were given a standardized visual and verbal encouragement throughout the duration of the protocol.

**Maximal Voluntary Isometric Contraction (MVIC).**

The 18 subjects participating in Experiment 2 completed the same MVIC protocol, as described earlier, except the contractions were performed on their contralateral left limb.

**Peak power output (Maximal cycling repeated-sprint test).**

The maximal cycling repeated-sprint test used in this study is similar to that used elsewhere (McGawley & Bishop, 2006). This test was conducted on day 1 (approximately 24 hours before the first visit to the chambers) and again 24, 48 and
72 hours following exposure. The reliability of this outcome measure in terms of work and power has been established previously by McGawley & Bishop (2006). All trials were performed at the same time of day, and subjects were instructed not to undertake strenuous exercises throughout the duration of the testing. Following a standardised five minutes warm-up at a self-directed pace, each subject performed a 5 x 6 second maximal cycle repeated-sprint test on a Monark cycle ergometer (874E, Vansbro, Sweden) that was dynamically calibrated. The 5 x 6 second cycle test comprised of five 6-second maximal sprints departing every 30 seconds. During the 24-seconds recovery period between sprints, subjects were permitted to turn the pedals at a self-selected pace. Subjects received a countdown before each sprint and performed the sprints in the standing position while receiving a standardised verbal encouragement. Like all the previous outcome measures, participants were familiarised with this procedure.

**Muscle Soreness Questionnaire.**

Muscle soreness was also assessed in the days following eccentric exercise with the aid of a questionnaire that has been used elsewhere in which a similar exercise protocol was used (Mackey et al., 2004). Soreness was measured by self-palpation of the knee extensors at eight specified sites, corresponding to the proximal and distal regions of the knee extensor and flexors. Soreness was rated on a visual-analogue soreness scale, ranging from 1 (normal, no pain) to 10 (very, very sore), and total soreness was calculated as the sum of the eight values (Mackey et al., 2004).

**Statistical Analysis.**

The Statistical Package for the Social Sciences (SPSS) for windows (v16.0, SPSS Inc, Chicago, IL, US) was used for statistical analysis. For each JPS trial, the actual error was calculated by subtracting the reproduced angle from the target angle. A positive angle represents an overestimation and a negative value represents an underestimation. For the purpose of this study, the absolute mean error (the average error in the three trials ignoring the direction of the error), relative error (the average of the errors in the three trials taking into account the direction of the error) and
variable error (the standard deviation of the three relative error measurements) were calculated (Olsson et al., 2004). In Experiment 1, the results were then analyzed using a mixed-design analysis of variance for repeated measure (ANOVA) to determine whether differences existed between control and cold application sessions (between subject), pre- and post-treatment (within subject) and the five sectors of movement (within subject). Pre-test PPO, MVIC (Experiments 1 and 2) and force reproduction data were normalised to 100% and analysed similar to JPS. The current study had an 80% power to detect a 1° difference in JPS error, a 7% difference in MVIC and a 0.2°C difference between cold and control conditions. Data are presented as means and standard deviation. For all analysis, statistical significant was set at $\alpha = 0.05$. All data are presented as mean ± SD.

4.4 Results

Experiment 1

Effects of WBC on Proprioception.

Comparisons of absolute, variable and relative angle errors for the two groups are displayed in Table 1. There was no significant between group differences for absolute ($F_{2,34} = 0.36, P = 0.36, 1 - \beta = 0.22$), relative ($F_{2,34} = 1.1, P = 0.34, 1 - \beta = 0.24$), or variable ($F_{2,34} = 2.91, P = 0.062, 1 - \beta = 0.55$), error over time. There was no significance differences in MVIC between groups following treatment ($F_{2,34} = 2.01, P = 0.89, 1 - \beta = 0.4$). Similarly, participants’ ability to reproduce either 25% or 50% of their MVIC was significantly better with visual and verbal feedback than without. However, there was no between group x time differences ($F_{2,34} = 0.05, P = 0.95, 1 - \beta = 0.06$).

Tympanic Temperature ($T_{TY}$).

$T_{TY}$ initial baseline values for the cold and control groups were 36.9 ± 0.3°C and 36.8 ± 0.3°C, respectively. The comparison of the change from baseline for both the cold and the control group revealed a significant difference in tympanic temperature, 3 and 8 minutes following exposure to the cold chamber ($P < 0.001$, Fig. 1). The
lower T<sub>TY</sub>, 36.6 ± 0.4°C, was recorded in the cold group 8 minutes after leaving the chamber. Twenty-two minutes post treatment T<sub>TY</sub> for the cold group returned to 36.8 ± 0.4°C. T<sub>TY</sub> for the control group did not change significantly over time.

Fig. 1. Tympanic temperature calculated as change from baseline in degrees Celsius. Values are means ± SD for cold (n=18) and control (n=18). Cold group significantly different from control group (P<0.001, using a repeated measures analysis of variance and 95% confidence intervals) at 3 and 8 min after the climatic chamber.
Fig. 2. Normalized maximal voluntary isometric contraction (MVIC) of the left knee extensors before and after eccentric muscle contractions (0 h) and in the days following treatment administered at 24 h. Values are mean ± SD for both the cold (n=9) and control (n=9) groups. *Both groups MVIC reduced significantly following eccentric exercise, P<0.05 using a repeated measures analysis of variance and 95% confidence intervals.

**Experiment 2**

**Effects of WBC on muscle recovery following eccentric exercise.**

MVIC significantly declined from 806 ± 138 Newtons to 483 ± 122 Newtons immediately after the damaging protocol ($F_{1,16} = 121.54, p < 0.001, 1 - \beta = 0.99$, Fig. 2) and recovered thereafter to 98.7 ± 12.3% of pre-exercise values on day 5. The WBC treatment did not effect MVIC ($F_{3,48} = 0.88, p = 0.49, 1 - \beta = 0.23$; Fig. 2) when compared to the control treatment in the days following treatment. Peak power output was also unaffected by the treatment ($F_{1,16} = 1.41, P = 0.24, 1 - \beta = 0.21$). Similarly, there were no significant changes in visual analogue scale between groups over time ($F_{4,64} = 0.3, P = 0.88, 1 - \beta = 0.11$; Fig. 3).
**Muscle Soreness**

![Graph showing muscle soreness over time](image)

Fig. 3. Normalized rating of muscle soreness measured on a visual analogue scale, before (0 h) and after eccentric muscle damage and in the days following treatment administered at 24 h. Values are mean ± SD for both the cold (n=9) and control (n=9) groups. *Both groups muscle soreness increased when compared with baseline, P<0.05 using a repeated measures analysis of variance and 95% confidence intervals.

### 4.5 Discussion

The purpose of this study was to assess the immediate effects of WBC on knee joint position sense, maximal voluntary isometric contraction of the knee extensors, knee submaximal force sensation and tympanic temperature (Experiment 1). This study, in Experiment 2, also aimed to assess the effectiveness of WBC in treating indices of muscle soreness and function, in the days following an eccentric exercise bout. The results of the current study suggest that despite a significant reduction in $T_{TY}$, there are no detrimental effects (in terms of proprioceptive acuity) of using WBC before exercise. This may have future impact on the use of WBC before athletic participation or between training sessions. The results of this study also suggest cold air cryotherapy, administered 24 hours after an eccentric muscle damaging protocol, is ineffective in the treatment of muscle soreness or indices of muscle damage.
WBC and proprioceptive acuity

Despite the widespread use of cryotherapy before, during and after athletic participation there are conflicting results regarding the effect of cold therapy on joint stability, neuromuscular and proprioceptive acuity (Costello & Donnelly, 2010). Any impairment in proprioceptive acuity could result in an increased predisposition to knee injury. Our findings demonstrate that knee JPS remained unaltered following the recommended exposure to WBC. These results support that of other published material using other forms of cryotherapy (LaRiviere & Osternig, 1994; Thieme et al., 1996; Uchio et al., 2003; Dover & Powers, 2004). Despite the significant reduction in tympanic temperature reported in this study and the significant reduction in core and skin temperature reported in other studies (Taghawinejad et al., 1989; Westerlund et al., 2003) it appears that a healthy individual’s ability to derive knee JPS is capable of withstanding the degree of cooling experienced in this cooling protocol. Since a methodology commonly employed by sports people was utilised in the current study, it does not exclude the possibility that a different protocol, using a different duration or temperature would reduce knee JPS.

This is also the first controlled study that has assessed force loss after WBC. Similar to the results ascertained from JPS, no significant between group differences were recorded for MVIC following the cold exposures. Previous studies have assessed MVIC in the hand follow cryotherapy applications with contradicting results (Coppin et al., 1978; Douris et al., 2003; Westerlund et al., 2009). Both Douris et al. (2003) and Coppin et al. (1978) have previously report a significant reduction in isometric grip strength follow cold water immersion (10°C). However, mirroring our results Westerlund et al. (2009) have found wrist flexion MVIC following both a single bout and repeated bouts of WBC was not significantly altered. It must be acknowledged that a potential explanation for the contrasting findings of the current study and those of Westerlund et al. (2009) to that of Douris et al. (2003) and Coppin et al. (1978) is the cryotherapy modality used. These results suggest the existence of a disparity in the degree of muscle and joint cooling that occurs during both the
locally applied cryotherapy and standardised -110° Celsius WBC. Also individuals can remain in cold water for longer durations than in cold air chambers, up to thirty minutes at 14°C; it is possible that greater reduction in skin, joint and muscle temperature are experienced in the water. This would be expected as a direct result of the greater thermal conductivity of water compared to air.

The relationship between a component of proprioception, force matching or force reproduction, in the knee joint and cryotherapy is poorly understood. Force reproduction in the present study involved the use of a reference force, 25 and 50% of a subjects’ MVIC of the right knee extensors, and attempting to replicate that force. Research encompassing cryotherapy and force reproduction is severely limited, with only two studies to date having assessed the effects of cooling on submaximal force reproduction (Tremblay et al., 2001; Rubley et al., 2003). Both Rubley et al. (2003) and Tremblay et al. (2001) found separate cryotherapy applications to have no effect on force matching. Rubley and colleagues (Rubley et al., 2003) addressed the relationship between cryotherapy, in the form of a 15 minute ice bath immersion (10°C), from 1 inch (2.54 cm) proximal to the medial epicondyle to the distal end of the fingers, and sub-maximal isometric force variability in the finger and thumb. They concluded the application of ice had little effect on motor control of the digits, by stating that cryotherapy does not increase isometric targeting error or mean force standard deviation. Similarly, Tremblay et al. (2001) also found no influence on proprioceptive acuity in the quadriceps muscles after cooling in the form of a crushed ice application for a period of 20 minutes. Nonetheless, they concluded that care must be taken in return to participation as performance is believed to be effected after cryotherapy.

Peripheral signals of cutaneous and muscle origin are very likely to be reduced after cooling, but skin afferent reductions have less implication on proprioceptive acuity than muscle afferents (Tremblay et al., 2001). An explanation to why weight discrimination (force proprioception) may not be effected according to La Riviere and Osternig (1994) may be that inputs from joint receptors may be able to
compensate for the reduction in muscle and skin afferents which were reduced during cooling.

Table 1. Comparison of absolute, relative and variable knee joint position angle errors of the right limb

<table>
<thead>
<tr>
<th></th>
<th>Pre-test (n = 18)</th>
<th>3 mins post (n = 18)</th>
<th>20 mins post (n = 18)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cold</td>
<td>Control</td>
<td>Cold</td>
</tr>
<tr>
<td>Absolute error</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-30°</td>
<td>2.1 ± 2.2</td>
<td>2.1 ± 1.3</td>
<td>2.7 ± 1.7</td>
</tr>
<tr>
<td>30-60°</td>
<td>4.4 ± 3.0</td>
<td>3.0 ± 2.0</td>
<td>5.2 ± 2.4</td>
</tr>
<tr>
<td>60-90°</td>
<td>3.9 ± 2.0</td>
<td>2.4 ± 2.4</td>
<td>3.7 ± 2.5</td>
</tr>
<tr>
<td>Relative error</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-30°</td>
<td>1.5 ± 2.6</td>
<td>-0.4 ± 2.4</td>
<td>2.0 ± 2.5</td>
</tr>
<tr>
<td>30-60°</td>
<td>4.0 ± 3.5</td>
<td>1.9 ± 3.1</td>
<td>5.2 ± 2.4</td>
</tr>
<tr>
<td>60-90°</td>
<td>3.4 ± 2.6</td>
<td>1.6 ± 3.0</td>
<td>3.5 ± 1.1</td>
</tr>
<tr>
<td>Variable error</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-30°</td>
<td>1.0 ± 0.7</td>
<td>1.1 ± 0.7</td>
<td>1.0 ± 0.7</td>
</tr>
<tr>
<td>30-60°</td>
<td>1.9 ± 0.8</td>
<td>2.5 ± 0.9</td>
<td>1.7 ± 0.9</td>
</tr>
<tr>
<td>60-90°</td>
<td>1.6 ± 1.1</td>
<td>1.3 ± 0.8</td>
<td>1.4 ± 0.9</td>
</tr>
</tbody>
</table>

Values are means ± SD for cold (n = 18) and control (n = 18). A negative value (-) represents an under estimation.
WBC and tympanic temperature

It has previously been reported that tympanic membrane thermometry is in good agreement with rectal thermometry (Dzarr et al., 2009). Scant data are available about thermal responses to WBC (Westerlund et al., 2003). Taghawinejad et al. (1989) found a slight decrease of 0.38°C in oral temperature, indicating that 90 seconds at -100°C does not affect core temperature. Unfortunately these authors did not report any values before or after the WBC. Westerlund et al. (2003) reported no significant decrease in rectal temperature following exposure to -110°C for 2 minutes. This is the first study that has investigated $T_{TY}$ after a 3 minutes exposure to -110°C, preceded by 20 seconds standing in -60°C, with the results suggesting that it takes up to 15 minutes for it to return to baseline levels (Fig. 1). A potential explanation to why these results are in contrast to that of Westerlund et al. (2003) is the modality of core temperature recorded ($T_{TY}$ and rectal) and the duration of the exposure (3 and 2 minutes). However, despite the use of similar thermometers in similar conditions, the reliability of the $T_{TY}$ recording (Ganio et al., 2009) may not give an accurate recording of core temperature.

WBC and recovery from eccentric exercise

Despite the wealth of literature on cold water based rehabilitation techniques, published data on WBC is scarce (Banfi et al., 2009; Banfi et al., 2010; Klimek et al., 2010) and the scientific principal are often based on pilot studies (Banfi et al., 2010). Previous research in the area of WBC has successfully examined the effect of the treatment on other measures such as; skin temperature (Westerlund et al., 2003), neuromuscular adaptations (Westerlund et al., 2009), serum mediators of inflammation and serum muscle enzymes (Banfi et al., 2009) and haematological values in athletes (Banffi et al., 2008). However, there is limited evidence to support the use of WBC in the recovery of exercise induced muscle damage. To our knowledge this is the first controlled study that has assessed muscle force recovery following eccentric muscle damage.
The current study shows a reduction of approximately 40% in knee extensor MVIC immediately after eccentric exercise and returned to baseline approximately 96 hours after the exercise. However, there was no significant between group (cold or control) differences throughout the duration of the study. The MVIC results of the current study are supported by others using cold water immersion (Goodall & Howatson, 2008) and ice application (Howatson et al., 2005). However these results are in conflict to those of another study using a different cryotherapy protocol (Vaile et al., 2008). As this is the first controlled study which has aimed to assess WBC as a rehabilitative therapy following eccentric exercise we cannot directly compare our finding to any other WBC study.

An individual’s ability to repeatedly produce short, maximal efforts with brief recovery periods is an important fitness requirement of team-sport athletes. Improving the repeated sprint ability of athletes has become a focus of training and indeed rehabilitative programmes for many sports (McGawley & Bishop, 2006). The repeated cycling sprint test utilised in the current study is similar to that used elsewhere (McGawley & Bishop, 2006). The results of the current study suggest that two 3 minute bouts of WBC (-110°) is ineffective in altering PPO following this specific eccentric muscle damaging protocol, when compared to a cold group. However, the results of the current study did not show any decrease, in either the control or the cold group, following eccentric exercise. A potential explanation for this is that either the subjects had sufficiently recovered 48 hours after eccentric exercise, as PPO was not assess at 24 hours, or that eccentrically exercising one leg did not reduce PPO during the two-legged cycling protocol.

Soreness is the most commonly measured marker of eccentric muscle damage (Warren et al., 1999). The most commonly used method for determining soreness is by palpation with a self-report questionnaire or Visual Analogue Scale (Warren et al., 1999). However, the limitation with self-reported assessments is that the measures are subjective, and therefore a comparison between subjects in studies is not the most reliable method of assessment. The application of cold for relieving pain and acting as an analgesic is common practise in clinical, medical, and sports
fields. This most likely reflects the potential of cold treatments to reduce the inflammatory response and consequent secondary muscle damage. As WBC has previously been shown to limit the increase of muscular enzymes creatine kinase (Wozniak et al., 2007; Banfi et al., 2009) and lactate dehydrogenase (Banfi et al., 2009), induce an increase of anti-inflammatory cytokines IL-10 (Banfi et al., 2009) and IL-6 (Lubkowska et al., 2010) and a decrease of pro-inflammatory cytokine IL-2, chemokine IL-8 and prostaglandin E$_2$ (Banfi et al., 2009) it is possible that this treatment may reduce muscle soreness after eccentric exercise. Different modalities of cryotherapy, including ice therapy (Howatson et al., 2005), cold water immersion (Goodall & Howatson, 2008), contrast water therapy (Vaile et al., 2008) and a combination of these treatments (Vaile et al., 2008), have been studied with conflicting results reading muscle soreness recovery. The results of the current study suggest that two 3 minute bouts of WBC (-110°) is ineffective in alleviating subjective assessments of muscle soreness following this specific eccentric muscle damaging protocol. These findings are supported by others using different modalities of cryotherapy (Howatson et al., 2005; Goodall & Howatson, 2008).

**Methodological considerations**

The eccentric exercise bout used in this study may not accurately reflect the soreness and damage experienced during participation during other exercise. In addition, further controlled studies are required to assess the effect of WBC on muscle soreness, muscle function and peak power output administered at a different time point other than that used in the current study (24 hours post exercise) and in different populations, including an athletic population. The current study did not record skin, muscle or joint temperature and further research is required to prove whether WBC alters these temperatures. Also, using ear thermometers when the ears are cold may give unreliable results, and therefore the $T_{TY}$ data needs to be treated with caution.

When compared to a control temperature the major findings of this investigation are, WBC significantly reduces $T_{TY}$; WBC does not deteriorate JPS, MVIC or force...
production and finally WBC, administered 24 hours following eccentric exercise, is ineffective in alleviating muscle soreness or improving recovery. To our knowledge this study is the first to report the effects of WBC on $T_{TY}$, knee JPS, MVIC and force reproduction. This is also the first controlled study to assess the effect of WBC, administered 24 hours after an eccentric muscle damaging protocol, on indices of muscle soreness and function (MVIC, PPO and subjective assessments of muscle soreness measured by questionnaires). Although we have reported no improvements following eccentric muscle damage these findings suggest that a healthy individual’s ability to perform MVIC of the knee extensors or proprioceptive related tasks is unaltered, following WBC.

4.6 Perspectives
Performing eccentric contractions is a fundamental part of athletic performance and often leads to delayed onset of muscle soreness. This relatively novel modality of cryotherapy (WBC) has been advocated a means of recovery following athletic participation. Similarly, the use of WBC has been supported either before or between sporting activities for various reasons. The results of the current study suggest that although WBC does not increase the risk of proprioceptive related injury, it is ineffective in improving recovery if administered 24 hours after eccentric exercise. Data presented here can only be applied when WBC is administered 24 hours after exercise and does not exclude the potential positive effects of using a different treatment regimen or using WBC as a prophylactic treatment.
4.7 References


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Part 2
Chapter 5

The Use of Thermal Imaging in Assessing Skin Temperature Following Cryotherapy: A Review
The Use of Thermal Imaging in Assessing Skin Temperature Following Cryotherapy: A Review

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Systematic acquisition of data: JC, CM
Data analysis: JC, CM
Interpretation of data: JC
Writing the article: JC
Critical revision of article: JC, JS, CB, AD, CM
Final approval: JC, JS, CB, AD
5.1 Abstract

**Background:** Cryotherapy is used in various clinical and sporting settings to reduce oedema, decrease nerve conduction velocity, decrease tissue metabolism and to facilitate recovery after exercise induced muscle damage. The basic premise of cryotherapy is to cool tissue temperature and various modalities of cryotherapy such as whole body cryotherapy, cold spray, cryotherapy cuffs, frozen peas, cold water immersion, ice and cold packs are currently being used to achieve this. However, despite its widespread use, little is known regarding the effectiveness of different cryotherapy modalities to reduce skin temperature. **Objectives:** To provide a synopsis of the use of thermal imaging as a method of assessing skin temperature following cryotherapy and to report the magnitude of skin temperature reductions associated with various modalities of cooling. **Design:** Structured narrative review. **Methods:** Three electronic databases were searched using keywords and MESH headings related to the use of thermal imaging in the assessment of skin temperature following cryotherapy. A hand-search of reference lists and relevant journals and text books complemented the electronic search. **Summary:** Nineteen studies met the inclusion criteria. A skin temperature reduction of 5-15°C, in accordance with the recent PRICE guidelines, were achieved using cold air, ice massage, crushed ice, cryotherapy cuffs, ice pack and cold water immersion. There is evidence supporting the use and effectiveness of thermal imaging in order to access skin temperature following the application of cryotherapy. **Conclusions:** Thermal imaging is a safe and non-invasive method of collecting skin temperature. Although further research is required, in terms of structuring specific guidelines and protocols, thermal imaging appears to be an accurate and reliable method of collecting skin temperature data following cryotherapy. Currently there is ambiguity regarding the optimal skin temperature reductions in a medical or sporting setting. However, this review highlights the ability of several different modalities of cryotherapy to reduce skin temperature.

**Key Words:** PRICE, tissue temperature, cooling, infrared technology,
Highlights

► Ambiguity exists regarding optimal skin temperature reductions after cryotherapy.
► This article reviews the use of thermal imaging to access skin temperature.
► Several techniques are available to assess skin temperature.
► Thermal imaging is a safe and non-invasive method of collecting skin temperature.
► Information is provided regarding a number of cooling modalities.

5.2 Overview

Cryotherapy, the therapeutic use of cold, is applied in various clinical, rehabilitative and sporting settings to reduce edema, decrease tissue metabolism and provide analgesia (Knight, 1995). The basic premise of cryotherapy is to cool tissue temperature (Bleakley and Hopkins, 2010); various modalities such as whole body cryotherapy, cold water immersion, ice and cold packs are currently used to achieve this. Each of these cooling modalities has a different thermal property and therefore a different skin cooling potential (Bleakley and Hopkins, 2010). Skin temperature is a very important physical attribute and is used as a diagnostic parameter in various medical and sporting settings (Cholewka et al. 2011). The magnitude of skin tissue cooling achieved in cryotherapy determines the treatment’s ability to simultaneously achieve a meaningful analgesic effect and avoid adverse effects. Recent guidelines suggest that skin temperature reductions to less than 12°C are optimal for achieving analgesia (Bleakley et al., 2011, Bleakley and Hopkins, 2010). An optimal or safe lower limit for skin temperature is less clear however. Several instances of ice burn and even amputation are reported in the literature following prolonged or inappropriate cooling (Selfe et al., 2007). Other adverse events associated with excessive cooling include: nerve damage (Hoiness et al., 1998; Moeller et al., 1997), cold urticaria (Dover et al., 2004) and a compartment syndrome (Khajavi et al., 2004).

There are a significant number of cold modalities available to practitioners and athletes; knowledge of their cooling capacity is central to clinical safety and effectiveness.
Non-contact thermal imaging (TI) is a safe non-invasive method of collecting real
time Skin Temperature (Tsk) data (Sherman et al 1996, Hildebrandt et al., 2010).
Infrared TI has been used in medicine since the early 1960’s (Ring and Ammer,
2000) and utilises the phenomenon that living and non-living objects all emit
infrared radiation to some extent (Ammer, 2004). When the emissivity, the relative
ability of a surface to emit energy by radiation, is known the intensity of infrared
radiation can be used for calculation of the temperature of the emitting object
(Ammer, 2004). The technology is a sophisticated way of receiving the
electromagnetic radiation and converting it into electrical signals (Hildebrandt et al,
2010). These signals are finally displayed in gray shades or colours which represent
temperature values (Hildebrandt et al, 2010). An example of an infrared thermal
image of the anterior human body is displayed in figure 1. TI is widely used in
medical settings such as cancer research (Head et a., 1995) and fever screening
(Hewlett et al., 2011) to detect and locate thermal abnormalities characterized by an
increase or decrease found at the skin surface (Hildebrandt et al, 2010). Selfe et al
(2006) and Kennet et al (2007) have previously highlighted the effectiveness and the
reliability of the use of TI to measure Tsk. The use of TI has recently become a
popular method of assessing skin temperature following cryotherapy such as cold air
cryotherapy, cold water immersion, ice cubes or cold packs in humans to assess skin
temperature (Ammer, 2004). TI has been advocated in cryotherapy research
primarily because it allows temperature data over the whole of the cooled area to be
collected as opposed to a spot measurement obtained with a thermocouple (Hardaker
et al, 2007).

Despite the significant number of original research studies and reviews assessing the
effects of cryotherapy on Tsk, the optimal Tsk reductions in a clinical or sporting
setting remains to be fully established (Bleakley et al, 2011). Consequently, answers
to questions such as “what method of cryotherapy is the most effective in reducing
skin temperature?”, “is thermal imaging a reliable method of assessing skin
temperature following cryotherapy?” and “what reduction in skin temperature is
safe?” remain to be fully elucidated. Therefore the objectives of this current review
were to determine a) the effectiveness of TI in assessing skin temperature following
cryotherapy and b) the effect of different modalities on reducing skin temperature.
5.2 Research Methods
We searched Medline, Pubmed and Science Direct search engines to identify studies that assessed skin temperature following a cryotherapy application using infrared thermal imaging. Keywords used included “thermal imaging and cryotherapy”, “thermal imaging and cooling”, “thermology and cryotherapy”, “skin temperature and cryotherapy”, “skin temperature and cooling” and “thermology and cooling”. No restrictions were made on study design or comparison group. Due to the advent of digital technology which has revolutionised the field of thermal imaging original papers published in the last decade were preferentially considered. The inclusion criteria for study selection were (1) the literature was written in English, (2) participants were human, (3) skin temperature assessed following a cryotherapy application, and (4) infrared thermal imaging was used to assess skin temperature. Articles were excluded if the title or abstract did not meet the inclusion criteria. Potentially relevant articles were also obtained by physically searching the

Fig. 1. An example of an anterior and posterior image of a subject in the anatomical position using infrared thermography. The inert markers, used to create regions of interest, are visible on the acromion, anterior superior iliac spine, posterior superior iliac spine, at the level of the olecranon, the popliteal fold, and 5 cm above and below the patella. The white frame, using the inert markers, creates a region of interest in the thigh.
bibliographies of included studies to identify any study that may have escaped the original search.

Fig. 2. Anterior and Posterior view of the maximum skin temperature reduction following the different cryotherapy modalities. Air=Localised Cold Air, (A)(P)CC=Analogue/Pump Cryo Cuff, IM=Ice massage, CI=Crushed Ice, CWI=Cold Water Immersion, DFCG=Deep Freeze Cooling Gel, FP¼Frozen Peas, GP=Gel Pack, WBC=Whole Body Cryotherapy (Cold Air). The superscripted numbers after the modality abbreviation indicate the relevant study where information was extracted. Cholewka et al. (2004)\textsuperscript{1}, Cholewka et al. (2006)\textsuperscript{2}, Cholewka et al. (in press)\textsuperscript{3}, Hardaker et al. (2007)\textsuperscript{4}, Herrera et al. (2010)\textsuperscript{5}, Karki et al. (2004)\textsuperscript{6}, Kennet et al. (2007)\textsuperscript{7}, Kim et al. (2002)\textsuperscript{8}, Rasmussen and Mercer (2004)\textsuperscript{9}, Ring et al. (2004a)\textsuperscript{10}, Ring et al. (2004b)\textsuperscript{11}, Robinson et al. (2010)\textsuperscript{12}, Selfe et al. (2007)\textsuperscript{13}, Selfe et al. (2009)\textsuperscript{14}, Selfe et al. (2010)\textsuperscript{15}. 

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Table 1

Studies assessing skin temperature following Cryotherapy using Thermal Imaging.

<table>
<thead>
<tr>
<th>Author</th>
<th>Population N (M:F)</th>
<th>Treatment</th>
<th>Methodology</th>
<th>Immediate Effects</th>
<th>Duration of Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cholewka et al. (2004)</td>
<td>a) N = 22 (17:5) LBP, Age = 47.1±10.1</td>
<td>WBC (-120°C w/-60°C)</td>
<td>- Back</td>
<td>a) 7 ºC&lt;sup&gt;a&lt;/sup&gt;</td>
<td>N/A</td>
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<td></td>
<td>b) N = 8 (7:1) Healthy, Age = 25±4.1</td>
<td>- t = N/A</td>
<td>- Pre &amp; Immediately Post Rx</td>
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<td></td>
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<td>- T&lt;sub&gt;room&lt;/sub&gt; = n/a</td>
<td>- T&lt;sub&gt;room&lt;/sub&gt; = 21.5 ± 1°C</td>
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<tr>
<td>Cholewka et al. (2006)</td>
<td>a) N = 16 (10:6) LBP, Age = 25.6±3.9</td>
<td>WBC (-120°C w/-60°C)</td>
<td>- T1/T2 to L5/S1</td>
<td>N/A</td>
<td>N/A</td>
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<td></td>
<td>b) N = 30 (23:7) Healthy, Age = 41.5±12</td>
<td>- t = 2 min (1st session), 3 min (2nd &amp; 3rd session)</td>
<td>- Pre &amp; Immediately Post Rx</td>
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<td></td>
<td></td>
<td>- T&lt;sub&gt;room&lt;/sub&gt; = 21.5 ± 1°C</td>
<td>- T&lt;sub&gt;room&lt;/sub&gt; = 21.5 ± 1°C</td>
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<tr>
<td>Cholewka et al. (2010)</td>
<td>a) N = 18 (18:0) Anylosingspondylitis, Age = 50.6±8</td>
<td>WBC (-120°C w/-60°C)</td>
<td>- T1/T2 to L5/S1</td>
<td>a) 8.31ºC&lt;sup&gt;a&lt;/sup&gt;, b) 10.16ºC&lt;sup&gt;a&lt;/sup&gt;</td>
<td>N/A</td>
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<td>- t = 3min</td>
<td>- Pre &amp; Immediately Post Rx</td>
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<tr>
<td>Study</td>
<td>Population</td>
<td>Age</td>
<td>Ice Bath Parameters</td>
<td>Room Temperature</td>
<td>Comment</td>
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<tr>
<td>Cholewa et al. (2011)</td>
<td>Healthy</td>
<td>Age = 47.1±10.1</td>
<td>WBC (-120°C w/-60°C)</td>
<td>5.8°C</td>
<td>N/A</td>
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<td></td>
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<td></td>
<td>- t = 3min</td>
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<tr>
<td></td>
<td>Cervical Disk Herniation</td>
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<td>- Whole body by summation feet, shank, back, chest, arms, hands, head</td>
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<tr>
<td></td>
<td>a) N = 10 (3:7) Control, Age = 35.1±5.8</td>
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<td>- Pre &amp; Immediately Post Rx</td>
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<td>b) N = 10 (2:8) WBC, Age = 34.8±4.2</td>
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<td>- d = 1.0-1.5m</td>
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<td>- T&lt;sub&gt;room&lt;/sub&gt; = 23 ± 1°C</td>
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Gong et al. (2011)

<table>
<thead>
<tr>
<th>Study</th>
<th>Population</th>
<th>Age</th>
<th>Ice Bath Parameters</th>
<th>Room Temperature</th>
<th>Comment</th>
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<tbody>
<tr>
<td></td>
<td>Cervical Disk Herniation</td>
<td></td>
<td>WBC (-110°C w/-60°C)</td>
<td>N/A</td>
<td>The study aims only to compare treatments' effects on bilateral differences in</td>
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<tr>
<td></td>
<td>a) N = 10 (3:7) Control, Age = 35.1±5.8</td>
<td></td>
<td>- t = 60sec (-60°C), 2.5min (-110°C), 30sec (-60°C)</td>
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<td>b) N = 10 (2:8) WBC, Age = 34.8±4.2</td>
<td></td>
<td>- Upper Trapezius, Biceps Brachii, Triceps Brachii</td>
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<td>- Pre &amp; Post Rx</td>
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<td>- T&lt;sub&gt;room&lt;/sub&gt; = 23-24°C</td>
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</table>

a) N = 15 (13:2) Sciatica, Age = 44.7±7.6
b) N = 6 (6:0) Spondylarthrosis, Age = 46±11.7
c) N =11 (11:0) Healthy, Age = 34±7.9
<table>
<thead>
<tr>
<th>Study</th>
<th>Participants</th>
<th>Condition</th>
<th>Intervention</th>
<th>Time</th>
<th>Thigh Temperature</th>
<th>Shank Temperature</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardaker et al. (2007)</td>
<td>Healthy, Age = 27.8 ± 9.0</td>
<td>CI</td>
<td>Thigh</td>
<td>t = 15 min</td>
<td>Thigh Pre &amp; Immediately Post Rx (image/min for 40 mins)</td>
<td>CI = 16°C</td>
<td>did not return to baseline Tsk after 40 min (remained 2-3°C lower)</td>
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<tr>
<td>Herrera et al. (2011)</td>
<td>Healthy, Age = 20.5 ± 1.9</td>
<td>CI, Ice massage, CWI</td>
<td>Shank</td>
<td>t = 15 min</td>
<td>Shank Pre &amp; Post Rx</td>
<td>CI = 24.43°C, Ice massage = 27.6°C, CWI = 18.23°C</td>
<td>N/A</td>
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<tr>
<td>Karki et al.</td>
<td>Healthy</td>
<td>CC</td>
<td>Patella</td>
<td></td>
<td>Patella Pre &amp; Post Rx (1 image/min for 40 mins)</td>
<td>a) 1.0°C</td>
<td>a) 2.2°C @ 16 min post Rx</td>
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<td>N = 19 (19:0), Age = 25.2</td>
<td>Knee Joint</td>
<td>T&lt;sub&gt;room&lt;/sub&gt; = 20.2 - 23.3 °C</td>
<td>CI, GP, FP, CWI</td>
<td>CI = 19.56±3.78 °C&lt;sup&gt;b&lt;/sup&gt;, GP = 13.19±5.07 °C&lt;sup&gt;b&lt;/sup&gt;, FP = 14.59±4.22 °C&lt;sup&gt;b&lt;/sup&gt;, CWI = 16.99±2.76 °C&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>N = 20 (0:20), Age = 25.6</td>
<td>t = 3 min</td>
<td>25mins</td>
<td>CI did not return to baseline T&lt;sub&gt;sk&lt;/sub&gt; after 35 min (remained 11.8°C lower)</td>
<td>GP did not return to baseline T&lt;sub&gt;sk&lt;/sub&gt; after 35 min (remained 5.2°C lower)</td>
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<td></td>
<td>- Lateral aspect of the ankle</td>
<td>- d = 0.6m</td>
<td>FP did not return to baseline T&lt;sub&gt;sk&lt;/sub&gt; after 35 min (remained 6.2°C lower)</td>
<td>CWI did not return to baseline T&lt;sub&gt;sk&lt;/sub&gt; after 35 min (remained 11°C lower)</td>
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<td>- Pre &amp; Immediately Post Rx (1 mage/min for 30 min), T&lt;sub&gt;room&lt;/sub&gt; = 20.5±1.4°C</td>
<td>- T&lt;sub&gt;room&lt;/sub&gt; = 20.5±1.4°C</td>
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<td>b) 1.1°C&lt;sup&gt;a&lt;/sup&gt;</td>
<td>b) 2°C&lt;sup&gt;b&lt;/sup&gt; @ 14 min post Rx</td>
<td>b) 2°C&lt;sup&gt;b&lt;/sup&gt; @ 14 min post Rx</td>
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<td></td>
<td>- did not return to baseline T&lt;sub&gt;sk&lt;/sub&gt; after 25 min (remained 1-2°C lower)</td>
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<tr>
<td>Study</td>
<td>Participants</td>
<td>Protocol</td>
<td>Temperature</td>
<td>Result</td>
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<td>Kim et al. (2002)</td>
<td>Healthy, Age = 33.8±12.7</td>
<td>Cold Air - Knee Joint – lateral aspect - t = 5 min</td>
<td>22.1°C</td>
<td>did not return to baseline after 120 min (remained 1-2°C lower)</td>
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<tr>
<td></td>
<td>20 (15:5)</td>
<td>- Pre Rx, During Rx (1 image/30 sec) &amp; Post Rx (1 image/min for 10 min + 5 min for 120 min)</td>
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<td>- T_{\text{room}} = 26-28°C</td>
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<tr>
<td>Klimek et al. (2011)</td>
<td>Age = 21.6±1.2</td>
<td>WBC (-110°C w/-60°C) - t = 30sec (-60°C), 3min (-110°C)</td>
<td>n/a</td>
<td>did not return to baseline after 90 min</td>
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<td>30 (15:15)</td>
<td>- Anterior and Posterior thigh - Pre Rx &amp; 15, 30, 45, 60, 75 and 90 min post treatment.</td>
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<td>- T_{\text{room}} = N/A</td>
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<tr>
<td>Radmus sen &amp; Mercer (2004)</td>
<td>Healthy</td>
<td>CWI - i) Hands and ii) Feet</td>
<td>ai) = 10°C</td>
<td>a) ii) demonstrated and maintained hyperthermia after ~20 min (remained 1°C higher)</td>
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<td></td>
<td>a) N = 12 (12:0) Young, Age = 24.8±3</td>
<td>- Pre Rx &amp; 2 image/min for 7 mins (first image taken 20s post), 1 image/min for following 8 mins, then 1 image/2mins</td>
<td>b) = 9°C</td>
<td>bii) did not return to baseline T_{sk} after 60 min (remained ~1°C lower)</td>
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<td>24 (24:0)</td>
<td>- T_{\text{room}} = 26-28°C</td>
<td>bi) = 10°C</td>
<td>bii) did not return to baseline T_{sk} after 60 min (remained ~1°C lower)</td>
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<td>bii) = 8°C</td>
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<tr>
<td>Study</td>
<td>Group Description</td>
<td>Protocol Details</td>
<td>Temperature Details</td>
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<tr>
<td>Ring et al. (2004a)</td>
<td>Healthy</td>
<td>DFCG &amp; IP</td>
<td>Lumbar Spine, Pre &amp; Post Rx (1 image/3 min for 1 hr)</td>
<td>DFCG = 4.5°C(^b), IP = 6°C(^b) DFCG did not return to baseline T(_{sk}) after 60 min (remained 4°C lower) IP demonstrated and maintained hyperthermia after 27 min (remained 2°C higher)</td>
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<td></td>
<td>N = 4 (4:0), Age = 26.5</td>
<td>t = 10 min</td>
<td>d = 0.7 m, T(_{room}) = 22°C</td>
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<td>N = 2 (0:2), Age = 32 &amp; 26</td>
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<tr>
<td>Ring et al. (2004b)</td>
<td>Healthy, Age = 20-45 years</td>
<td>DFCG1 - direct application, DFCG2 - rubbed in</td>
<td>Lumbar Spine, Pre &amp; Post Rx (1 image/3 min for 1 hr)</td>
<td>DFCG1 = 6°C(^b), DFCG2 = 6°C(^b) DFCG1 did not return to baseline T(<em>{sk}) after 60 min (remained 6°C lower) DFCG2 did not return to baseline T(</em>{sk}) after 60 min (remained 4°C lower)</td>
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<td></td>
<td>6 (n/a)</td>
<td>L2/L4, t = 60 min</td>
<td>T(_{room}) = 23±1°C</td>
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<tr>
<td>Robinson et al. (2010)</td>
<td>Carpal Tunnel Syndrome, Age = 54.7</td>
<td>CC</td>
<td>PreOp Hand-i = 6.2°C(^b)</td>
<td>PreOp Hand-I demonstrated and maintained hyperthermia after ~15 min (remained ~0.2°C higher)</td>
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<tr>
<td></td>
<td>14 (6:8)</td>
<td>2(^{nd}) digit, 5(^{th}) digit</td>
<td>PreOp Hand-ii = 6.3°C(^b)</td>
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<td>- Hand and Wrist, t = 3 min</td>
<td>PreOp Finger-i = 8.5°C(^b)</td>
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<td>PreOp Finger-ii</td>
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<td>PreOp Finger-i = did not</td>
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<td>Selfe et al. (2006)</td>
<td>Anterior Knee Pain 9 (n/a)</td>
<td>CC</td>
<td>- Knee, Pre &amp; Post Rx (1 image/min for 20 min), d = 0.8m, T_{room} = N/A</td>
<td>= 9°C(^b) return to baseline T(_{sk}) after 20 min (remained 1.5°C lower)</td>
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<td>Selfe et al. (2007)</td>
<td>Sufferer of ice burn, Age = 43 1 (1:0)</td>
<td>GP</td>
<td>- Knee, Pre &amp; Post Rx (1 image/min for 25 min), T_{room} = N/A</td>
<td>17.9°C(^b) did not return to baseline T(_{sk}) after 25 min but demonstrated a steep temperature gradient of 29.7°C</td>
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<td>Selfe et al. (2009)</td>
<td>Healthy, Age = 29.6±9.3 11 (11:0)</td>
<td>CI, Analogue CC, Pump CC</td>
<td>- Knee, Pre &amp; Immediately Post Rx, d = 0.91m</td>
<td>CI = 14.6±3.7°C(^b), Analogue CC = 12.3±2.4°C(^b), Pump CC = N/A</td>
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<td>Selfe et al. (2010)</td>
<td>Anterior Knee pain, accentuated by cold</td>
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<sup>a</sup> = p<0.05 vs pre-treatment, <sup>b</sup> = p<0.05 vs control group, (male : female), T<sub>sk</sub> = skin temperature, T<sub>room</sub> = room temperature, Rx = treatment, t = time, n/a = not available, N/A = follow ups not measured beyond the immediate stages post Rx, T1/T2 = First/Second thoracic vertebra, L5/S1 = fifth lumbar vertebra/first sacral vertebra, PreOp = pre operative, Air = Localised Cold Air, CC = Cryo Cuff, CI = Crushed Ice, CWI = Cold Water Immersion, DFCG = Deep Freeze Cooling Gel, FP = Frozen Peas, GP = Gel Pack, WBC = Whole Body Cryotherapy.
5.3 Magnitude and Duration of Skin Tissue Cooling

Physiotherapists, coaches, athletic trainers, and clinicians administer cryotherapy for numerous reasons, including the reduction of pain and swelling, to relieve muscle spasm, and to facilitate movement (Costello & Donnelly, 2011, Costello et al., epub). It has previously been suggested that cold application may relieve pain by numerous mechanisms including altered nerve conduction velocity (NCV), inhibition of nociceptors, a reduction in muscle spasm and/or a reduction in metabolic activity (Algafly & George, 2007, Airaksinen et al., 2003). The magnitude of tissue cooling following cryotherapy is therefore critically important as nerve conduction velocity is significantly and progressively reduced concomitantly with skin temperature following cold application (Algafly and George, 2007).

Of the 19 reviewed studies, which satisfied the inclusion criteria, 6 (Cholewka et al., 2004, Cholewka et al., 2006, Cholewka et al., 2010, Cholewka et al., 2011, Gong et al., 2011, Klimek et al., 2011) assessed skin temperature following Whole Body Cryotherapy (WBC), 5 utilised a cryotherapy cuff (Selfe et al., 2010, Selfe et al., 2006, Robinson et al., 2010, Karki et al., 2004, Selfe et al., 2009), 4 after crushed ice (Kennet et al., 2007, Hardarker et al., 2005, Herrera et al., 2011, Selfe et al., 2009), 4 after cold water (Kennet et al., 2007, Fushimi et al., 1996, Herrera et al., 2011, Radmussen and Mercer, 2004), 2 after gel pack (Kennet et al., 2007, Ring et al., 2004a, 2004b), 2 ice massage (Ammer et al., 1996, Herrera et al., 2011), 1 after frozen peas (Kennet et al., 2007), while a further 1 after localised cold air (Kim et al., 2002). The duration of cooling ranged between 2 (Radmussen & Mercer, 2004) and 20 minutes (Selfe et al., 2007, Selfe et al., 2000, Kennett et al., 2007) with the average duration of cooling being 8.5 minutes. Five studies (Ring et al., 2004a, Ring et al., 2004b, Herrera et al., 2011, Kennett et al 2007 and Selfe et al 2009) included a comparison of different cooling modalities, while no study compared different cooling durations. In addition to reporting skin temperature one study reported intra-muscular temperature (Hardaker et al., 2007) while no study reported core temperature.
The 19 eligible studies comprised of a total of 440 participants. Of these 273 were male, 152 women and the gender of 15 participants was not specified. The average sample size was 23 with the largest study based on 58 participants. A number of the reviewed studies used a healthy control group as a comparison to a patient population, with symptoms including lower back pain (Cholewka et al, 2004, Cholewka et al, 2006), anterior knee pain (Selfe et al, 2010), spondylarthrosis (Cholewka et al, 2010), anylosing spondylitis (Cholewka et al, 2010) or sciatica (Cholewka et al, 2010). Three studies (Robins et al 2011, Selfe et al., 2006, Gong et al 2010) assessed only a patient population while the remaining focused on a healthy population. The purpose of three studies was to assess the effects of gender (Karki et al 2004, Klimek et al., 2011) and age (Radmussen & Mercer, 2004) on skin temperature following the application of cold. One study (Selfe et al 2007) was a case report on an individual who suffered from ice burn following an application of a gel pack for 20 minutes.

The temperature distribution over the body's surface provides useful information for many research and clinical applications. According to recent PRICE guidelines a reduction of 5-15 °C in tissue temperature, with the critical level of absolute skin temperature less than 12°C, is required to provide analgesia (Bleakley et al., 2011, Bleakley and Hopkins, 2010). However, larger reductions in skin temperature may cause injury (Bleakley and Hopkins, 2010). Figure 2 displays the maximum skin temperature reduction recorded by TI following the different cryotherapy modalities. Skin temperature of less than 12°C were achieved using ice massage, cold air, crushed ice, cryo cuff, ice pack and cold water immersion (Figure 2). WBC, cold air, gel packs, cryo cuff, cold water immersion, ice packs and frozen peas were all effective in reducing skin temperature by more than 5°C at various locations. WBC did not reach the PRICE guidelines, with reductions of less than 5°C at the hands, chest and forehead. However, it must be noted that during WBC in order to protect the face and extremities against the extreme cooling, subjects have to wear a mask, ear protection, socks, shoes and gloves and this attire may explain why these skin temperatures were not as significantly reduced as other regions. Similarly, a 10 minute application of Deep Freeze Cooling Gel and a 3 minute application of a cryo cuff were ineffective at reducing skin temperature in the back and knee respectively.
Of the 19 included studies the lowest absolute skin temperature reported was 3.98°C, a mean reduction of 27.6 (±1.32) °C, following the application of ice massage (Herrera, 2011). However, it must be noted that Malone et al (1992) have previously stated that if the peripheral nerve is cooled below 10°C or if skin temperature is cooled to between 0 and 5 °C, cryotherapy can disturb function and cause motor/sensory loss.

In both a clinical and sporting setting, what happens to the temperature of the skin in the recovery period subsequent to the removal of the cold modality is of interest. In addition to reported skin temperature measurements immediately after the removal of the cryotherapy application, eleven of the reviewed studies reported follow up assessments of skin temperature. An interesting finding in all of these studies was that subjects’ skin temperature, during follow up data collection, did not return to baseline levels after cryotherapy. In one study skin temperature still had not returned to baseline levels 120 minutes after exposure to cold air (Kim et al., 2002). In another study skin temperature 35 minutes after cold water immersion remained 11°C lower than baseline (Kennett et al., 2007). Furthermore, Klimek and colleagues (2011) utilising a WBC protocol have reported significant reduction in thigh surface temperature 90 minutes following exposure in both males and females. It is common practise that cold is applied intermittently with periods of application and removal. The time period following removal of the cold modality should therefore be considered an important part of cryotherapy treatment sessions to achieve full therapeutic benefit (Hardaker et al., 2007). Clinicians must therefore be aware that during these cycles skin temperature may not have returned to baseline levels and need to be cognisant of the potential for cold induced injury.

As cryotherapy is often applied to treat muscle injuries it is also important to consider the relationship between skin and intramuscular temperature. The reporting of skin temperature has been criticised as being of limited value when observing the influence of cooling on subcutaneous tissues, with a number of studies suggesting there is no relationship between skin and muscle temperature. However, Hardaker et al. (2007) have reported that a strong negative quadratic relationship exists between
intramuscular and skin temperature. These authors (Hardaker et al., 2007) report that the amount of heat an object can hold is directly proportional to its volume and therefore the temperature of the muscle may be derived using the dispersion in the underlying tissue volume and the surface area of the skin that is being cooled. Interestingly as the skin temperature increases following the removal of the cryotherapy application intramuscular temperature decreases as the superficial tissues draw heat from the deeper tissues (Hardaker et al. 2007). Therefore, this is why the maximum reduction of muscle temperature is often recorded after the removal of cold, when the skin temperature has increased.

5.4 Technical Issues with the Methodology of Thermal Imaging following Cryotherapy

Hardware and analysis software produced by Flir Systems (Danderyd, Sweden) was the most commonly used in this review. In terms of the area thermographed the knee (Selfe et al., 2010, Selfe et al., 2009, Selfe et al., 2007, Kim et al., 2002, Karki et al., 2004) was the most common with five studies focusing on that joint. Other studies focused the ankle (Kennet et al), chest (Cholewka et al., 2011), thigh (Hardarker et al., 2005) and back (Cholewka et al., 2011, Cholewka et al., 2006, Cholewka et al., 2004) following a cryotherapy application. While Cholewka et al. (2011) reported skin temperature information from the head, chest, back, arms, tibias, hands and feet in order to calculate mean skin temperature following WBC.

The majority of the reviewed studies utilised the mean temperature from a Region of Interest (ROI) rather than spot measurements. In general, an area read-out should be used instead of spot measurements (Plassmann et al., 2006). In relation to data extraction the use of ROI has been advocated for a number of years (Kennet et al., 2007). A ROI, typically constructed as a quadrilateral on the post process computer software, is often applied to a pre-determined area of skin. Using skin or inert markers, attached to bony landmarks or anatomical locations, appear more reliable than using regions of interest determined from an image. The use of these inert markers, as used by (Selfe et al., 2006), means one has a clearly defined anatomic
frame, through which a range of temperatures and images can be assessed consistently both within and between subjects.

Two further components to consider during thermal imaging is the distance the camera is from the area or region being thermographed, the room temperature of the laboratory where the TI took place (Ring and Ammer, 2000) and the emissivity factor. A limitation with the majority of the studies in this review was the failure to report either of these. The distance the area being thermographed is from the camera lens will affect the pixel resolution and has potential to alter the robustness of the data. It has also been suggested that a range of temperatures from 18°C to 25°C should be used during TI (Ring and Ammer, 2000). If the temperature range is below thermoneutral, the subject is likely to shiver, and above 25°C room temperature is likely to cause sweating, which will affect the reading (see table 1). In addition, during the analysis of skin temperature following the use of TI an emissivity of 0.97-0.98 has been recommended and used regularly in the literature (Steketee, 1973, Cholewka et al., 2011). However, a number of the reviewed studies have again failed to reports what emissivity factor was used during data collection. This is perturbing as the use of an incorrect emissivity would lead to an erroneous recoding of skin temperature.

5.5 Advantages and Limitations of Infrared Imaging Following Cryotherapy

A number of methods and devices of recoding skin temperature following the application of cryotherapy have been reported in the literature including thermocouples (Merrick et al, 2003), thermistors (Gregson et al., 2011), and other wireless sensors such as an iButton (Lichtenbelt, 2006). The greatest advantage of TI over these other methods of assessing skin temperature is the fact this it is non-invasive and portable. TI does not have to be in contact with the skin, an obvious advantage for measurement, especially in a clinical context. Skin thermistors and thermocouples often consist of a thin metallic foil which serves as a heat spreader backed by a foam insulation pad. This has the potential of creating a layer of insulation over the area of skin being assessed and therefore significantly degrades
the accuracy of the measured temperature (Boetcher et al 2009). This artefact of testing, recording and reporting erroneous skin temperature data is therefore troublesome, especially if the temperature of the skin is being assessed during (or after) a cryotherapy treatment. The prime advantage that TI has over thermistors is the wealth of data that TI collects. Temperature variation over large areas of skin can be quantified quickly and accurately, with high resolution rendering each image the equivalent of hundreds or thousands of individual thermistor readings.

With the ability to create a ROI (see figure 1), using anatomical landmarks or inert markers as reference points, TI also allows an investigator to study a number of different (and larger) skin temperature sites. As a result the clinician can be confident that it is the actual temperature of the area of interest and is not confined to the spot measurements like the other techniques. In addition, of particular interest following cryotherapy or thermotherapy applications, TI has the capability to record the maximum, minimum and average skin temperature at any site. An ability to record the minimum skin temperature may be useful in future research on potential cold induced injury, which the minimum skin temperature rather than the average is pertinent. Furthermore, TI allows you to record, store and prints print images. This may be useful if recorded data needs to be retrospectively revisit, view or reanalysed.

In order to collect and report robust skin temperature data, clinicians and researchers alike face a number of challenges. In essence skin temperature data collection is inherently difficult to standardise due primarily to intrinsic and extrinsic factors. Intrinsic variables describe factors relating to the individual subject/patient and include caffeine/alcohol consumption, smoking, recent physical activity, circadian rhythm and gender. The influence of draughts, environmental temperature, heat sources (e.g. sun, radiators), acclimation period and clothing are some examples of extrinsic variables that may also have a significant effect on TI data. The majority of these variables can be relatively well controlled through effective protocol planning and communication with the subject prior to the commencement of TI but clinicians and researchers should be cognisant of these variables and endeavour to reduce their contribution. Although these intrinsic and extrinsic variables are not isolated to skin
temperature assessments via TI, individually or collectively these factors could have a significant physiological effect and alter skin temperature recordings. Consequently, any protocol that included skin temperature assessment requires a great deal of planning and consistency.

One of the major limitations of TI is that to date, no standardised framework has been established (Ammer, 2008). Compared to other techniques that can assess skin temperature data, such as thermocouples or thermistors, TI can be expensive. Additionally, as moisture emits radiation, in order to use TI the skin surface must be completely dry. Any excess water on the skin (which is likely to occur following cold water immersion or any ice application) needs to be removed. Finally, compared to thermocouples or thermistors which could utilise a hand help battery operated devise, a computer with specialised software is usually required for TI and often a power source is required. This may reduce the effectiveness of TI as a technique of assessing skin temperature outside or in a field based study, as we have previously highlighted the potential effects varying ambient temperature or draughts may have on skin temperature.

5.6 Conclusion
Thermal imaging is a safe and non-invasive method of collecting skin temperature. Although further research is required, in terms of structuring specific guidelines and protocols, thermal imaging appears to be an accurate and reliable method of collecting skin temperature data following cryotherapy. Despite the ambiguity regarding optimal skin temperature reductions in a clinician or sporting setting, this review highlights the ability of several different modalities of cryotherapy, including WBC, cold air, gel packs, cryo cuff, cold water immersion, ice packs and frozen peas, to reduce skin temperature in accordance with the recent PRICE guidelines.

Conflict of Interest Statement
The authors declare they have not conflict of interest on the content of this paper.
5.7 References


Chapter 6

Effects of -110°C Cold Air and 8°C Water on Muscle, Skin and Core Temperature
Effects of -110°C Cold Air and 8°C Water on Muscle, Skin and Core Temperature, Submitted to Medicine and Science in Sport and Exercise.

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Writing the article: JC
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Final approval: JC, AD, JS, KC
6.1 Abstract

**Purpose:** To establish the reductions in muscle, skin and core temperature following exposure to -110°C Whole Body Cryotherapy (WBC), and compare these to 8°C Cold Water Immersion (CWI). **Methods:** Twenty active male participants were randomly assigned to a 4-min exposure of WBC or CWI. A minimum of 7 days later participants were exposed to the remaining treatment. Muscle temperature in the right *vastus lateralis* (n = 10); thigh skin (average, maximum and minimum) and rectal temperature (n = 10) were recorded before and 60 min after treatment. **Results:** The greatest reduction (P < 0.05) in muscle (mean ± SD; 1cm: WBC, 1.6 ± 1.2°C; CWI, 2.0 ± 1.0°C; 2cm: WBC, 1.2 ± 0.7°C; CWI, 1.7 ± 0.9°C; 3cm: WBC, 1.6 ± 0.6°C; CWI, 1.7 ± 0.5°C) and rectal temperature (WBC, 0.3 ± 0.2°C; CWI, 0.4 ± 0.2°C) were observed 60 min after treatment. The largest reductions in average (WBC, 12.1 ± 1.0°C; CWI, 8.4 ± 0.7°C), minimum (WBC, 13.2 ± 1.4°C; CWI, 8.7 ± 0.7°C) and maximum (WBC, 8.8 ± 2.0°C; CWI, 7.2 ± 1.9°C) skin temperature occurred immediately after both CWI and WBC (P < 0.05). Skin temperature was significantly lower (P < 0.05) immediately after WBC compared to CWI, but tended to recover quicker after WBC. Muscle, skin or core temperature (P < 0.05) did not return to baseline 60 min after treatment. **Conclusion:** The present study demonstrates that a single WBC exposure decreases muscle and core temperature to a similar level of those experienced after CWI. Although both treatments significantly reduced skin temperature, WBC elicited a greater decrease compared to CWI.

**Key Words:**

Cooling; PRICE; infrared thermal imaging; recovery.
6.2 Introduction

Whole Body Cryotherapy (WBC) is a treatment involving very short exposures to extreme cold, and is growing in popularity amongst athletes and coaches (8,16). Most WBC protocols repeatedly expose minimally dressed individuals to extremely cold dry air (-110°C to -140°C) in an environmental controlled room for a short duration of time (2-4 min) (3). Although the use of cryotherapy or therapeutic tissue cooling is a common form of treatment dating back to ancient Greece (14), WBC is a relatively novel modality of cryotherapy. The first WBC chamber was built in Japan in the late 1970’s, but it was only introduced to Europe in 1982 and America in the last decade (25).

A range of claims have been made about the benefits of WBC, but the evidence base supporting these claims is extremely limited (3). Studies examining WBC are traditionally limited, in terms of quality and statistical power, or published in non-English literature. Initial WBC studies have reported a reduction in creatine kinase activity after training (2,40), total oxidative status in plasma (21) as well as increase in the anti-inflammatory cytokines IL-10 (20) and IL-6 (20,22). Hausswirth and colleagues (16) have recently reported that three WBC sessions accelerated recovery from exercise induced muscle damage (EIMD), but it has also been show that WBC administered 24 h after eccentric exercise, is ineffective in alleviating muscle soreness or enhancing muscle force recovery (8). Despite the increasing popularity and use of WBC in sports medicine, very few randomised controlled studies have tried to verify its efficacy (3). Presently, clinicians and sporting organizations are exposing individuals to these extreme temperatures based on anecdotal evidence and very little is known regarding its effectiveness or the physiological changes that occur during or after the treatment (8).

Similarly, despite its widespread adoption in an attempt to alleviate some of the physiologic and functional deficits associated with EIMD and to treat some clinical conditions, the use of Cold Water Immersion (CWI) remains controversial owing in part to the lack of data regarding underlying mechanisms (15). Although there is much confusion around how much cooling is clinically adequate the basic premise of
Cryotherapy is to cool injured or damaged tissue (6). As thermal conductance in water can be as much as 3 times greater than in air (35), both of these cooling modalities (WBC and CWI) have a different thermal conduction property and therefore a different skin, muscle and core cooling potential. Currently there is a paucity of published research addressing the thermodynamics of these cooling modalities, especially WBC.

In cryotherapy research there is perhaps no more relevant and divisive question than ‘what is the optimal modality, temperature and duration required to elicit the required physiological response?’ For example, in order to reduce nerve conduction velocity, and consequently pain, the magnitude of tissue cooling following cryotherapy is critically important. Nerve conduction velocity has been shown to progressively reduce concomitantly with skin temperature (1). Similarly, a reduction of 5-15 °C in tissue temperature, with the critical level of skin temperature less than 12°C, is required to provide analgesia (6). Cooling has also been shown to decrease the dynamic contractile force by 4–6% for each 1°C reduction in muscle temperature (4), alter EMG activity during submaximal leg extensions (11) and reduce power output in humans (32). In addition, if administered incorrectly or for a prolonged period of time clinicians and researchers need to be aware that cryotherapy can result in cold injury, with cases such as ice burn (33) and even amputation (39) previously being reported within the literature. Consequently, despite the optimal tissue temperature following cryotherapy yet to be established, it is pivotal that practitioners are familiarised with the thermodynamic of different cooling modalities.

The majority of claims regarding the effectiveness of WBC refer to the ability of the treatment to reduce muscle, skin and core temperature. These claims have yet to be substantiated. To our knowledge no researchers have sought to simultaneously establish the effects of WBC on muscle, skin and core temperature and compare it to the more commonly used method of cryotherapy, CWI. Therefore, the purpose of this study was to investigate and compare the effects of two modalities of cryotherapy, cold air (WBC) and water (CWI), on muscle (vastus lateralis), skin and
core (rectal) temperature. This was achieved using an identical treatment duration of 4 minutes. It was hypothesized that CWI would facilitate a more rapid reduction in all three temperature measurements, primarily due to the thermal conductivity of water versus that of air. A second purpose of this study was to evaluate the participants’ subjective assessment of thermal comfort and sensation following exposure to both treatments.

6.3 Methods

Participants

Twenty healthy active males volunteered to participate in this study. Ten volunteers completed the intramuscular component of the study (mean ± SD, age 23.6 ± 2.7 yr, height = 180.9 ± 5.8 cm, mass = 87.2 ± 17.8 kg, Body Mass Index (BMI) = 26.5 ± 4.3 kg/m², body fat = 23.4 ± 8.7% measured via Dual Energy X-ray Absorptiometry, mid anterior thigh skin fold = 10.5 ± 5.9 mm). A further ten participants (mean ± SD, age = 26.5 ± 4.9 yr, height = 183.4 ± 6.4 cm, mass = 88.4 ± 19.9 kg, BMI 26.1 ± 4.9 kg/m², body fat 23.9 ± 9.5%) completed the skin and core component of the study. All participants were moderately trained (exercised a minimum of 3 times per week) and between the age of 18-35. Participants were familiarized with the experimental procedures and associated risks, completed a medical questionnaire and gave their written informed consent prior to participation. Participants were excluded if they had had any contradiction to cryotherapy including Raynaud's disease. All participants were required to refrain from smoking and consumption of alcohol and caffeine 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 experimental protocol was approved by the University of Limericks Education and Health Sciences Research Ethics Committee and conformed to the human experimentation policy statement of the American College of Sports Medicine.
Experimental protocol

This study was a randomized controlled crossover design. The participants were assigned, using a random numbers generator, to start with either the WBC or CWI. A minimum of seven days later participant repeated the remaining treatment. We have previously described the methodology for the WBC exposure (8). The WBC exposure was 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 ± 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 sec before entering the second room (-110 ± 3°C) for 3 min and 40 sec. 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 exposure. In the chamber, participants wore shorts, two pairs of gloves and their nose and mouth were covered with a surgical mask; their ears were covered with a woollen headband and they wore their own dry shoes and socks. All jewellery, piercings glasses and contact lenses and were removed before entry to the chamber.

The temperature and duration of the CWI exposure was similar to other studies in the literature and (15,38) and a protocol similar to our previous work was employed (9). 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 post-tests. The temperature of the water was measured throughout using a digital aquarium thermometer.

Muscle Temperature

The temperature of the vastus lateralis in the right limb was recorded manually on a Medical Precision Thermometer (DM852, Ellab A/S, Hvidovre, Denmark), with an accuracy of 0.1 °C, every min for 60 min before and after each of the cryotherapy treatments. Pilot tests demonstration that a maximum of 60 min, lying in a semi
reclined position with an indwelling muscle probe, was comfortable for the participants. A flexible intramuscular temperature probe (MAC flexible probe, Ellab, Denmark) was inserted through an indwelling flexible cannula (venflon 18GA Becton Dickinson, Sweden) into the muscle in the direction of the muscle fibres and advanced 0.5 cm beyond the end of the cannula into the muscle (12). The participants thigh skinfold (Harpenden Skinfold Caliper Baty International, West Sussex, UK) was measured, prior to insertion, and the probe was inserted 3-cm below the subcutaneous fat layer (skinfold x 0.5) (13) by a trained physician. Participant remained in a semi reclined position throughout. The location of the probe in the *vastus lateralis* was verified during pilot tests by the use of a GE Logiq e ultrasound scanner ultrasound (GE Medical, Wauwatosa, WI, USA). After 60 min of recording the temperature at 3cm depth, the probe was withdrawn incrementally to ascertain the muscle temperature at 2 cm and 1cm respectively below the subcutaneous fat layer. The probe was inserted again within 4-5 min after the exposure to both treatments. When the probe was removed, the injection site was covered with waterproof dressing. The ambient temperature of the laboratory during each testing session (WBC and CWI) was 22.0 ± 0.5°C and participants spent 20 min acclimatising to the room before the commencement of testing.

**Skin Temperature**

Skin temperature was assessed using a ThermoVision A40M Thermal Imaging camera (Flir Systems, Danderyd, Sweden) in accordance with the standard protocol of infrared imaging in medicine (30). The camera, with the emissivity set at 0.97-0.98, was connected to a personal computer (Portege A100, Toshiba, Japan) with appropriate software (Thermacam Researcher Pro 2.8, Flir systems, Danderyd, Sweden). The camera was mounted on a tripod and the distance between the camera and the participant ranged from 3.7 – 4.2 m (depending on the height and the size of the individual). The validity and reliability of using noncontact, digital, infrared, Thermal Imaging (TI) cameras to measure skin surface temperature has previously been established (34) and we have recently reviewed the benefits of TI as a method of assessing skin temperature following cryotherapy (10). To create a quadrilateral Region of Interest (ROI) around the thigh area an inert marker was placed 5cm
above the most superior aspect of the patella (10). This marker created the inferior horizontal line of the quadrilateral, while the apex of the groin created the superior line during post process analysis (10). The minimum, maximum and average skin temperature within this ROI on the participants’ right thigh was manually recorded every two min for 20 min before and 60 min after both exposures. The participants wore shorts, stood for the duration of the testing period and were asked to remain in the anatomical position while images were being recorded.

**Core Temperature**

To record core temperature a rectal probe (MRV Adult Rectal Probe, Ellab A/S, Hvidovre, Denmark) was inserted by the volunteers 10-12 cm beyond the external anal sphincter (37). The thermistor was connected to a portable thermometer (DM852, Ellab A/S, Hvidovre, Denmark) and the rectal temperature was recorded manually every min for 20 min before and 60 min after each of the cryotherapy treatments. For both outcome measures (skin and rectal) volunteers wore the same attire and spent 20 min acclimatising to the room before the commencement of testing. Post treatment assessments of skin and core temperature also commenced within 4-5 min after treatment.

**Thermal Comfort and Thermal Sensation**

Ratings of thermal sensation were recorded every 5 min throughout the duration of the study. Participants were asked to rate their thermal sensation on a nine point standard scale (37) before and after both the WBC and CWI. The question the participants were asked was ‘How are you feeling now?’ The Participants then answered by pointing to a scale from -4 to 4. 4 = very hot, 3 = hot, 2 = warm, 1 = slightly warm, 0 = neutral, -1 = slightly cool, -2 = cool, -3 = cold, -4 = very cold). Thermal comfort was also assessed immediately after exposures with a five-point scale (‘Do you find this,’ 0 = comfortable, 1 = slightly uncomfortable, 2 = uncomfortable, 3 = very uncomfortable, 4 = extremely uncomfortable). The participants were instructed to relate their sensations at the time of reporting.
Demographic Data

A Lunar iDXA™ scanner (GE Healthcare, Chalfont St Giles, Bucks., UK) with enCORE™ 2007 v.11 software was used to perform the total body scans and record percentage body fat. Daily calibration of the scanner was performed using a phantom spine containing composites of bone, fat and lean tissue. Participants were positioned on the scanner bed according to the manufacturer’s recommendations and instructed to remain as still as possible for the duration of the scan. All of the 20 participants were scanned by a certified technician within 1 week of commencing the study and the participants’ age, height and weight was also recorded at this time.

Statistical Analysis

All data are presented as group means and SD. We performed a priori analysis where the final baseline (°C) recording of muscle, skin (minimum, maximum and average) and core temperature was compared to that of the post treatment temperature at 0, 10, 20, 30, 40, 50 and 60 min following both cryotherapy modalities and analysed. A two-way repeated measures ANOVA (treatment x time) was used to investigate changes in time with one between-subjects variable, treatment, with two levels (WBC and CWI) and one within-subject variable, time, with eight levels (baseline, 0, 10, 20, 30, 40, 50 and 60 min post) for muscle, skin and core temperature. To determine the relationship between treatment and muscle temperature depth, we ran a further repeated measures AVOVA (treatment x time x subcutaneous depth) with one between-subjects variable, treatment, with two levels (WBC and CWI) and two within-subject variable, time and subcutaneous depth, with two levels in each (time: pre, post; subcutaneous depth: 1cm, 2cm). 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 while a paired sample t-test was used to investigate between-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 muscle, 1°C in skin and 0.25°C in core temperature between conditions. Ratings of thermal comfort were analysed using the Wilcoxon signed-rank test. A Friedman test was used to detect differences across time for the nonparametric data obtained from the Likert-type measurement scale for thermal sensation. A follow up analysis using the Wilcoxon signed-rank procedure, with a Bonferroni correction applied, to examine differences between baseline and data obtained during each follow-up was completed for all variables. All statistical analyses were performed in SPSS (Statistical Package for the Social Sciences), version 19.0 (SPSS Inc, Chicago, IL) with the level of significance set at P < 0.05.

6.4 Results

Muscle Temperature

Baseline temperature in the *vastus lateralis* muscle before CWI and WBC were similar (P > 0.05) at a probe depth of 1 cm (WBC, 34.0 ± 0.7; CWI, 33.8 ± 1.2°C), 2 cm (WBC, 34.9 ± 1.0°C; CWI, 35.1 ± 0.8°C) and 3 cm (WBC, 35.7 ± 0.7°C; CWI, 35.7 ± 0.7°C). A significant effect over time was observed in superficial (1 and 2 cm subcutaneous; F<sub>1,9</sub> = 79.713, P < .001, 1-β = 1.0) and deep muscle temperature (3 cm subcutaneous; F<sub>7,63</sub> = 70.175, P < 0.001, 1-β = 1.0). Post-hoc tests showed significantly lower temperatures (P < 0.05) compared to baseline at 20, 30, 40, 50 and 60 min after both WBC and CWI, at a depth of 3 cm (Fig. 1). The greatest reduction in muscle temperature at 1 cm (WBC, 1.6 ± 1.2°C; CWI, 2.0 ± 1.0°C), 2 cm (WBC, 1.2 ± 0.7°C; CWI, 1.7 ± 0.9°C) and 3 cm (WBC, 1.6 ± 0.6°C; CWI, 1.7 ± 0.5°C) was observed 60 min after both treatments. No differences were observed at any point between treatments in superficial (F<sub>1,9</sub> = 0.733, P = 0.414, 1-β = 0.12) or deep muscle temperature (F<sub>1,9</sub> = 0.14, P = 0.717, 1-β = 0.063). Despite observing a higher temperature at a depth of 2 cm compared to 1 cm throughout the study (F<sub>1,9</sub> = 119.398, P < 0.001, 1-β = 1.0) no other significant differences (P > 0.05) were observed in muscle temperature.
FIGURE 1- Muscle temperature (recorded 3cm below the subcutaneous fat layer in the right Vastus lateralis), before (1a) and after (1b) both Cold Water Immersion (CWI) and Whole Body Cryotherapy (WBC). Values are means ± SD (N = 10). *Statistical significance (P <0.05) between pre and post conditions for both modalities.
FIGURE 2- Muscle temperature (recorded 1cm and 2cm below the subcutaneous fat layer in the right *Vastus lateralis*), after both Cold Water Immersion (CWI) and Whole Body Cryotherapy (WBC). Data recorded 1 hr after exposure. Values are means ± SD (N = 10). *Statistical significance (P < 0.05) between pre and post conditions for both modalities.

**Thigh Skin Temperature**

Baseline thigh skin temperature was similar before treatment (P > 0.05; table 1). Similar to muscle temperature there was a significant reduction in average (F\(_{7,63}=1001.354, P < 0.001, 1-\beta = 1.0\); Fig. 3 and table 1), minimum (F\(_{7,63}=709.71, P < 0.001, 1-\beta = 1.0\); table 1) and maximum (F\(_{7,63}=141.831, P < 0.001, 1-\beta = 1.0\); table 1) skin temperature over time. Post-hoc analysis showed these differences occurred at 0, 10, 20, 30, 40, 50 and 60 min after both treatments compared to baseline (P < 0.05) in average, minimum and maximum skin temperature. A significant treatment by time effect was also observed in average (F\(_{7,63}=105.454, P < 0.001, 1-\beta = 1.0\), minimum (F\(_{7,63}=52.401, P < 0.001, 1-\beta = 1.0\)) and maximum (F\(_{7,63}=7.173, P < 0.001, 1-\beta = 1.0\)) skin temperature. Average, minimum and maximum skin temperature was significantly lower (P < 0.05) immediately after WBC compared to CWI. However, average skin temperature from 20 to 60 min, minimum temperature
40 and 60 min and maximum skin temperature at 10, 30, 40, 50 and 60 min was significantly lower after CWI compared to WBC (P < 0.05).

Table 1- Comparison of right thigh skin temperature change after exposure to Cold Water Immersion (CWI) and Whole Body Cryotherapy (WBC).

<table>
<thead>
<tr>
<th></th>
<th>WBC Pre (°C)</th>
<th>WBC Post (°C)</th>
<th>WBC ΔT (°C)</th>
<th>CWI Pre (°C)</th>
<th>CWI Post (°C)</th>
<th>CWI ΔT (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>30.0 ± 0.8</td>
<td>17.9 ± 1.4</td>
<td>12.1 ± 1.0*</td>
<td>29.7 ± 0.8</td>
<td>21.3 ± 1.2</td>
<td>8.4 ± 0.7*</td>
</tr>
<tr>
<td>Min</td>
<td>28.9 ± 0.8</td>
<td>15.7 ± 1.5</td>
<td>13.2 ± 1.4*</td>
<td>28.8 ± 0.7</td>
<td>20.1 ± 1.0</td>
<td>8.7 ± 0.7*</td>
</tr>
<tr>
<td>Max</td>
<td>31.5 ±1.0</td>
<td>22.7 ± 2.3</td>
<td>8.8 ± 2.0*</td>
<td>31.1 ± 1.2</td>
<td>23.9 ± 2.7</td>
<td>7.2 ± 1.9*</td>
</tr>
</tbody>
</table>

Values are means ± SD (N = 10). *Statistical significance (P < 0.05) between pre and post conditions. ΔT; temperature difference between pre and post treatment.
FIGURE 3- Average thigh skin temperature before (4a) and after (4b) both Cold Water Immersion (CWI) and Whole Body Cryotherapy (WBC). Values are means ± SD (N = 10). Statistical significance (P < 0.05) between *pre and post conditions and †between modalities.
Core Temperature

Baseline rectal temperature before CWI and WBC were similar (WBC, 37.7 ± 0.3°C; CWI, 37.7 ± 0.3°C; P > 0.05). A decline in rectal temperature was observed over time (F_{7,63} = 24.693, P < 0.001, 1-β = 1, Fig. 4). Significant reductions (P < 0.05) in rectal temperature occurred at 40, 50 and 60 min after treatment. However, there were no significant differences at any time between treatments (P > 0.05). The greatest reduction from baseline was observed 60 min after WBC (0.3 ± 0.2°C) and CWI (0.4 ± 0.2°C).
FIGURE 4- Rectal temperature before (3a) and after (3b) both Cold Water Immersion (CWI) and Whole Body Cryotherapy (WBC). Values are means ± SD (N = 10). *Statistical significance (P < 0.05) between pre and post both treatment exposure.
**Thermal Comfort and Thermal Sensation**

Participants tended to find the WBC (2.7 ± 1.4) exposure more uncomfortable than CWI (1.8 ± 1.1; Z= -2.553, P = 0.011). Significant differences were observed in thermal sensation 0 and 5 min post both modalities compare to their respective baseline sensation (P < 0.05). During a post-hoc analysis using the Wilcoxon signed-rank tests no significance were found between CWI and WBC (P > 0.05).

### 6.5 Discussion

The present study used a randomised controlled crossover design to establish the effect of -110°C WBC, an increasingly popular method of cryotherapy in sports medicine, on muscle, skin and core temperature. To our knowledge this study is the first to a) establish the effects of -110°C WBC on intramuscular temperature and b) compare the muscle, skin and core temperature cooling potential of both WBC and a more establish method of cryotherapy, CWI.

Several modalities of cryotherapy are currently employed by physiotherapists, sports physicians and physical therapists for athletic recovery, injury and rehabilitative purposes to reduce tissue temperature, nerve conduction velocity and to provide analgesia. As heat conductance is greater in water than in air (35) it was hypothesized that WBC would not reduce muscle temperature to the same degree as CWI. This hypothesis has to be rejected as a similar reduction, in both deep and superficial muscle temperature, was observed in a population of healthy active males after both treatments (Fig. 1). Significant differences compared to baseline were observed for both treatments at 20, 30, 40, 50 and 60 min post treatment (P < 0.001; Fig 1). Deep muscle temperature (3cm) continued to decline up to 60 min after both treatments. Interestingly, there were no significant differences (P > 0.05) between the WBC and the CWI at any time and both modalities display very similar reductions in muscle temperature following treatment (Fig. 1). Similarly, there was also a significant reduction (P < 0.001) in superficial muscle temperature (1cm and 2 cm subcutaneous) after treatment but no differences between treatments were observed (P > 0.05; Fig 2)
Although researchers have not reached consensus regarding ideal reductions in muscle or skin temperature (5) it has been suggested that, in the absence of definitive data, better treatment outcomes (e.g. analgesia following acute injury) may result from greater and faster cooling (13,24). Reductions in muscle temperature following various modalities of cryotherapy including cold packs (14), ice packs (27), CWI (15,26) and deep freeze cooling gel (31) is widely reported within the literature. Although previous studies have also shown the WBC is effective in reducing tympanic (8) and skin temperature (7,37) it has, until now, yet to be fully elucidated whether or not WBC was effective in reducing superficial or deep muscle temperature. We have previously highlighted the need to establish the potential of WBC to reduce muscle temperature (8) and this data will help inform sport physician, physiotherapists, coaches and athletes alike.

The CWI methodology employed in the current study was similar to that of Gregson and colleagues (15) who assessed muscle temperature (1, 2, 3 cm below the subcutaneous fat layer in the vastus lateralis) after immersion in 8°C water for 10 min. Despite employing a similar protocol in terms of water temperature, these authors reported a greater reduction (3 cm subcutaneous) in muscle temperature of ~0.5°C than the current study, 30 min after immersion. It is likely that the duration of immersion (6 min longer than the current study) employed may explain this discrepancy. The reductions in muscle temperature observed after a 4 min exposure to WBC and CWI do not compare well to that of other cryotherapy modalities. Muscle temperature in the calf (3 cm subcutaneous) has been shown to be reduced by almost 8°C after a 20-min crushed-ice pack application (28). Furthermore, a 30-min application of Wet-Ice has been shown to reduce quadriceps muscle temperature by 5.62°C and 8.44°C, at 1 cm and 2 cm subcutaneously respectively (14).

A significant reduction in average (P < 0.001; Fig. 3 and table 1), minimum (P < 0.001; table 1) and maximum (P < 0.001; table 1) skin temperature was observed after both treatments. Despite the similar reductions in skin temperature after both
treatment modalities, we observed evidence of a greater reduction in thigh temperature immediately after WBC (Fig. 3). However, both modalities display different recoveries patterns and average skin temperature after CWI was significantly ($P < 0.001$) lower than WBC at 20, 30, 40, 50 and 60 min after treatment. In order to record accurate TI data, moisture from the CWI would affect the analysis of skin temperature, the participants in the current study were asked to towel dry after immersion and this friction may have helped to slightly increases skin temperature. As towel drying is an artefact of CWI, we considered this an integral component of the treatment.

The present findings of a skin temperature reduction of 12.1 ± 1.0°C in the thigh immediately after WBC exposure is similar to that reported elsewhere after WBC (7,37). Furthermore, using a similar CWI protocol Gregson and colleagues (15) have also reported a comparable reduction of ~10°C (8.4 ± 0.7°C in the current study) in thigh skin temperature after a 5 min treatment. Although a skin temperature reduction of ~2°C less than these results were found after CWI in the current study it is possible that the extra min of immersion employed by Gregson (15) explains the slight discrepancy. Similar to muscle temperature, these findings do not compare favourably to other modalities of locally applied cryotherapy such as ice bag or wet ice application. Other investigators have reported skin temperature reductions of between 21-25°C following the local application of various types of cryotherapy for 20-30 min (24). Based on the information reported by Bleakley and Hopkins (6) it can be deduced that, although a skin temperature reduction of within the 5-15°C range was reached after both CWI and WBC in the thigh, analgesia was not achieved as the skin temperature remained above the critical 12°C mark. Similarly, as a skin temperature of 12.5–13.5°C is required to observe a 10% decrease in nerve conduction velocity (23), although not measured as part of the current methodology, it can be assumed that a reduction in nerve conduction velocity of less than 10% would have been observed following both treatments.

A reduction in rectal temperature was observed 40, 50 and 60 min after both treatments compared to baseline ($P < 0.001$), but no significance was observed
between treatments. Our results are similar to the reductions reported by others after CWI’s (15), but data on the effects of WBC on core temperature are scant. Although, we have previously shown that WBC reduces tympanic temperature by 0.3°C (8), it has previously been reported that WBC exposure does not cause a change in rectal temperature in an older population (48 ± 7.9 years) (37). However, Westerlund and colleagues (37) utilised an exposure duration of 2 min shorter than the current study and only recorded data for 30 min after exposure despite a steady decline similar to the current study.

The thermodynamics of cryotherapy, or cooling, works on the principle that heat is transferred unidirectional from high heat to low heat (19). In essence, tissue temperature loses heat to the external cooling modality. Our results fit well with this concept as we see muscle temperature fall and the skin temperature increase after treatment. This transfer of heat from one body to another depends on several factors including the relative masses of the bodies, the size of the contact area, the difference in starting temperatures, the heat capacity of each material and the re-warming of the tissue from its own metabolic activity and perfusion (24). Considering the methodology of the two cooling modalities employed in the current study (WBC and CWI) the duration was the same (4 min), the masses of the bodies were the same during both treatment (randomized crossover), the contact area was similar (whole body versus heat out immersion) and the baseline temperature of the skin was similar. The major discrepancies between the modalities in the current study were the temperature difference of the two treatments (~118°C), the hydrostatic pressure of water and the difference in the ability of air and water to conduct heat.

The temperature of the muscle, skin and core did not return to baseline levels 60 min following treatment and this agrees with the finding of others (10). Furthermore, rectal temperature continued to decline up to 60 min after treatment. It has previously been reported that it may take as long as 4 hours for tissue temperature to return to baseline following cooling and both Merrick (24) and Enwemeka (14) have highlighted the need for continued monitoring of tissue temperature following the removal of the cooling agent. Therefore, an extended period of temperature
recording (60 min after both treatments) was utilised in the current study. The results of this study are limited to a homogenous group of active healthy male participants, between the ages of 18 to 35, as the depth of subcutaneous fat is a significant factor in the magnitude and rate of intramuscular cooling. The insulation effects of adipose tissue during cryotherapy treatment and re-warming after treatment has previously been established (28). The mid-thigh skinfold thickness of this group was 10.5 ± 5.9 mm and these results are similar to that of other studies using physically active male volunteers (36). Future research studying the effects of WBC is therefore warranted on females, who tend to have a different percentage and distribution of body fat.

One limitation of the present study was that methodological constraints did not allow the assessment of muscle, skin and rectal temperature on the same participants at the same time. However, we used a homogeneous population of healthy active males between the ages of 18-35, and the treatment protocols conditions remained constant throughout. As the equipment used in the current study was not functional in temperatures below -100°C, skin and rectal temperatures were not recorded during WBC or CWI. Furthermore, in an attempt to reduce the risk of infection, muscle temperature was not recorded during the treatments.

6.6 Conclusion
The present study demonstrates that a single WBC exposure decreases muscle and core temperature to a similar level of those experienced after CWI. Although both treatments significantly reduced skin temperature from baseline, WBC elicited a greater decrease compared to CWI. It is likely that the a temperature deficit of 118°C experienced during WBC exposure compensated for the reduced thermal conductivity of air compared to water. These data may provide a mechanistic rationale for the physiological changes reported following WBC exposure, which has previously only been speculated. As such, further investigation is warranted to explore the effects of a reduction in tissue temperature following WBC in athletic recovery and acute injury.
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6.7 References


Chapter 7

Discussion & Main Conclusions
7.1 Introduction

The current thesis was divided into two parts; Part 1 (Chapters 2, 3, 4) and Part 2 (Chapters 5, 6). The overall aim of Part 1 of this thesis was to assess the effects of cryotherapy on proprioception. To address this aim a systematic review of the literature, focusing on the effects of cryotherapy on JPS, was completed (Chapter 2). Following the recommendations provided in this systematic review, the effects of two commonly used modalities of cryotherapy, CWI and WBC, on knee joint position sense were explored (Chapters 3 and 4 respectively). In Part 1 of this thesis it became evident that research into the effects of cryotherapy, in particular WBC, on muscle, skin and core temperature was required and Part 2 helps address this paucity of research. As outlined in Chapter 5 little is known regarding the safe or optimal reductions in skin temperature following cryotherapy and several techniques of assessing skin temperature are being used in the literature. Chapter 5 critically reviews the use of one method, Infrared Thermal Imaging, and synthesises the effects of different cooling modalities on skin temperature around the entire body. This thesis culminates in Chapter 6, where the effects of WBC on muscle, skin and core temperature are established. Furthermore, Chapter 6 also compares the muscle, skin and core cooling potential of WBC and CWI. The concept, methodological design and rationale of Chapter 6 were based on the methodology and recommendations for future research established in Chapters 2, 3, 4 and 5. While the results of each chapter have been discussed individually, this chapter aims to combine all the finding and explore the overall conclusions from this Ph.D. work. Limitations of the work will also be considered and recommendations for future research will also be suggested.

7.2 Discussions of Results

Why is Cryotherapy Used?

As outlined in Chapter 1, various modalities of cryotherapy are used in medical, clinical, rehabilitative and sporting settings. The premise of cooling in each of these individual settings is different. Consequently, generic guidelines regarding the
optimal modality, duration and temperature are not available. In a clinical setting the local application of cryotherapy, including modalities such as ice packs, cold spray and cryotherapy cuffs are used to achieve a reduction in pain, swelling, muscle spasm and nerve conduction velocity (Knight, 1995). Although the guidelines are equivocal it has been suggest that to induce analgesia a skin temperature of 12°C, or less, is required (Bleakley et al., 2011, Bleakley and Hopkins, 2010, Bleakley et al., 2012). Furthermore, a tissue temperature of between 5-15°C is needed for a metabolic reduction. However, these guidelines are only applicable in a clinical setting during the management of acute injury or injury rehabilitation.

In an athletic setting, cooling is also used before exercise in the heat and after intense training. However, in this setting the optimal reductions in muscle, skin and core temperature are unknown. Pre-cooling enables an individual to start exercise with a cooler body temperature, increase their heat storage capacity and perform more work before reaching a limiting core body temperature (Marino et al., 2002, Quod et al., 2006). The benefits of lower limb, torso and whole body pre-cooling before exercise, especially in the heat, are documented within the literature (Marino et al., 2002, Quod et al., 2006, Ranalli et al., 2010). However, a core temperature reduction of 0.17 (Mitchell et al., 2003) to 1°C (Schmidt and Bruck, 1981) has been used and consensuses has yet to be reached regarding the optimal core temperature reduction during pre-cooling. Furthermore, despite a wealth of research published in the area in the last 30 years, very few practical recommendation have been made to athletes competing in the heat (Quod et al., 2006)

Cryotherapy is commonly used after exercise in an attempt to alleviate the debilitating effects of exercise induced muscle damage (Leeder et al., 2011). It is also used as a recovery strategy between training sessions completed on the same day (Vaile et al., 2008). Several groups (Leeder et al., 2011, Vaile et al., 2008, Goodall and Howatson, 2008, Wilcock et al., 2006) have suggested that cold may benefit athletic recovery by reducing muscle blood flow and tissue temperature. These reductions have been proposed as a mechanism by which cooling decreases inflammation induced via strenuous exercise (Leeder et al., 2011). To date, these
theories have not been fully elucidated and the effectiveness of cryotherapy as a treatment for EIMD is unclear.

As highlighted above it is commonplace for athletes to return to competitive activity, shortly or immediately after the application of a cold treatment. Unfortunately, there is little evidenced-based consensus on the effects of cooling on functional performance or whether cryotherapy could implicate sporting performance and injury risk (Bleakley et al., 2012). A recent systematic review (Bleakley et al., 2012) on the area suggests that an individual will probably be at a performance disadvantage if they return to activity immediately after cooling. This is based on reductions reported in upper (Chen et al., 2010) and lower limb (Howard et al., 1994) strength, vertical jump (Cross et al., 1996), agility (Patterson et al., 2008), speed (Fischer et al., 2009), performance accuracy (Wassinger et al., 2007), endurance (Petrofsky and Lind, 1980) and dexterity (Cheung et al., 2003) following various methods of cooling. The general consensus is that this decrease in functional performance is attributed to reductions in muscle and skin temperature. Consequently, it is has also been hypothesized that proprioception may also be reduced following cooling.

**Cryotherapy and Proprioception**

Proprioception is a complex entity encompassing several different components, such as the sense of position, velocity, movement detection, and force, (Gandevia and Burke, 1992, Lonn et al., 200). Proprioceptive information travels to the higher brain centres through the dorsal lateral tracts (conscious appreciation) and the spinocerebellar pathways (stimulation and regulation of motor activities) (Rieman and Lephart, 2002, Riemann et al., 2002). However, the afferent signals that give rise to proprioception may well have origin in various types of receptors (McCloshe, 1973) and the sources of conscious proprioceptive information potentially include joint, muscle, and cutaneous mechanoreceptors (Riemann et al., 2002, Burke et al., 1988, Proske et al., 1988, Wassinger et al., 2007). For a brief period in mid-1900’s it was speculated that joint receptors were the primary sources of proprioceptive input
(Matthews, 1982). However, there is a plethora of conflicting evidence supporting each tissue’s receptors (joint, muscle, and cutaneous) as the predominant source and this topic remains controversial (Riemann and Lephart, 2002). Riemann and Lephart (2002) have stated that the precise quantities being conveyed to both ascending tracts (dorsal lateral tracts and the spinocerebellar pathway) from each type of mechanoreceptor, as well as the temporal relationship between arrival at the cerebellum and the somatosensory cortex, remain unknown. Regardless of the source(s) of proprioceptive information, as cryotherapy has been shown to reduce nerve conduction velocity (Algafly and George, 2007), tissue (Gregson et al., 2011) and joint (Ohkoshi et al., 1999) temperature it is possible that proprioceptive acuity would be altered after cooling.

JPS is only one component of proprioception but it is regularly used in the literature as an indicator of proprioceptive acuity. As discussed in Chapter 1 the effect of EIMD (Saxton et al., 1995), age (Skinner et al., 1984), injury (Boyle and Negus, 1998), pain (Baker et al., 2002), neurologic disease (Wingert et al., 2009) and fatigue (Skinner et al., 1986, Ribeiro et al., 2011) on JPS have all been studied in the literature. Knee JPS was chosen as an outcome measure in the current thesis as decreases in knee JPS acuity has the potential to a) decrease athletic performance and b) predispose an individual to proprioceptive related injury (Surenkok et al., 2008, Costello and Donnelly, 2010, Costello and Donnelly, 2011, Costello et al., 2011, Oliveria et al., 2010). Knee injuries are common in athletic participation and the Anterior Cruciate Ligament (ACL) is the most frequently injured ligament requiring surgery in the United States, with 250,000 ruptures and 100,000 surgeries per annum (Genuario et al., 2012). The potential cost of knee related injuries are excessive and the cost of ACL surgery range from €3,772 to €5,789 (Janssen et al., 2011). The total estimated hospital costs associated with ACL reconstruction surgery are over €45 million per year in Australia alone (Janssen et al., 2011). In the United States these costs have been estimated at over one billion dollars (Kramer et al., 2007). Furthermore, the associated psychological effects of knee injury and the extended absence from playing time are detrimental to an athlete’s career (San Jose, 2003). Therefore, three chapters (Chapter 2, 3, 4) have sought to address the effects
of whole body cooling on proprioception, with a particular emphasis on JPS, in **Part 1** of this thesis.

**Chapter 2** systematically reviews the area of cryotherapy and JPS and provides the foundation for subsequent studies completed in **Chapter 3** and **4**. In the section titled ‘Recommendations for Future Research’ in **Chapter 2** it was highlights that, until now, no authors have addressed knee JPS after CWI or indeed JPS after exposure to WBC. **Chapters 3** and **4** aimed to address this gap in the literature. The findings of **Chapter 3** suggest that both weight-bearing and non-weight-bearing knee JPS were unaltered following a 30-minute CWI (14°C) to the level of the umbilicus. Similarly, in **Chapter 4** no differences in knee JPS, MVIC or force proprioception were observed after a 3 minute 20 second exposure to -110°C WBC.

These findings are similar to those described by others (Wassinger et al., 2007, LaRiviere and Osternig, 1994, Ozmun et al., 1996, Dover and Powers, 2004, Khanmohammadi et al., 2011) who found cryotherapy to have no effect on JPS. Four other studies (Hopper et al., 1997, Uchio et al., 2003, Surenkok et al., 2008, Oliveira et al., 2010) report contradictory finding to those presented in **Part 1** of this thesis. Furthermore, Sekihara et al (2007) found elbow JPS errors enhanced after bicep cooling, but their study combined cooling with thixotropy and muscle vibrations. As outlined in **Chapter 2**, methodological differences have prevented a direct comparison between **Chapter 3** and **4** and those reported in the literature. This difficulty is a result of differences in the joints being assessed, the modality of cooling and the measurement techniques used in the existing literature.

In the 7 studies reviewed in **Chapter 2** and the two additional studies (Oliveira et al., 2010, Khanmohammadi et al., 2011) published subsequently, 2 focused on the shoulder (Wassinger et al., 2007, Dover and Powers, 2004), 4 on the knee (Uchio et al., 2003, Surenkok et al., 2008, Ozmun et al., 1996, Oliveira et al., 2010), and 3 on the ankle (Khanmohammadi et al., 2011, Hopper et al., 1997, LaRiviere and Osternig, 1994). Cryotherapy modalities included a cooling pad (Uchio et al., 2003),
cold spray (Surenkok et al., 2008), cold water immersion (Khanmohammadi et al., 2011, Hopper et al., 1997, Ozmun et al., 1996, LaRiviere and Osternig, 1994) and some form of ice-pack application (Wassinger et al., 2007, Ozmun et al., 1996, Dover and Powers, 2004, Oliveira et al., 2010) for durations of 5 (LaRiviere and Osternig, 1994) to 30 (Surenkok et al., 2008, Dover and Powers, 2004) minutes have all been employed in the literature.

In Chapter 3 knee JPS was assessed using 3D motion analysis in the Biomechanics Lab on campus in the University of Limerick. This method of recording JPS was employed for a number of reasons. Firstly, this system has previously been shown to have excellent reliability for reporting knee motion (Ford et al., 2003). Moreover, after calibrating the system, in accordance with the manufactures guidelines, it was possible to record joint angle to 3 decimal places. This ensured that even small discrepancies in JPS error were detected. Finally, it was feasible to attach the reflective marker to the same position during pre-test and the subsequent post-tests. This was achieved by leaving the adhesive cloth the marker attached to the subject during water immersion and potentially increased the test re-test reliability of the technique. In Chapter 4 electrogoniometry was used to record the participants JPS. As data collection for this study (and Chapter 6) was completed off campus at the cryogenic chamber in Ennis, Co. Clare, it was not practicable to use the methodology employed in Chapter 3. It was not possible to transport the software or the hardware required for this method. Furthermore, there was no access to a ‘dark room’, which is essential for the reliability of the system, on the premises in Ennis. The use of electrogoniometry was chosen over other methods of assessing joint angles, such as 2D motion analysis or goniometry, as it has previously been validated (Rowe et al., 2001, Piriyparasarath and Morris, 2007, Kiran et al., 2010) and is frequently used in the literature to assess knee JPS (Pánics et al., 2008, Ghaffarinejad et al., 2007).

As outlined earlier, research encompassing the effects of cryotherapy and another component of proprioception, force reproduction, is severely limited. To date only two studies have assessed the effects of cooling on sub-maximal force reproduction (Tremblay et al., 2001, Rubley et al., 2003). The technique employed to assess sub-
maximal force reproduction, after WBC exposure in the current thesis, were heavily influenced by the methodologies of these studies (Tremblay et al., 2001, Rubley et al., 2003). The methodological design of Dover and Powers (2003) was also employed as they have provided an excellent reliability study on force proprioception. Although the modality of cooling was different, the findings of both Tremblay et al. (2001) and Rubley et al. (2003) are similar to those in Chapter 4. These groups also reported no reduction in participants’ ability to reproduce a sub-maximal force after cold water (Rubley et al., 2003) or ice pack application (Tremblay et al., 2001).

In addition, no reduction in knee extensor MVIC following WBC were found in Chapter 4. Several other studies using different modalities of cryotherapy have found contradictory results to these (Howard et al., 1994, Zhou et al., 1998, Dewhurst et al., 2010). However, these finding are similar to those of Westerlund et al. (2009) who reported that wrist flexion MVIC following WBC was not significantly reduced. For each 1°C reduction in muscle temperature it is believed that dynamic contractile force reduces by 4–6% (Bergh and Ekblom, 1979). The data on muscle temperature reported in Chapter 6 may help to explain these findings in Chapter 4.

In this thesis JPS, MVIC and force proprioception were assessed immediately after WBC exposure and again 15 later. Using an exposure duration of 40 seconds longer (also at -110°C), muscle temperature (3 cm subcutaneous) was not significantly different to baseline immediately after WBC and was only ~0.5°C lower 15 minutes after exposure. Based on the information provide by Bergh and Ekblom (1979) this is potentially an explanation for these findings. In addition, Zhou and colleagues (1998) found peak knee extension force decreased when quadriceps muscle temperatures were cooled below 34°C, with further decreases at 30°C (Dewhurst et al., 2010) reported in the literature. Deep muscle temperature in Chapter 6 remained above 34°C throughout the duration of testing, while superficial muscle temperature (1 and 2 cm subcutaneous) remained above 31°C.
The findings of Part 1 of this thesis suggested that proprioceptive acuity is not reduced following exposure to CWI or WBC. This suggests that the risk of proprioceptive related injury in not exaggerated following these treatments. However, based on the limited and ambiguous evidence provided in the literature, coaches and athletes need to be cognisant of the potential negative effects of cryotherapy on proprioception. Furthermore, the existing literature is limited, in terms of the methodological design and the statically analysis employed (Chapter 2). In the future, researchers must be cognisant of the importance of including reliable proprioceptive related outcome measures, sufficient sample sizes, power analysis and using the absolute mean error as the method of statistical analysis. Moreover, the inclusion of joint, muscle, skin, core and joint temperature is also required to establish what reductions are required to observe a reduction in JPS or any other form of proprioceptive. In summary, the conclusions drawn about the effects of cryotherapy on JPS following the systematic review in Chapter 2 are still applicable; “until further evidence is provided clinicians should be cautious when returning individuals to tasks requiring components of proprioceptive input immediately after a cryotherapy treatment” (Costello and Donnelly, 2010).

Whole Body Cooling and Muscle, Skin and Core Temperature

In Part 1 of this thesis the importance of reporting tissue temperature when assessing the effects of cooling on proprioceptive acuity were addressed. Unfortunately, due to methodological constraints this was not feasible in Chapters 3 or 4. The effects of different CWI protocols on muscle, skin and core temperature are reported in the literature (Gregson et al., 2011, Bleakley and Hopkins 2010, Peiffer et al., 2009a, Peiffer et al., 2009b). Therefore, in Chapter 3 it was possible to estimate the level of muscle, skin and core cooling experienced during the CWI treatment as others had employed a similar protocol (Peiffer et al., 2009a, 2009b). In Chapter 4 it became evident that limited data was available on the effects of WBC on skin, core and particularly muscle temperature. Furthermore, no authors have sought to compare the cooling potential of the two modalities of cooling (CWI and WBC). Part 2 of this thesis aimed to address this gap in the literature.
In order to reliably examine the effects of WBC on muscle, skin and core temperature it was important to use validated and reliable techniques. Several method of recording temperature, especially skin (Smith et al., 2010) and core (Morris et al., 2009) temperature have been used in the literature. However, the validity of these techniques often limits the quality of the research.

Core temperature, described more fully as deep body temperature, is relatively constant despite wide fluctuations in environmental conditions (Childs et al., 1999). In man, this temperature is close to 37°C (Edholm, 1978). The use of rectal temperature, as recommended by the National Athletic Trainers’ position statement (Binkley et al., 2002), was selected as a measure of core temperature because of its validity (Lee et al., 2002) and practicality of use in this type of investigation (Booth et al., 1997, Crowley et al. 1991, Marsh and Sleivert, 1999, Gregson et al., 2011). Furthermore, the probe was inserted to a depth of 10-12 cm past the anal sphincter based on the information provided by others (Marsh and Sleivert, 1999, Gregson et al., 2011). Tympanic temperature was used as an estimation of core temperature following WBC exposure in Chapter 4 but the limitations of this outcome measure, especially in extremely cold environmental conditions, have already been discussed (Chapter 4; methodological consideration). It is important to note that rectal temperature has been shown to significantly lag behind other core sites such as the oesophageal site, especially during acute temperature alterations (Robinson et al., 1998, Molnar and Read, 1974). To address this, rectal temperature was recorded for 60 minutes after exposure to both CWI and WBC.

Similarly, the technique of assessing muscle temperature used in Chapter 6 is the most commonly used method within the literature (Dewhurst et al., 2010, Gregson et al., 2011, Drust et al., 2005). In addition, as the temperature at different depths in the muscle are known to vary after cooling (Myrer et al., 2001, Enwemeka et al., 2002), the temperature at 1, 2 and 3 cm below the subcutaneous fat layer were recorded. The temperature in the vastus lateralis was chosen as this allowed for comparisons with existing literature using different modalities of cryotherapy (Dewhurst et al., 2010, Gregson et al., 2011).
The same rationale applied for thigh skin temperature (Westerlund et al., 2003, Enwemeka et al., 2002). However, the use of skin thermistors, the most commonly used method of assessing skin temperature, were considered problematic in the current research. As discussed in Chapter 5, few authors have considered the potential implications of using skin thermistors in cryotherapy research. Skin thermistors and thermocouples often consist of a thin metallic foil which serves as a heat spreader backed by a foam insulation pad. This has the potential of creating a layer of insulation over the area of skin being assessed and therefore significantly degrades the accuracy of the measured temperature (Boetcher et al., 2009). This artefact of testing, recording, and reporting erroneous skin temperature data is therefore troublesome, especially if the temperature of the skin is being assessed during (or after) a cryotherapy treatment. Although not commonly used in the literature, primarily due to the associated costs, infrared TI was considered the best method of assessing skin temperature in the current research. At the time of data collection, limited guidelines or information about the use of TI in sports medicine or cryotherapy research, were available. Therefore the objectives Chapter 5 were to establish (a) the effectiveness of TI in assessing skin temperature following cryotherapy and (b) the effect of different modalities on cooling on skin temperature.

A total of 18 articles were critically reviewed in Chapter 5. Although this method (TI) of assessing skin temperature is expensive and requires some technical training it offers several advantages over other methods currently available to researchers. These advantages include the capability to record the maximum, minimum, and average skin temperature; temperature variation over large areas of skin and the capacity to reanalyse data in the post process analysis. Furthermore, one of the techniques foremost advantages is the fact that there is no skin contact. Although further research is required, in terms of structuring specific guidelines and protocols, it was concluded that TI appears to be an accurate and reliable method of collecting skin temperature data following cryotherapy.
This thesis culminated in **Part 2 Chapter 6**. The necessity of establishing the effects of WBC on muscle temperature, in particular, was established in **Chapters 4 and 5**. As previously mentioned comparisons with the methodology of **Chapter 2**, in particular, were feasibly due to the wealth of research on the effects of cold water on tissue temperature (Bleakley and Hopkins, 2010, Gregson et al., 2011, Peiffer et al., 2009a, Peiffer et al., 2009b). Although alterations in other neuromuscular (NCV, firing rate) and hormonal (cortico-steroids) aspects may also be attributed to proprioceptive deficits, reductions in muscle and skin temperature have been credited as a potential mechanism for reduced proprioceptive acuity. Therefore, the aims of **Chapter 6** were to a) establish the reductions in muscle, skin and core temperature following WBC and b) compare these reductions to that experienced during a similar duration of CWI exposure.

The findings of **Chapter 6** suggest WBC reduces superficial and deep muscle temperature to a similar degree as CWI. The maximum reductions in both superficial (1cm: WBC, 1.6 ± 1.2°C; CWI, 2.0 ± 1.0°C; 2cm: WBC, 1.2 ± 0.7°C; CWI, 1.7 ± 0.9°C) and deep (3cm: WBC, 1.6 ± 0.6°C; CWI, 1.7 ± 0.5°C) muscle temperature were observed 60 minutes after exposure (at the end of the testing protocol). Interestingly, the reduction in muscle temperature observed in the thigh region following a 4 minute exposure to WBC and CWI do not compare well to those experienced following other modalities of locally applied cryotherapy. A locally applied 30-minute application of Wet-Ice for example has been shown to reduce quadriceps muscle temperature by 5.62°C and 8.44°C, at 1cm and 2cm subcutaneously respectively (Dykstra et al., 2009). Moreover, muscle temperature in the calf (3cm subcutaneous) has been shown to be reduced by almost 8°C after a 20-min crushed-ice pack application (Myrer et al., 2001). It is likely that the different cooling modality and longer duration used in these studies (Myrer et al., 2001, Dykstra et al., 2009) was responsible for the greater reductions in muscle temperature.
Immediately after treatment average, minimum and maximum skin temperature were 3.4°C, 4.4°C and 1.2°C cooler after WBC compared to CWI. As discussed in Chapter 6 (Section 6.5) this discrepancy may be a consequence of the friction created during towel drying following CWI. The minimum temperature (group average) was 13.2± 1.4°C and 20.1± 1.0°C after WBC and CWI respectively. Again these results do not compare well to other locally applied modalities of cryotherapy such as ice massage or crushed ice application (Herrara et al., 2010). A more detailed comparison of the effects of different cooling modalities on skin temperature is proved in Chapter 5 and by Blakeley and Hopkins (2010). As WBC is purported to be effective in the management of acute injury, these findings have several clinical and medical implications. Based on the information reported by Bleakley and Hopkins (2010) it can be deduced that, although a skin temperature reduction of within the 5-15°C range was reached after both CWI and WBC in the thigh, analgesia was not achieved as the skin temperature remained above the critical 12°C mark. Therefore, the effectiveness of these protocols during thigh injury rehabilitation is ambiguous.

The WBC and the CWI protocols employed in Chapter 6 differ from those utilised earlier in Chapters 3 and 4. There are two reasons why these protocols were modified. Firstly, by the time the research in Chapter 6 commenced, almost two years later after Chapter 4, the duration of exposure had being increase by the owners of the chamber. An exposure of 3 minutes at -110°C, preceded by 20 second in the -60°C chamber, was used in Part 1. However, a duration of 3 minutes and 40 seconds at -110 °C, also preceded by 20 second in the -60°C chamber, was being used by the clinic in the summer of 2011. As no guidelines for the temperature or duration of WBC have been providing within the literature, the research in Chapter 6 was based on the duration being employed by the owners and used by their clients at the time of data collection. Secondly, although Chapter 6 used a similar CWI protocol to Chapter 3, the duration and temperature of the immersion were different. In Chapter 4 it was suggested that CWI may elicit a greater reduction in muscle, skin and core temperature compared to cold air exposure. Therefore, the purpose of using an immersion duration of 4 minutes in Chapter 6 was to compare and contrast the two modalities (CWI and WBC). As the duration of immersion in Chapter 6 was
24 minutes shorter than the one used in Chapter 3 it was necessary to use a lower temperature. A temperature of 8°C was chosen based on research using a similar CWI protocol (Gregson et al., 2011). Consequently, the methodology of the two cooling modalities employed in the study (WBC and CWI) were similar in terms of duration (4 min), the masses of the bodies (randomized crossover) and the contact area (whole body versus heat out immersion), it was possible to compare and contrast the cooling potential of these two treatments. The major differences between the modalities were the temperature between the two treatments (~118°C), the hydrostatic pressure of water and the ability of air and water to conduct heat. Furthermore, comparing the effects of these two similar treatments (in terms of duration) was believed to be more beneficial for practitioners when considering what modality of cryotherapy to use for various reasons.

It was hypothesized in Part 1 that a healthy individual’s ability to derive knee JPS is capable of withstanding the degree of cooling experienced during the cooling protocols used in Chapters 2 and 3. However, JPS and proprioceptive acuity were recorded immediately after (Chapters 2 and 3) and 15 minutes (Chapter 3) after exposure to CWI and CWI. Significant differences from baseline muscle temperature were only observed 20 minutes after both CWI and WBC Chapter 6. Furthermore, Riemann and Lephart (2002) postulate that muscle spindles and joint receptors have a more significant role in joint proprioception than cutaneous afferents. Consequently, it is possible that any reductions in proprioceptive acuity would not have been observed until later that assessed in Part 1. As discussed in Chapter 5 and shown in Chapter 6, the maximum reduction of muscle temperature is routinely observed after the removal of cold, when the skin temperature has started to recover. As the focus of this thesis was to investigate the immediate effects of whole body cooling on proprioception, the effects of a delayed reduction in muscle temperature, following the removal of cryotherapy, warrants further investigation. Furthermore, the potential benefits of performing a warm-up on proprioceptive acuity following cooling needs to be examined.
Whole Body Cryotherapy and EIMD

As discussed in Chapters 1, 4 and 6 several claims have been made about the benefits of WBC as a treatment for muscle soreness following exercise. Chapter 4 was the first controlled study which sought to assess the effects of WBC as a treatment following EIMD. Although MVIC significantly declined from 806 ± 138 to 483 ± 122N immediately after the damaging protocol (P < 0.05) and recovered thereafter to 98.7 ± 12.3% of pre exercise values 96 hours after exercise, no differences were observed between treatments. Similarly, no significant differences in peak power output or muscle soreness were observed between groups.

These results are in agreement with others who have used various modalities of cryotherapy, including ice massage (Isabell et al., 1992, Yackzan et al., 1984, Howatson and van Someren, 2003, Howatson et al., 2005) and cold water immersion (Howatson et al., 2009, Eston and Peters 1999; Goodall and Howatson 2008; Paddon-Jones and Quigley 1997; Sellwood et al. 2007) as a method of recovery following EIMD. A recent systematic review by Leeder and colleagues (2011) concluded that CWI is an effective strategy to reduce delayed onset muscle soreness following a range of exercise types. However, Torres et al (2011) have suggested there is a lack of evidence to support the use of cryotherapy, stretching and low-intensity exercise relief of symptoms and signs of exercise-induced muscle damage. Interestingly, the mechanisms by which cooling are believed to be beneficial remain elusive (Leeder et al., 2011, Torres et al., 2011).

Since the online publication of Chapter 4 in the Scandinavian Journal of Medicine and Science in Sports, a further two studies have assessed the effectiveness of WBC as a treatment following EIMD (Hausswirth et al., 2011, Pournot et al., 2011). Pournot and colleagues (2011) used a 48 minute simulated trail running race (15 minutes downhill) to induce EIMD in 11 endurance trained males. In a randomized crossover design participants were treated with either passive recovery or 3 minutes -110 °C WBC, one hour post and daily for 4 days after exercise. The inflammatory markers IL-1β (Post 1 hour) and protein C-reactive (Post 24 hours) levels decreased
and the natural inhibitor of the pro-inflammatory IL1β (Post 1 hour) increased following WBC when compared to passive recovery. Overall, the authors conclude that WBC was effective in reducing the inflammatory process. Using the same simulated race as Pournot et al. (2011), Hausswirth and colleagues (2011) found maximal isometric voluntary contractions of the knee extensors and perceived sensations were recovered after the first WBC session (one hour post). Although no differences in plasma CK activity were recorded between conditions the authors (Hausswirth et al., 2011) also concluded that three exposures to WBC (one hour post, 24 and 48 hours post) accelerates recovery from EIMD to a greater extent than passive recovery.

The disparity between the findings of these studies (Pournot et al., 2011, Hausswirth et al., 2011) and those in Chapter 4 of this thesis may be attributed to the methodological designs employed. Firstly, the participants in the studies of Pournot et al. (2011) and Hausswirth et al. (2011) were well trained athletes who completed a simulated race on a treadmill. This trial consisted of 15 minutes downhill running, which the authors suggest is well-known to induce muscle damage. However, this duration a) appears shorter than those cited in the methodology (Easthope et al., 2008 = 55 km road race, Braun and Dutto, 2003 = 30 minutes downhill running; Chen et al 2008 = 30 minutes downhill running) and b) may not be damaging for well-trained athletes. In addition, the participants in Chapter 4 (who were active at least 3 times per week) performed a controlled bout of 100 eccentric contractions on an isokinetic dynamometer which has previously been shown to induce muscle damage (Mackey et al., 2004). Secondly, Hausswirth et al. (2011) and Pournot et al. (2011) exposed their volunteers to WBC one hour after exercise and again 24 and 48 hours after exercise (Pournot et al. (2011) also treated 72 and 96 hours post exercise) while participants were treated twice (separated by two hours) 24 hours after exercise in this thesis. The rationale for waiting 24 hours before treating the participants in Chapter 4 was that it accurately represented the way the Irish population use WBC and the time when muscle soreness peaks after EIMD (Cleak and Eston, 1992, Cheung et al., 2003 Howatson and Van Someren, 2008, Howatson et al., 2009). Thirdly, Hausswirth et al. (2011) and Pournot et al. (2011) used a homeoegous group of male participants, while a group of healthy male and female
volunteers was used in this Chapter 4. A significant gender effect in serum CK activity, inflammatory cell infiltration, and activation of protein degradation pathways has previously been reported in the literature (Stupka et al., 2000) following a similar protocol to the one used herein. Consequently, the contradictory findings reported in these studies (Hausswirth et al., 2011, Pournot et al., 2011) and those reported in this thesis may be attributed to the different methodologies employed. As no blood samples were collected in this thesis, inflammatory markers were not measured and further compassions between these studies are not possible.

In conclusion, despite reports showing WBC to be effective if athletes are exposed one hour after exercise, the findings of Chapter 4 suggest that that WBC is ineffective as method of improving recovery when used 24 hours after eccentric exercise.

7.3 Limitations and Recommendation for Future Research

The limitations of the individual chapters have previously been addressed. This section will focus on the limitation of the thesis a whole.

- The primary focus of this thesis was to investigate the effects of whole body cooling on proprioception, with particular emphasis on knee JPS. Force reproduction was also addressed in Chapter 4. Other components of proprioception including touch acuity, balance, kinaesthesia and JPS in ankle, shoulder, elbow and wrist warrant further investigation after cryotherapy.

- The findings of this thesis are limited to a group of young, healthy, active participants. Part 2 of this thesis is limited to a male population. Future research should examine the effects of cooling on proprioception in an injured or elderly population.

- The procedures, in terms of duration and temperature, employed in this thesis were based on previous research or anecdotal reports. Although there is evidence to support the use of pre-cooling before exercise in the heat, the effectiveness of cryotherapy as a treatment for EIMD has not been elucidated. Consequently, further research is required to establish the optimal reduction in core temperature.
for pre-cooling and the effectiveness of cryotherapy as a method of recovery from intense exercise.

- The WBC and the CWI protocols used in Part 1 and Part 2 of this thesis are different. The rationale for this is explained in the Section 7.2.

- This thesis focused on skin and muscle temperature in the thigh. Temperature reductions in other muscle groups, such as the gastrocnemius, following WBC are required. In addition, as WBC is usually repeated on the same day, the effects of several WBC exposures on muscle, skin and core temperature needs to be established.

- Although the volunteers who participated in Chapter 3, 4 and 5 were unaware of the working hypothesis, it was not possible to blind them to the treatment they received (cold or control). Furthermore, due to methodological constraints the assessor was not blinded to the treatment each participant received.

- Two potential contributing factors to proprioceptive acuity joint temperature and nerve conduction velocity were not assessed in this thesis. Research is required to determine the effect of whole body cooling, especially WBC, on these outcome measures.

- Future research is required to establish the effects of cooling, especially WBC, on other neuromuscular aspects of muscle function including the H-reflex, M wave, V wave and muscle fibre conduction velocity.

- The eccentric exercise bout used in Chapter 4 may not accurately reflect the soreness and damage experienced during participation during other exercise. The level of muscle damage experiences after this protocol may be more extreme than after normal training. Furthermore, no blood samples were collected in this thesis and consequently neither blood markers of muscle damage nor markers of inflammation were measured.
7.4 Main Conclusions
Several novel findings regarding the effects of whole body cooling on; proprioception, muscle skin and core temperature and EIMD were presented in this thesis. In summary based on this work (and on the treatment protocols used in this work):

- CWI does not reduce weight-bearing or non-weight-bearing knee JPS
- WBC does not reduce knee JPS
- WBC does not reduce force proprioception in the knee extensors
- WBC does not reduce MVIC of the knee extensors
- WBC is ineffective as a method of reducing muscle force loss and soreness when used 24 hours after eccentric exercise.
- WBC reduces muscle temperature (1, 2 and 3 cm subcutaneous) in the vastus lateralis
- WBC treatment reduces rectal and tympanic temperature by ~0.3°C
- The core and muscle cooling potential of a 4 minute exposure to CWI and WBC are similar
- Infrared thermal imaging has several advantages over other methods of assessing skin temperature in cryotherapy research
- WBC reduces thigh average, maximum and minimum skin temperature.
- WBC elicits a greater reduction in skin temperature immediately after exposure when compared to a similar duration of CWI

7.5 Perspective and Implications of this Thesis
This thesis explored a number of exiting and novel theories regarding the use of WBC and CWI. In sports medicine, the use of WBC and CWI, either before or between athletic participation, has been supported for various reasons. In addition, as
whole body cooling is used in a clinical and a rehabilitative setting and this thesis has several implications for clinicians, practitioners, coaches and athletes alike.

The findings of this thesis suggest that WBC and CWI do not increase the risk of proprioceptive related injury. Furthermore, WBC does not appear to be deleterious to muscle force production. Therefore, the use of either of these methods of whole cooling does not appear to predispose injury or cause a detriment in muscle performance. However, as the existing literature on the effects of other modalities of cooling on proprioception and athletic performance are contradictory, caution is still advised if returning individual to sporting activities after cryotherapy.

It is believed that cryotherapy reduces pain, swelling and oedema by reducing skin and muscle temperature. It has also been postulated that cryotherapy improves recovery by the same mechanism. However, few studies have examined the physiological effects of WBC. This is the first time the effects of WBC on muscle temperature have been reported. It is also the first time the muscle, skin and core cooling potential of WBC has been compared to a more established method of cryotherapy (CWI). Although, similar reductions in muscle and core temperature were observed after both modalities, WBC elicited a greater reduction in skin temperature immediately after exposure. However, the clinical significance of these reductions is ambiguous as skin temperature did not reach the critical 12°C mark required for analgesia. Moreover, findings from this work also indicates that WBC administered 24 hours after eccentric exercise, is ineffective in alleviating muscle soreness or enhancing muscle force recovery.

This information will provide guidance for coaches and athletes when using cryotherapy before or after exercise. The finding of this thesis will also will provide direction to clinicians when deciding what modality of cryotherapy to use after acute injury or in a rehabilitation setting. These data may provide a mechanistic rationale for the purported physiological changes following WBC exposure, which has previously only been speculated. As such, further investigation is warranted to
explore the effects whole body cooling on joint temperature, acute injury and on athletic recovery.

7.6 Guidelines for the Practitioner
Based on the treatment protocols used in this work:-

- Pre-cooling using CWI or WBC does not appear to increase the risk of proprioceptive related injury.
- WBC employed 24 hours post exercise is not, in itself, an effective treatment for muscle soreness recovery.
- Both WBC and CWI reduce muscle and core temperature to a similar degree. Neither treatment reached the recommended 12°C skin temperature mark required to achieve an analgesic effect.

7.7 References


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Appendices
Cryotherapy and Joint Position Sense in Healthy Participants: A Systematic Review

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**Objective:** To (1) search the English-language literature for original research addressing the effect of cryotherapy on joint position sense (JPS) and (2) make recommendations regarding how soon healthy athletes can safely return to participation after cryotherapy.

**Data Sources:** We performed an exhaustive search for original research using the AMED, CINAHL, MEDLINE, and SportDiscus databases from 1973 to 2009 to gather information on cryotherapy and JPS. Key words used were cryotherapy and proprioception, cryotherapy and joint position sense, cryotherapy, and proprioception.

**Study Selection:** The inclusion criteria were (1) the literature was written in English, (2) participants were human, (3) an outcome measure included JPS, (4) participants were healthy, and (5) participants were tested immediately after a cryotherapy application to a joint.

**Data Extraction:** The means and SDs of the JPS outcome measures were extracted and used to estimate the effect size (Cohen d) and associated 95% confidence intervals for comparisons of JPS before and after a cryotherapy treatment. The numbers, ages, and sexes of participants in all 7 selected studies were also extracted.

**Data Synthesis:** The JPS was assessed in 3 joints: ankle (n = 2), knee (n = 3), and shoulder (n = 2). The average effect size for the 7 included studies was modest, with effect sizes ranging from 0.08 to 1.17, with a positive number representing an increase in JPS error. The average methodologic score of the included studies was 5.4/10 (range, 5–6) on the Physiotherapy Evidence Database scale.

**Conclusions:** 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.

**Key Words:** cryotherapy, somatosensory system, proprioception, therapeutic modalities

**Key Points**
- Because of a limited number of publications, the potential for cryotherapy to degrade joint position sense is unknown.
- An increase in joint position sense error after cryotherapy has been demonstrated in 3 studies. Therefore, clinicians should be cautious in returning an athlete to dynamic activities immediately after a cryotherapy treatment.

Cold, in the form of cryotherapy, has been used since the time of the ancient Greeks, as an analgesic to reduce inflammation after acute musculoskeletal injury or trauma. Cryotherapy is commonly used to reduce tissue temperature, metabolism, inflammation, pain, circulation, tissue stiffness, muscle spasm, and symptoms of delayed-onset muscle soreness. Cryotherapy protocols, including ice application, water immersion, and commercially available cooling pads, are used by athletic trainers despite the lack of conclusive scientific research regarding the potential risks facing athletes or patients. Although the potential negative effects of cryotherapy itself and its possible influence on proprioception are unknown and despite equivocal evidence supporting its effectiveness, some clinicians continue to use cryotherapy in the treatment of acute soft tissue injury and to alleviate the symptoms of delayed-onset muscle soreness.

The effect of cryotherapy on proprioception, which is a component of the somatosensory system, is poorly understood. Proprioceptive acuity has previously been defined as an individual’s ability to sense joint position, movement, and force to discriminate movements of the limbs. Consequently, proprioceptive acuity is an essential component of injury prevention and rehabilitation, but it is often ignored with devastating consequences, because proprioceptive deficits may be responsible for many acute ankle and knee injuries. The term proprioception, developed as a result of Sherrington’s landmark work in the early 1900s, is commonly defined as the cumulative neural input to the central nervous system from mechanoreceptors. These receptors are located in the joint capsules, ligaments, muscles, tendons, and skin to detect stimuli such as pain, pressure, touch, and movement. Therefore, their function is critical to both sport performance and activities of daily living.

A number of techniques for clinically examining proprioceptive acuity are described in the literature, including threshold detection of passive movement, the absolute method, and joint position sense (JPS). An individual’s JPS primarily determines his or her ability to perceive a target joint angle or limb position and then, after the limb has been returned to its starting position, to reproduce the predetermined angle. The conscious ability to position a limb is a highly specialized proprioceptive function and is a vitally important clinical outcome measure, involving both the control of movement and stability. The JPS tests are routinely administered by clinicians to assess any proprioceptive deficits in the knee.
joint after anterior cruciate ligament injury,7,17–19 stretching,20 fatigue,14,21,22 pain,16 patellar taping,23,24 and cooling.12,25–30 The primary reason JPS is assessed by clinicians is to identify any reduction that may predispose an individual to proprioception-related injury.4,7–9,12,25–30

A systematic review is necessary to evaluate the effects of locally applied cryotherapy to a joint, specifically in relation to JPS. The brevity of quality research addressing the potential for cryotherapy, when applied to a joint, to reduce JPS and hence to potentially predispose an individual to injury needs to be addressed through further research. Similarly, no review authors have systematically evaluated the available literature regarding the effect of cryotherapy on proprioception or JPS. A comprehensive summary of the available literature is needed, so that both the health care profession and the sporting community alike can make educated clinical decisions as to how soon healthy athletes can train or compete after cryotherapy. Our purpose was to search the English-language literature for original research addressing the effect of cryotherapy on JPS and to recommend how soon healthy athletes can safely return to participation after a cryotherapy treatment.

METHODS

Search Strategy

We performed an exhaustive search for original research using AMED (1986–May 2009), CINAHL (1981–May 2009), MEDLINE (1973–May 2009), and SportDiscus (1982–May 2009) to gather information on cryotherapy, proprioception, and JPS. Searches were performed using the key terms cryotherapy and proprioception, cryotherapy and joint position sense, cryotherapy, and proprioception. Potentially relevant articles were also obtained by physically searching the bibliographies of included studies to identify any study that may have escaped the original search. A total of 74 articles were identified (Figure 1).

Study Selection

The criteria for study selection were (1) the literature was written in English, (2) participants were human, (3) JPS was included as an outcome measure, (4) participants were healthy, and (5) participants were tested immediately after a cryotherapy application to a joint. Articles were excluded if the title or abstract did not meet the inclusion criteria. We then obtained the full text of each relevant study to see if the study could be included in this systematic review. Ultimately, the article had to address at least 1 outcome measure of JPS before and after a cryotherapy application.

Assessment of Methodologic Quality

A total of 7 studies, which provided at least 1 outcome measure of JPS before and after a cryotherapy treatment, were included. The Physiotherapy Evidence Database (PEDro) scale was used to rate the quality of the selected articles. The PEDro scale is an 11-item scale designed for rating the methodologic quality of randomized controlled trials.31 Each satisfied item (except for the first item, which relates to external validity) contributes 1 point to the total PEDro score.31 The items include random allocation; concealment of allocation; comparability of groups at baseline; blinding of patients, therapists, and assessors; analysis by intention to treat; and adequacy of follow up.32 The PEDro scale gives a potential scoring range of 0 to 10, where 0 points (the worst possible score) are awarded to a study that fails to satisfy any of the included items and 10 points (the best possible score) are awarded to a study that satisfies all included items. Studies scoring 9 or 10 on the PEDro scale are considered to have methodologically excellent internal validity, those scoring 6 to 8 are considered good, those scoring 4 or 5 are fair, and those scoring less than 4 are poor.33 Two evaluators who had previous experience with the PEDro scale first scored each study individually. Together, the reviewers then discussed the methodologic quality of each study before agreeing on the final score. All studies graded using the PEDro scale were included.

Data Extraction and Statistical Analysis

In order to calculate effect sizes and associated 95% confidence intervals for the change in JPS before and after the cryotherapy treatment, we computed the Cohen d by the following method: ([mean of posttest] – [mean of pretest])/(pooled SD of pretest and posttest).34 To interpret the strength of the effect sizes, values from 0 to 0.2 were considered weak; 0.21 to 0.5, modest; 0.51 to 1, moderate; and greater than 1, strong.35 Figures 2 through 4 illustrate the point estimates for the effect sizes and associated 95% confidence intervals for the studies conducted on the shoulder, knee, and ankle, respectively.

The quality of the evidence was then assessed using the Strength of Recommendation Taxonomy (SORT).36 The SORT gives a recommendation level to individual studies of 1 through 3, where 1 indicates good-quality patient-oriented evidence, 2 indicates limited-quality patient-oriented evidence, and 3 indicates non–patient-oriented evidence or other evidence.36,37 The SORT also included a strength of recommendation that ranges from A to C.36 A indicates a recommendation based on consistent and good-quality patient-oriented evidence, B indicates a recommendation based on inconsistent or limited-quality patient-oriented evidence, and C indicates a recommendation based on consensus, usual practice, opinion, disease-oriented evidence, or case series for studies of diagnosis, treatment, prevention, or screening.36

DATA SYNTHESIS

Study Quality

The average PEDro score for the 7 articles was 5.4/10 (range, 5–6; mode = 5, median = 5; Table). The SORT also included a

The Effects of Cryotherapy on JPS in Healthy Participants

Seven articles met the inclusion criteria for this review (Table). In the 7 studies, 204 participants (77 men, 112 women; the sex of 15 participants was unknown28) were tested. The mean number of volunteers per study was 29.1 ± 11.5, with a mean age of 22 ± 1.6 years.

The 7 studies reviewed herein assessed 3 specific joints after a cryotherapy intervention: the ankle,26,29 knee,27,28,30 and shoulder.12,25 The modality for assessing JPS was...
primarily unilateral active joint repositioning, with only Surenkok et al using a passive reproduction test. Active joint repositioning was selected primarily because active testing is believed to be more functional than passive testing. Two methods of limb positioning or placement at the target angle were reported in the literature, namely passive and active. Three groups assessed individuals' self-reported dominant limb, classified as one's kicking leg or throwing shoulder arm; 1 group chose the left limb only; 2 groups randomly choose the tested limb; and only 1 group assessed both limbs.

Cryotherapy was judged to have negatively affected JPS if the degree of positional error was greater posttreatment when compared with baseline or control results. The α level was set at .05 for all 7 studies. Cryotherapy had a negative effect on JPS in 3 studies, whereas cryotherapy had no effect on JPS in 4 studies. All investigators included a pretest-posttest within-subjects design with a cryotherapy application.

Three of the groups that administered a superficial ice application reported no change in JPS posttreatment. Dover and Powers and Wassinger et al both applied cubed ice, contained in a bag, for durations of 30 minutes and 20 minutes, respectively, to the shoulder. Although Wassinger et al reported no differences in positional error after the ice application, they noted a decrease in movement patterns and throwing accuracy after treatment. Similarly, Ozmun et al applied an ice pack to the knee for 20 minutes, but they did not state if their ice packs were commercially available or constructed by them specifically for this purpose. Also, the focus of Ozmun et al appeared to be on movement reproduction pattern and not joint angle reproduction. All the researchers reported their result in degrees, except Wassinger et al, who reported positional error in centimeters of vertical displacement.

Figure 1. Flow chart describing the selection and exclusion of articles. PEDro indicates Physiotherapy Evidence Database.
<table>
<thead>
<tr>
<th>Authors</th>
<th>PEDro Score; Missing Items</th>
<th>Cryotherapy Protocol</th>
<th>Joint</th>
<th>No. of Participants</th>
<th>Propiroceptive Test</th>
<th>Instrument Used</th>
<th>No. of Trials</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wassinger et al12</td>
<td>5; no random allocation, no concealed allocation, no blinding</td>
<td>Ice bag, filled with 1500 g cubed ice, applied to the acromion and secured by elastic bandage for 20 min</td>
<td>Shoulder</td>
<td>22</td>
<td>AR while standing after passive placement in 2 target positions: 90° of shoulder flexion to 20° of flexion and 20° of flexion to 90° of flexion</td>
<td>Biodex&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3 in each direction</td>
<td>&gt;.05 (all trials)</td>
</tr>
<tr>
<td>Dower and Powers25</td>
<td>6; no concealed allocation, no blinding</td>
<td>1 kg cubed ice applied to the tip of the acromion, covering the deltoids and lateral scapula for 30 min</td>
<td>Shoulder</td>
<td>30</td>
<td>AR while standing after an actively assisted placement in 2 target positions: 90% of total external rotation and internal rotation</td>
<td>Inclinometer</td>
<td>3 in each direction</td>
<td>.181</td>
</tr>
<tr>
<td>Hopper et al26</td>
<td>5; no random allocation, no concealed allocation, no blinding</td>
<td>Ice-water immersion of the ankle for 15 min at 5°C to depth of 5 cm above the medial malleolus</td>
<td>Ankle</td>
<td>49</td>
<td>AR after passive placement at 40% and 80% of active full range of inversion</td>
<td>Pedal goniometer</td>
<td>3 in each section</td>
<td>.049&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Uchio et al27</td>
<td>5; no random allocation, no concealed allocation, no blinding</td>
<td>Icing System 2000&lt;sup&gt;c&lt;/sup&gt; cooling pad applied to 1 knee for 15 min at 4°C</td>
<td>Knee</td>
<td>20</td>
<td>Cybex dynamometer&lt;sup&gt;d&lt;/sup&gt;</td>
<td>10</td>
<td>0.003&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Surenkok et al28</td>
<td>5; no random allocation, no concealed allocation, no blinding</td>
<td>(1) Cold pack applied to cover the knee joint and secured by elastic bandage for 30 min, temperature NA; (2) cold spray (ethyl chloride) applied to the knee until participants reported a feeling of cold, temperature NA</td>
<td>Knee</td>
<td>15</td>
<td>Cybex dynamometer</td>
<td>4</td>
<td>&lt;.05&lt;sup&gt;b&lt;/sup&gt; (all trials)</td>
<td></td>
</tr>
<tr>
<td>LaRiviere and Osternig29</td>
<td>6; no concealed allocation, no blinding</td>
<td>Ice immersion of the ankle to 4 cm distal from the knee joint line for 5 and 20 min at 4°C</td>
<td>Ankle</td>
<td>31</td>
<td>Cybex isokinetic dynamometer&lt;sup&gt;d&lt;/sup&gt;</td>
<td>4 at each angle</td>
<td>&gt;.05 (all trials)</td>
<td></td>
</tr>
</tbody>
</table>
a result, although Wassinger et al.\(^1\) had a substantial intraclass correlation coefficient of 0.61 to 0.8 between trials for the assessment of proprioception on the electromagnetic tracking device, the findings of this study are hard to interpret and correlate with the literature. Nonetheless, all 3 authors\(^{12,25,30}\) using an ice application concluded that cryotherapy did not adversely affect JPS at the location measured. The point estimates of effect sizes for these 3 studies ranged from −0.08 to 0.28 (Figures 2 and 3), with a positive effect size reflecting an increase in JPS error. Most of the 95% confidence intervals around these points crossed zero, which indicates that a reduction in JPS was unlikely. Therefore, a superficial ice application appeared to have little effect on JPS.

Two groups\(^{27,28}\) employing a cooling pad to the knee for a period of 15 minutes and 30 minutes, respectively, between tests, found that knee joint repositioning was affected posttreatment (\(P < .05\)). Unfortunately, the results of these studies (Table) are difficult to compare because Surenkok et al.\(^{28}\) failed to state the temperature of their cooling pad and used passive joint reposition, compared with Uchio et al.,\(^{27}\) who employed active testing after using a cooling pad maintained at 4°C. Despite the methodologic differences, Uchio et al.\(^{27}\) found a reduction in their participants’ level of accuracy in matching knee joint placement immediately posttreatment of 1.7° ± 2.1° postcooling (\(P < .05\)), although the reduction was not significant 15 minutes later (0.9° ± 1.7°, \(P > .05\)). This reduction was reported by the authors\(^{28}\) as similar to that of an individual with a cruciate ligament injury who is receiving potentially inadequate position sense feedback for athletic activity. Similarly, Surenkok et al.\(^{28}\) reported inaccuracies in JPS posttreatment of 1.05° ± 1.09° and 0.4° ± 2.66° using 2 separate movement protocols (extension to flexion and flexion to extension, respectively). The results of the effect size analysis (Figure 3) for the studies using a cooling pad are less consistent, with point estimates ranging from 0.09 to 0.9 (weak to moderate); positive effect sizes indicate an increase in joint repositioning sense error. Even though Surenkok et al.\(^{28}\) reported a reduction in JPS error, the 95% confidence intervals for both trials using the cooling pad crossed zero. However, the study conducted by Uchio et al.\(^{27}\) had a moderate effect size, and the 95% confidence interval did not cross zero. These findings suggest that using a cooling pad may be more effective in achieving greater reductions in joint, skin, and intramuscular temperatures but, as temperature changes were not reported by Surenkok et al.,\(^{28}\) this possibility is difficult to confirm.

The 2 groups\(^{26,29}\) using a water-immersion cryotherapy protocol found different results for ankle JPS. Both Hopper et al.\(^{26}\) and LaRiviere and Osternig\(^{29}\) used similar immersion durations (15 and 20 minutes, respectively) and water temperatures (4°C and 5°C, respectively), and neither group immersed the knee joint (Table). Hopper et al.\(^{26}\) found JPS in the ankle reduced by 0.5° ± 0.75° after an ice-water immersion at 4° for 15 minutes. However, they concluded that a decrease of 0.5°, although statistically significant, would not be deemed clinically significant. These results are in contrast to those of LaRiviere and Osternig,\(^{29}\) who found ankle JPS unaffected after water immersion. This difference is also recognizable in relation to effect size (Figure 4). Hopper et al.\(^{26}\) unanimously

### Table. Continued

<table>
<thead>
<tr>
<th>Authors</th>
<th>PEDro Score; Missing Items</th>
<th>Instruments Used</th>
<th>Proprioceptive Test Used</th>
<th>Muscle Force Testing Protocol</th>
<th>Cryotherapy Protocol</th>
<th>Joint Placement Measured</th>
<th>Error Measure</th>
<th>Intraclass Correlation Coefficient</th>
<th>Reporting Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ozmun et al.</td>
<td>6; no concealed allocation, no blinding</td>
<td>Kin-Com, Cybex International, Isokinetic International, Biodex Medical Systems, Inc, Nippon Sigmax Co, Ltd, Tokyo, Japan, Isokinetic International, Harrison, TN.</td>
<td>All after passive placement, angles measured between 90° and 60°, 60° and 30°, and 30° and full extension</td>
<td>Dynamometer, electromechanical dynamometer, Cybex International, Inc, Medway, MA.</td>
<td>2 ice packs applied to the left knee for 20 min; 1 left knee for 20 cm above and covered 10 cm above and below the patella and the other the popliteal space</td>
<td>Between tests, found that knee joint repositioning was affected posttreatment ((P &lt; .05))</td>
<td>Between tests, found that knee joint repositioning was affected posttreatment ((P &lt; .05))</td>
<td>0.61 to 0.8 between trials</td>
<td>Reported statistical significance if 0.05 was met.</td>
</tr>
</tbody>
</table>
showed a reduction in JPS after immersion, with a modest effect size for 40° of inversion and a strong effect for 80° of inversion; neither 95% confidence interval crossed or came close to crossing zero, indicating a significant effect. Conversely, both tests conducted by LaRiviere and Osternig had weak effect sizes, and both 95% confidence intervals crossed zero. Two possible explanations could account for the disparity in the studies: the different predetermined test angles and participant positioning during testing. Hopper et al.26 assessed each volunteer’s ability to match a predetermined angle of 40° and 80° of the individual’s full range of ankle inversion while seated, whereas LaRiviere and Osternig assessed 30° and 40° of ankle flexion in a supine position. Because both used similar treatment protocols but found different results, the effect of cold may be angle dependent.

Based on this evidence, it appears that some cryotherapy modalities may adversely affect components of JPS. We have awarded the current evidence a level of 2, with a grade of B on the SORT scale, as the result of methodologic design variations and inconsistencies in the findings of the reviewed studies.

**DISCUSSION**

*Joint position sense* has been defined as the awareness of the position of a joint in space, and the term is used erroneously as a synonym for *proprioception* within the literature. This is primarily because *proprioception* encompasses a number of different components, including kinesthesia, somatosensation, balance, reflexive joint stability, and JPS.28,30,39 To date, 7 groups12,25–30 have addressed the effect of cryotherapy on JPS, with conflicting results. Four groups of authors12,25,29,30 found cryotherapy had no effect on JPS, whereas 3 others26–28 found JPS was reduced after cryotherapy. Given the pressure on athletes to maximize their availability and possible performance enhancements in endurance events after cryotherapy, individuals may sometimes be required to either train or return to competition after a cryotherapy treatment.26 Despite the general consensus that cryotherapy is an effective analgesic, clinicians are concerned about the potential effects of cryotherapy on an individual’s neuromuscular functioning.12,27,40

**Absolute mean error** proved the most common measurement in the analysis of JPS throughout the reviewed studies.12,25–29 This method has been defined by Olsson et al.41 as the average actual errors on a number of trials, ignoring the direction. Two groups25,29 measured variable error, defined as the SD of a number of trials.41 In addition, only 2 groups25,26 assessed constant error, which is similar to absolute mean except that it takes directional error into account.41 Ozmun et al.30 used the most accurate trial, determined as the most accurate reproduction of the
predetermined angle, for statistical analysis. We believe that this may be a factor in the authors’ finding that ice application had no effect on JPS. However, the authors still reported an average 2° error across all 3 trial angles after cryotherapy when compared with control. If the authors had analyzed mean error, they might have found a statistically significant reduction in knee JPS after cryotherapy. Using the most (or the least) accurate trial has the potential to increase the risk of an unbalanced method of data recording when trials that produced either a greater or lower degree of angle error are disregarded. Using the mean of a number of trials would, therefore, give a better indication of an individual’s joint position accuracy.

**Cryotherapy Modalities and Degrees of Muscle and Joint Cooling**

The disparity in findings reported in the literature is likely to result from the methodologic differences in individual studies. Cryotherapy modalities varied from ice-pack application to water immersion and durations from 5 to 30 minutes. Also, the outcome measures assessed varied from active to passive reproduction and incorporated different anatomical locations, including the shoulder, knee, and ankle.

Surenkok et al were the only investigators to employ proprioceptive tests (JPS and static balance) after 2 separate cryotherapy interventions in a crossover study design. The tests were completed after the application of cold spray (ethyl chloride applied to the knee until volunteers reported a feeling of cold), and after 1 week, the same testing procedures were repeated after the application of a cooling pad. These procedures presumably were conducted to compare and contrast the effects of different cryotherapy modalities on neuromuscular functioning. The authors found similar results using these techniques: both methods negatively affected JPS after treatment. The JPS acuity was reduced by an average of more than 1° during 2 testing procedures (flexion to extension and extension to flexion) after cold-spray application. However, applying spray until participants report a feeling of cold is a subjective measurement. Because neither application duration nor skin temperature was reported, the findings should be treated with caution.

The impairment in JPS reported by 3 groups posttreatment may be associated with a greater reduction in intramuscular or joint cooling, reduced nerve conduction velocity, shivering, or cold-induced change in proprioceptive sensitivity. This possibility is pertinent when the findings are compared with those of other authors who used more superficial applications and reported no effect posttreatment. However, only 3 of these groups recorded skin temperature and none reported intramuscular temperatures, so this theory is difficult to establish. Riemann and Lephart suggested that, even though all 3 groups who measured skin temperature reported reductions in skin temperature, cutaneous afferents play only a minor role in joint proprioception, whereas muscle spindles

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**Figure 3.** Effect sizes and 95% confidence intervals comparing those who experienced an increase in joint position sense error in the knee after cryotherapy and those who did not. E-F indicates extension to flexion; F-E, flexion to extension.
and joint receptors have a much more significant role. Therefore, whether superficial applications of cryotherapy, such as cold spray or ice, can cool deep tissue sufficiently to elicit a reduction in proprioceptive or joint position acuity is questionable. More research regarding the effects of cryotherapy on intramuscular and joint cooling, reduced nerve conduction velocity, shivering, and cold-induced changes in proprioceptive sensitivity is required before conclusions can be reached as to why JPS error was increased postcryotherapy in these studies.

Previous investigators, however, have also suggested that nerve conduction velocity decreases in a linear fashion with tissue cooling and not skin cooling and the rate of decrease in muscle tissue temperature depends on the cooling temperature. Yet skin temperature is a good indicator of intramuscular temperature. Furthermore, ice massage reduces muscle temperature more than an ice-bag application, and a cool-whirlpool treatment is better than crushed-ice packs in maintaining muscle temperature reductions. Different cooling techniques may produce different degrees of joint cooling, so we believe that the modality of cooling (ice-water immersion, a cooling pad, or ice application) may be critical in governing the effect on JPS.

Although it has caused much debate, the cryotherapy modality applied appears to be an important factor affecting ground reaction force (GRF). According to Hart et al, any alteration in the neuromuscular or biomechanical adaptations during landing in the aftermath of a cryotherapy intervention might place an individual at risk of injury. This alteration may result from a reduction in the usually quick and efficient communication of sensory information after cryotherapy. Two groups using an ice application found no effects on peak vertical GRF at landing posttreatment when compared with baseline or control measurements. In contrast, Kinzey et al, using cold-water immersion, found that peak vertical GRF was negatively affected posttreatment.

A number of authors have noted similar findings in relation to closed kinetic chain proprioception (balance) or postural sway after cryotherapy. The detection and response to sway during quiet standing or, indeed, dynamic balance is vital in preventing injury, such as lateral ankle sprain. Cryotherapy in the form of an ice application or cold spray had no effect on balance posttreatment when compared with baseline or control measurements. The results of these studies contrast with those of researchers who used cold-water immersion and found balance was negatively affected immediately after treatment. Therefore, because of the increased area of surface contact, water immersion likely causes more joint and muscle cooling than other, more superficial applications, such as ice. However, although this theory is plausible, it is refuted by those who found balance unaffected after immersing participants in cold water. This topic will continue to be the subject of debate until a conclusive answer is established.

### Study Quality

The average PEDro score for the 7 articles was 5.4/10 (low-high range, 5–6; mode = 5, median = 5; Table). Overall, the
quality of the studies was fair to good.\textsuperscript{33} Disguising a cryotherapy application from the participants or therapists was difficult, so the criteria relating to blinding of volunteers and therapists were not met in any of the included studies. All authors used a single-group precryotherapy and postcryotherapy testing design and, as a result, no study was awarded a point for between-groups statistical comparisons. In terms of statistical power, only Dover and Powers\textsuperscript{25} performed a priori power analysis to identify the required number of volunteers needed to establish statistical differences between error scores. Similarly, none of the authors\textsuperscript{12,25–30} reported giving a sham or a placebo treatment to a control group.

Effect Sizes

The relatively small sample sizes of many of the studies reviewed, along with the discrepancies in both the joint assessed and the modality of cryotherapy, have also made comparisons difficult. The number of participants in each study was low, with 3 of the groups testing fewer than 22 volunteers\textsuperscript{12,27,28} and no group examining more than 50. This is one factor that may influence the strength of the effect size. To interpret the strength of the effect sizes, values from 0 to 0.2 were interpreted as weak, 0.21 to 0.5 as modest, 0.51 to 1 as moderate, and greater than 1 as strong, with the terms weak, modest, moderate, and large describing the difference in JPS between pretest and posttest.\textsuperscript{35} The average point estimate of the effect size of the included studies was modest, with a weak to modest effect size reported in many studies.

Many of the 95\% confidence intervals derived from the studies cross zero. This observation leads us to question how significant an effect, if any, cryotherapy has on JPS. As a result, we cannot report a significant effect on JPS after cryotherapy. In the 3 studies\textsuperscript{26–28} that showed a decrease in JPS, the magnitude to which cryotherapy modalities influenced JPS appears minimal. However, subtle proprioceptive deficits can both predispose an individual to a greater risk for injury and impair sport performance.\textsuperscript{12}

Recommendations for Future Research

For researchers who intend to study the effects of cryotherapy on JPS further, we have several recommendations. First, research is required to address how much of a reduction in nerve conduction velocity, skin, core, or intramuscular or joint temperature is required before the decline in limb reproduction acuity becomes apparent. Once this is identified, investigators can then establish whether various modalities of cryotherapy, including climatic chambers, ice application, cooling vests, water immersion, and cold spray, are capable of achieving this reduction.

Second, reliable and validated proprioceptive measurements (eg, threshold detection of passive movement, force acuity, and static and dynamic balance) must be conducted in conjunction with joint repositioning tests after a cryotherapy intervention to give a balanced account of the effect of cryotherapy on proprioception and neuromuscular functioning. When assessing proprioceptive acuity, administering the correct number of trials is essential because a single proprioceptive assessment may provide erroneous data postcryotherapy.\textsuperscript{57} Also, these outcome measures need to be repeated until researchers are satisfied that proprioception acuity has returned to baseline measurements after a deficit has occurred.

Investigators should also recruit sufficient numbers of participants before undertaking future clinical trials involving cryotherapy and JPS. To assist this process, we recommend an a priori analysis be conducted before any testing is undertaken. Within this review, only 1 group\textsuperscript{25} reported completing such analysis, and the relatively low sample sizes of fewer than 30 participants\textsuperscript{12,25–30} are troublesome.

To our knowledge, no authors have addressed JPS in the wrist or elbow after cryotherapy, JPS after exposure to cold climatic chambers, knee JPS after water immersion, JPS after cryotherapy in an injured population, or JPS after the use of cooling vests. Future researchers should target these areas.

Finally, we advocate that investigators assessing an individual’s ability to reproduce a predetermined joint angle should use absolute mean error as the outcome measure. This method is the most reliable and validated method of reporting joint error and should be used instead of the most or least accurate trial. Reporting constant error in conjunction with absolute mean may also prove beneficial in determining the trend of directional error during repositioning trials.

Recommendations for Clinicians

We have highlighted a number of concerns for clinicians with regard to the effect of cryotherapy on JPS. First, little is known about the potential for cryotherapy to deteriorate JPS, primarily because of the small number of relevant publications. Second, because clinicians administer cryotherapy using different modalities, durations, and application areas, the variability of these factors may result in different effects on proprioceptive acuity. Finally, with 3 of the 7 reviewed studies\textsuperscript{26–28} showing an increase in JPS error postcryotherapy, we recommend clinicians consider that proprioceptive functioning may be altered and increase the risk of injury. In light of this review, we would therefore suggest caution when the athlete must perform dynamic activities (such as twisting, turning, landing, or running) immediately after a cryotherapy treatment.

CONCLUSIONS

Based on the limited and ambiguous evidence addressing the effect of cryotherapy on JPS, we are unable to support or discourage its use before athletic participation. In the 7 studies we reviewed, 3 joints were assessed (shoulder, knee, and ankle) in a combined 204 healthy participants after a cryotherapy intervention. Four groups found cryotherapy to have no effect on JPS, whereas 3 others found JPS reduced after a cryotherapy treatment. Because of differences in the joints being assessed, the modality of cooling, measurement techniques, and quality of the reviewed studies, further research is needed before a conclusive answer as to whether cryotherapy reduces JPS can be determined. Given this brevity of research, we are also unable to make a recommendation as to when athletes can safely return to participation after treatment. Despite the suggested benefits of cryotherapy, until further evidence is
provided, athletic trainers and clinicians should be cautious when returning individuals to physically demanding or dynamic tasks after cryotherapy.

REFERENCES


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Effects of cold water immersion on knee joint position sense in healthy volunteers
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Effects of cold water immersion on knee joint position sense in healthy volunteers

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Abstract

The purpose of this study was to determine the effects of cryotherapy, in the form of cold water immersion, on knee joint position sense. Fourteen healthy volunteers, with no previous knee injury or pre-existing clinical condition, participated in this randomized cross-over trial. The intervention consisted of a 30-min immersion, to the level of the umbilicus, in either cold (14 ± 1°C) or tepid water (28 ± 1°C). Approximately one week later, in a randomized fashion, the volunteers completed the remaining immersion. Active ipsilateral limb repositioning sense of the right knee was measured, using weight-bearing and non-weight-bearing assessments, employing video-recorded 3D motion analysis. These assessments were conducted immediately before and after a cold and tepid water immersion. No significant differences were found between treatments for the absolute ($P = 0.29$), relative ($P = 0.21$) or variable error ($P = 0.86$). The average effect size of the outcome measures was modest (range –0.49 to 0.9) and all the associated 95% confidence intervals for these effect sizes crossed zero. These results indicate that there is no evidence of an enhanced risk of injury, following a return to sporting activity, after cold water immersion.

Keywords: Cryotherapy, joint position sense, proprioception, pre-cooling, knee injury

Introduction

Cryotherapy, or “cold therapy”, is widely used by physiotherapists, clinicians, athletes, and others for various clinical purposes. Cryotherapy has been used for decades by sports people to decrease pain, swelling, secondary hypoxic injury, arterio/venous constriction, relieve muscle spasm, facilitate movement, and to reduce core and skin temperature (Knight, 1995). More recently, cryotherapy before exercise, or pre-cooling, has been reported to improve endurance activities in humid conditions (for a review, see Quod, Martin, & Laursen, 2006). Similarly, a number of authors have suggested that pre-cooling may allow individuals with multiple sclerosis to exercise with greater physical comfort (Kinnman, Andersson, & Andersson, 2000; White, Wilson, Davis, & Petajan, 2000). However, cryotherapy users should also consider the potential negative effects of pre-exercise cryotherapy on proprioception and neuromuscular functioning.

Decreases in muscle temperature, following cryotherapy, have been shown to reduce muscle force and muscle power (Sargeant, 1987), possibly due to a reduction of myosin ATPase activity. Similarly, reductions in tissue temperature have been shown to decrease nerve conduction velocity (Algafly & George, 2007), by reducing action potential propagation. Limited research is available on the potential of cryotherapy, especially in the form of cold water immersion, to reduce proprioceptive acuity. Proprioceptive acuity, which is a component of the sensorimotor system (Riemann & Lephart, 2002a, 2002b), has previously been defined as an individual’s ability to sense joint position, movement, and force to discriminate movements of their limbs (Gandevia, Refshauge, & Collins, 2002). Muscle spindles and skin stretch receptors play a major role in position sense (Proske & Gandevia, 2009). As cold water decreases skin, intramuscular, and rectal temperatures (Peiffer, Abbiss, Nosaka, Peake, & Laursen, 2009a; Peiffer, Abbiss, Watson, Nosaka, & Laursen, 2009b), where the muscle spindles and skin stretch receptors are located, it is possible that knee joint position sense may be altered. The resultant abnormal proprioception could potentially predispose musculoskeletal pathology by altering movement control, hence leading to
abnormal stresses being exerted on tissues (Baker, Bennell, Stillman, Cowan, & Crossley, 2002).

To date, no study has addressed the effects of cold water immersion on knee joint position sense. Several studies have suggested that cryotherapy before exercise may change the biomechanical properties of the joint, resulting in inadequate peripheral feedback and potentially leading to injury when rehabilitation or exercise is resumed (Hopper, Whittington, & Davies, 1997; Oliveira, Ribeiro, & Oliveira, 2010; Surenkok, Aytar, Tüzün, & Akman, 2008; Uchio et al., 2003). As cold exposure has previously been shown to reduce nerve conduction velocity (Algafly & George, 2007; Ochs & Smith, 2004), balance (Makinen et al., 2005) and alter neuromuscular transmission in muscles (Coulange et al., 2006), it is possible that cold water immersion could also reduce knee joint position sense. Five studies (Hopper et al., 1997; Oliveira et al., 2010; Sekihara et al., 2007; Surenkok et al., 2008; Uchio et al., 2003) have previously reported a reduction in joint position sense acuity after cryotherapy treatment, while four others (Dover & Powers, 2004; LaRiviere & Osternig, 1994; Thieme, Ingersoll, Knight, & Ozmun, 1996; Wassinger, Myers, Gatti, Conley, & Lephart, 2007) reported no effect. The joints assessed by these studies included: the shoulder (Dover & Powers, 2004; Wassinger et al., 2007), knee (Oliveira et al., 2010; Surenkok et al., 2008; Thieme et al., 1996; Uchio et al., 2003), elbow (Sekihara et al., 2007), and ankle (Hopper et al., 1997; LaRiviere & Osternig, 1994).

Thus, the aim of the present study was to determine if cold water altered healthy individuals’ knee joint position sense following immersion. Both weight-bearing and non-weight-bearing clinical assessment of knee joint position sense, using three-dimensional motion analysis, were used before and after a water immersion to determine if cold water immersion reduces knee joint position sense.

Methods

Design

This was a prospective, randomized, cross-over design where volunteers acted as their own controls. The volunteers were immersed at two temperatures (detailed below) and these sessions were separated by 6–10 days. The order of the testing was randomly assigned using a random number generator. Ethical approval of the design was gained from the University of Limerick’s Research Ethics Committee, and signed informed consent was obtained from each participant before any data collection took place.

Volunteers

Fifteen participants (9 males, 6 females) aged 21.9–25.1 years (mean 23.2 years) agreed to participate in this study. One male participant dropped out as he was unable to attend the second test session due to personal commitments. The anthropometric data of the 14 participants who completed the study are displayed in Table I. Individuals were excluded from the study if they had Reynaud’s disease, ankle or knee injuries in the previous 12 months, a history of ear or vestibular conditions. Individuals were also excluded if they were not between the ages of 18 and 40 years or if they were not comfortable with being blindfolded during testing.

Intervention

All participants reported to the test location on two separate occasions, once for cold water (14°C ± 1°C) immersion treatment and once for tepid water (28°C ± 1°C) immersion (control). The temperature of the water immersions was measured using a digital aquarium thermometer. In both the cryotherapy and the control sessions, the participants were seated in a water tank and immersed to the level of the umbilicus for 30 min. The water was stirred at regular intervals by the experimenter. Male participants wore only shorts, while females were allowed to wear shorts and a T-shirt. Immediately after the water immersion the participants were asked to towel-dry their body, change into dry shorts and T-shirts, and transfer to the laboratory. On both occasions, the participants completed the joint position sense tests immediately before and after the water immersion (approximately 5 min post-immersion). During the initial visit, demographic variables (age, height, weight, lower limb dominance) were ascertained and recorded (Table I). Limb dominance was determined by asking the participants which leg they would normally use to kick a ball.

Table I. Characteristics of the 14 participants who completed the study (mean ± i).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Females (n = 6)</th>
<th>Males (n = 8)</th>
<th>Total (n = 14)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>23.1 ± 0.7</td>
<td>23.4 ± 1.2</td>
<td>23.3 ± 1.0</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.69 ± 0.07</td>
<td>1.81 ± 0.07</td>
<td>1.76 ± 0.09</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>63.9 ± 9.4</td>
<td>78.9 ± 6.0</td>
<td>72.0 ± 10.8</td>
</tr>
<tr>
<td>Body mass index</td>
<td>22.4 ± 3.3</td>
<td>24.0 ± 1.5</td>
<td>23.2 ± 2.6</td>
</tr>
<tr>
<td>(kg · m⁻²)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limb dominance</td>
<td>Right (n = 6)</td>
<td>Right (n = 8)</td>
<td>Right (n = 14)</td>
</tr>
</tbody>
</table>
Outcome measure

Knee joint position sense was assessed under both weight-bearing and non-weight-bearing test conditions. All of the measurements were performed in a controlled environment, as this has previously been shown to improve reliability (Piriyaprasarth & Morris, 2007). Before testing began, all participants were familiarized with the procedures through explanation, demonstration, and at least two practice repetitions. All test procedures were performed in an isolated room, by the same experimenter who was not blinded to the experimental design. To eliminate vestibular and visual information, the participants wore blindfolds (Olsson et al., 2004) and wore headphones over which white noise was played during testing. Active ipsilateral matching was chosen because it is a commonly used and validated method of assessing knee joint position sense (Olsson et al., 2004).

For all the trials described below, three reflective markers were attached to 2-cm cloth adhesive and then positioned on the greater trochanter, the lateral epicondyle of the femur, and the lateral malleolus of the right limb (Harato et al., 2008). These markers were used to facilitate the recording of the internal joint angle throughout the trials. During the immersion period, these markers were removed from the participants. However, the cloth adhesive backing was not removed so that the three markers could be placed at the same locations following the immersion. Knee joint angle was recorded using an Eagle five-camera system (Motion Analysis Corporation, Santa Rosa, CA, USA) sampling at 400 Hz. The cameras were placed 3–5 m around the participant at various heights of 0.5–1.5 m to facilitate the recording of the movement of the markers during the trials. The system was calibrated each morning before testing with an L-frame and a wand, as described in the manufacturers’ guidelines. This system has previously been shown to have excellent reliability for reporting knee motion (Ford, Myer, & Hewett, 2003). A default Butterworth fourth-order zero-phase-shift filter (20 Hz cut-off) was used to smooth the data before exporting it into Microsoft Excel 2000 to calculate error scores.

For the non-weight-bearing assessment, each participant was positioned in a seated position with the leg resting at approximately 90° of flexion and the popliteal fossa not touching the edge of the seat (Panics, Tallay, Pavlik, & Berkes, 2008). The limb was then extended by the examiner at a slow steady speed (~10° per second) to a randomly assigned index angle of approximately ~35°, ~55° or ~70° of flexion (Aydog et al., 2005). The examiner asked the participant to hold this position for ~5 s, which the participant was asked to remember with particular emphasis on the knee joint, and then the examiner returned the leg to it starting position at the same angular velocity. This time period, which has been used previously (Mohammadi, Taghizadeh, Ghaffarinejad, Khorrarni, & Sobhani, 2008), enables the participant to become aware of the position of their limb. The participants were then asked to actively reproduce the predetermined target angle with the ipsilateral limb. Participants attempted to replicate the predetermined angle three times (Olsson et al., 2004) and the average was taken. Taking the average of several trials has previously been shown to be more reliable than taking a single measurement (Piriyaprasarth & Morris, 2007). After the assessment of each angle, the participants were asked to leave the chair and walk around briefly, which helped them to concentrate on the new test angle and not the previous angle.

For the weight-bearing assessment of knee joint position sense, we used a similar protocol that has previously been described (Mir, Hadian, Talebian, & Nasseri, 2008; Stillman & McMeeken, 2001). The weight-bearing assessment included two unique movements: (a) flexion to extension and (b) extension to flexion. For both movements, the participants wore a blindfold and were allowed to place their left hand on a flat table for balance. This table stood at a height of 0.5 m. The participants were instructed to stand with approximately 95% of their body weight directed through their right foot, and with the back foot touch-weight-bearing (Hopper et al., 2003). The starting position of flexion to extension movement was a semi-squat (~60°), with the right hand placed across the chest so not to obscure the markers. Participants extended the weight-bearing right leg, at a slow angular velocity, until instructed to stop (~45°). They were asked to “remember” this position while focusing on the knee joint position as they held the test position for approximately 5 s, before returning to the normal erect stance (~7 s). Finally, the participants reproduced the unilateral flexed position while concentrating on the knee. For the extension to flexion movement, the starting position was a normal erect stance. While wearing a blindfold and with their right hand across their chest, participants were instructed to place approximately 5% of their weight on their left foot. They then flexed their right limb until instructed to stop (~45°). The participants were instructed by the experimenter to “remember” this position while focusing on the knee as they held the position isometrically (~5 s). After this, the participants returned to an erect stance (~7 s) before attempting to reproduce the unilateral flexed position, while concentrating on the knee. The holding times used in this study have previously been used in other published work (Mir et al., 2008).
For both these procedures, the participants repeated the movements three times (Mir et al., 2008) after the predetermined angle was established. Similar to the study of Stillman and McMeeken (2001), the target angle was subjectively judged by the experimenter for both movements (flexion to extension approximately 43.4’ and extension to flexion approximately 44.3’). For the purpose of this study, the absolute mean error (the average error in the three trials ignoring the direction of the error), relative error (the average of the errors in the three trials taking into account the direction of the error), and variable error (the standard deviation of the three relative error measurements) were analysed (Olsson et al., 2004). The reliability of the chosen method (using mean differences and 95% limits of agreement) was established in our 14 participants using the pre-experimental and pre-control results. The mean difference for absolute error between the first and second test was 0.037”, with a standard deviation of 3.1”, and limits of agreement (mean difference ± 1.96 times the standard deviation) ranging from –6.039” to 6.113”.

**Data analysis**

The Statistical Package for the Social Sciences (SPSS) version 15.0 for Windows (SPSS Inc., Chicago, IL) was used for statistical analysis. For each trial, the absolute error was calculated by subtracting the reproduced angle for the target angle. A positive angle represents an overestimation and a negative value represents an underestimation. The middle 3 s of the reproduced angle, correct to three decimal places, was used to analyse the data. Data are presented as means and 95% confidence intervals (95% CI). Three scores were calculated for the absolute, relative, and variable error. Variables were tested for normal distribution with the Shapiro-Wilk test. The results were then normalized and analysed using a 2 × 2 × 5 (ice/control × pre/post × 5 angles) mixed-design, repeated-measures analysis of variance (ANOVA) to determine if differences existed between control and cold application sessions, pre and post treatment, and the five sectors of movement. The current study had an 80% power to detect a 1.6’ difference between experimental and control conditions. For all analyses, statistical significant was set at \( P < 0.05 \). To calculate effect sizes (Cohen’s \( d \)) and associated 95% confidence intervals for the change in joint position sense before and after the cryotherapy treatment, Cohen’s \( d \) was calculated using the following method: (mean of post-test – mean of pre-test)/(pooled standard deviation of pre-test and post-test) (Morris, 2008). To interpret the strength of the effect sizes, values of 0–0.2 were interpreted as being weak, 0.21–0.5 as modest, 0.51–1.0 as moderate, and values that were greater than 1 were interpreted as being a strong effect (Cohen, Manion, & Morrison, 2007).

**Results**

No significant differences, between pre and post tests with both the cold and tepid water using a repeated-measures ANOVA, were found for absolute error (\( P = 0.29 \)), relative error (\( P = 0.21 \)) or variable error (\( P = 0.86 \)) scores (see Table II). In addition, no other main effects or interactions were found to be significant. Figure 1 illustrate the point estimates for the effects sizes (Cohen’s \( d \)) and associated 95% confidence intervals for the five angles on the day of the cold water immersion and the five angles on the day of the tepid water immersion. The average effect size of the cold water immersion was modest, with effect sizes ranging from –0.1 to 0.9, with a positive number representing an increase in joint position sense error. For the tepid water treatment, the average effect size was weak, with point estimates ranging from –0.49 to 0.6 (Figure 1).

**Discussion**

The aim of this study was to determine whether cold water immersion reduced knee joint position sense in healthy participants. No significant difference in knee joint position sense was detected following cold water immersion for 30 min. Our findings are similar to those of other published work using different cryotherapy protocols and joint position sense assessments (Dover & Powers, 2004; LaRiviere & Osternig, 2004; Sekihara et al., 2007; Thieme et al., 1996; Uchio et al., 2003; Wassinger et al., 2007). Despite previous research showing changes in thixotropy of the forearm muscles following cold water immersion (Lakie, Walsh, & Wright, 1986), to date no published study has elucidated the biomechanical and neurophysiological effects on the healthy knee joint and this study is the first to address the potential decrease in joint position sense acuity after cold water immersion.

In relation to the methodological design of this study, we used a temperature of 14°C for 30 min, as similar protocols have been adopted by other researchers using pre-exercise cryotherapy (Marsh & Sleivert, 1999; White et al., 2000). Similarly, this duration has been noted as the minimum necessary for clinicians and physiotherapists to use to suppress the metabolism of the knee and reduce inflammation (Knight, 1995). During the 5-min delay between leaving the water tank and commencing joint position sense testing, it is possible that skin and muscle temperature increased in the experimental group (cold water immersion) and this may also be
a factor in the findings of the present study. This point is supported by Surenkok et al. (2008) and Uchio et al. (2003), who indicated that joint position sense is normalized at 5 and 15 min following the application of a cold pack/spray and a cooling pad respectively. However, after cold water immersion, it is more likely that individuals would take time to dry off and change into dry clothing before exercise. The rationale behind this protocol was also to prevent the participants experiencing any effect of wearing wet clothing. Similarly, having the control group perform the assessments in wet clothing was not desirable, as this may have altered their results. The current study emulated a pre-exercise cryotherapy protocol by Marsh and Sleivert (1999), who reported improvements in short-term cycling performance following treatment, and a delay of 10 min between the end of the cold water immersion and the start of a warm-up (Marsh & Sleivert, 1999). This time delay, similar to the current study, was necessary for each participant to dry off, dress, and transfer to the assessment area (Marsh & Sleivert, 1999). Consequently, we think our results are valuable to those concerned about the increased risk of proprioceptive-related injury following cold water immersion, as they emulate a protocol supporting the use of pre-exercise cryotherapy.

We included both weight-bearing and non-weight-bearing assessments because it has been suggested that weight-bearing assessments have more clinical relevance for assessing proprioceptive function in relation to injury (Waddington, Adams, & Jones, 1999). On the other hand, non-weight-bearing assessments replicate other movement patterns including the swing phase in gait (Stillman &
McMeeken, 2001) and limb position before heel strike (Co, Skinner, & Cannon, 1993). Combining the two types of assessment allowed a better evaluation of proprioceptive acuity in the form of knee joint position sense following cryotherapy. The error in knee joint position sense reported in this study is similar to that of a number of other studies, in both the weight-bearing (Mir et al., 2008) and non-weight-bearing assessment (Olsson et al., 2004; Panics et al., 2008; Stillman, 2000).

Previous work has attributed a reduction in joint position sense following cryotherapy to reduced skin temperatures, a reduction in nerve conduction velocity, the eventual blocking of conduction, and alterations in motor output (Surenkok et al., 2008; Uchio et al., 2003). A potential reason why Hopper et al. (1997) found a significant reduction in ankle inversion reproduction is the temperature of the water. These authors used a water immersion of 9°C lower that the present study (i.e. 5°C) and this may explain the reduction due to increased skin and intramuscular temperature. Using water immersion of 5°C elicited a 14°C drop in skin temperature, measured at the antero-lateral aspect of the ankle. The reporting of skin, muscle, and core temperature would allow for a more comprehensive comparison of this study to other published work. However, significant reductions in skin and intramuscular temperature have recently been reported following similar immersion protocols (14.3°C for 20 min to the level of the mid-sternum) to the current study (Peiffer et al., 2009a, 2009b). Peiffer and colleagues (2009a, 2009b) reported reductions in skin (right calf, right quadriceps, right biceps, and chest) and muscle temperature (rectus femoris) to 21°C and 32°C respectively after 20 min of immersion. Approximately 5 min after immersion, the time the current study started the assessments, these values only deviated minimally. This reduction is approximately 4°C less than that reported by Hopper et al. (1997) and may explain the disparity in the findings.

The degree of skin, muscle, and joint cooling experienced is important in the assessment of joint position sense, as nerve conduction velocity has been shown to decrease linearly with tissue cooling (Ruiz, Myrer, Durrant, & Fellingham, 1993). It has previously been reported that to reduce nerve conduction velocity by approximately 10%, a skin temperature of 12.5–13.5°C is required (McMeeken, Lewis, & Cocks 1984). Similarly, Algafly and George (2007) reported that a skin temperature of 15°C was required for a 17% reduction in nerve conduction velocity and 10°C for a reduction of 33%. Despite not measuring nerve conduction velocity or skin temperature, from the information derived from similar studies (Algafly & George, 2007; McMeeken et al., 1984; Peiffer et al., 2009a, 2009b) we can deduce that participants experience a reduction in nerve conduction velocity of less than 10%. The results of this study, recorded 5 min after cold water immersion, indicate that the ability to derive knee joint position sense helps to withstand the muscle, joint, and skin cooling experienced during the immersion, and that for a reduction in knee joint position sense tissue temperature together with nerve conduction velocity has to be reduced further. As we used a protocol commonly employed by sports people in the current study, it does not exclude the possibility that a different protocol, using a different duration, temperature or modality, would reduce knee joint position sense. Despite the use of a mixed-design repeated-measures analysis of variance, some of the variables in the current study were not normally distributed and this is a statistical limitation. In addition, the current study was only powered to detect large discrepancies in knee joint position sense and smaller increases in joint position sense error would have been outside the scope of the study.

Physiotherapists, coaches, athletic trainers, and clinicians administer cryotherapy, in the form of cold water immersion, for a number of reasons, including the reduction of pain and swelling, to relieve muscle spasm, and to facilitate movement. The benefits of using cold water immersion for athletes (Quod et al., 2006), injured individuals (Cochrane, 2004), and people with multiple sclerosis (White et al., 2000) have been well publicized. However, Thieme et al. (1996), Uchio et al. (2003), and Surenkok et al. (2008), as recently reviewed by Costello and Donnelly (2010), have all highlighted the potential of various modalities of cryotherapy to reduce proprioceptive acuity and hence predispose injury. The change in joint position sense accuracy following this protocol proved statistically insignificant (Table II). The evaluation of effect sizes (Cohen’s d) and associated 95% confidence intervals supports these findings (Figure 1).

Further research is required to determine whether different durations and locations of application of ice-packs, cooling pads, whole-body cryotherapy or spray have a negative effect on joint position sense. Similarly, no published study has assessed the potential of any of the modalities of cryotherapy, listed above, to alter joint position sense acuity in elite athletes, patients with multiple sclerosis or an injured population. Joint position sense is not the only component of proprioception that has the potential to be altered following a cold application. Further research could also assess other aspects of proprioception, including balance, touch acuity, and force reproduction in the immediate aftermath of a cryotherapy application.
Conclusion

In conclusion, we found no evidence of impaired knee joint position sense in healthy individuals following a cryotherapy protocol commonly employed in athletic training. These results were obtained using an accurate technique (3D motion analysis) of measuring knee joint position sense. Furthermore, our study provides no evidence of an enhanced risk of injury, due to a detriment in angle proprioception, following this specific cryotherapy protocol. However, further research is required to address the equivocal evidence that exists regarding the effects of different durations and temperatures of cryotherapy applications on proprioceptive acuity.

References


Effects of whole-body cryotherapy (−110 °C) on proprioception and indices of muscle damage

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The purpose of this study was to investigate the effects of whole-body cryotherapy (WBC) on proprioceptive function, muscle force recovery following eccentric muscle contractions and tympanic temperature (TY). Thirty-six subjects were randomly assigned to a group receiving two 3-min treatments of −110 ± 3 °C or 15 ± 3 °C. Knee joint position sense (JPS), maximal voluntary isometric contraction (MVIC) of the knee extensors, force proprioception and TY were recorded before, immediately after the exposure and again 15 min later. A convenience sample of 18 subjects also underwent an eccentric exercise protocol on their contralateral left leg 24 h before exposure. MVIC (left knee), peak power output (PPO) during a repeated sprint on a cycle ergometer and muscles soreness were measured pre-, 24, 48 and 72 h post-treatment. WBC reduced TY by 0.3 °C, when compared with the control group (P < 0.001). However, JPS, MVIC or force proprioception was not affected. Similarly, WBC did not effect MVIC, PPO or muscle soreness following eccentric exercise. WBC, administered 24 h after eccentric exercise, is ineffective in alleviating muscle soreness or enhancing muscle force recovery. The results of this study also indicate no increased risk of proprioceptive-related injury following WBC.

Cryotherapy, in the form of cold water immersion and ice packs, has been used for decades as a post-exercise recovery strategy in a variety of sports. The application of cold is believed to work by decreasing muscle temperature levels, diminishing pain and muscle spasm and reducing the inflammatory process, thus aiding the recovery process after trauma (Knight, 1995; Banfi et al., 2010). Cold water immersion has also been used before exercise (pre-cooling) or during exercise to improve endurance activities in humid conditions (Duffield et al., 2010). A new modality of cryotherapy, called whole body cryotherapy (WBC), is currently being offered by clinicians as an alternative to cold water immersion or ice packs. WBC involves repeatedly exposing participants to very cold air (−110 °C) while dressed in minimal clothing for a short period of time (Westerlund et al., 2009). WBC is used in a clinical setting to treat the pain, edema and inflammation of various rheumatic diseases, so patients can do therapeutic exercises after WBC (Westerlund et al., 2003). In sports medicine, WBC is promoted as a treatment for muscle injuries, syndromes of overuse and to enhance recovery between training sessions (Banfi et al., 2010). WBC has previously been shown to reduce skin (Westerlund et al., 2003) and oral (Taghawinejad et al., 1989) temperature, lower total oxidative status in plasma (Lubkowska et al., 2008), increase anaerobic capacity (Klimek et al., 2010), lower creatine kinase activity (Wozniak et al., 2007; Banfi et al., 2008) and alter the concentration of cortisol (Wozniak et al., 2007). As a result, Klimek et al. (2010) suggest that this type of treatment should therefore be recommended during the recovery process due to the recognized benefits of cryostimulation/cryotherapy in athletes. However, despite the extreme temperatures utilized by this treatment, little is known about the potential of WBC to reduce proprioceptive function or enhance recovery from delayed onset of muscle soreness.

Proprioceptive acuity, which is a component of the sensorimotor system, has been defined previously as an individual’s ability to sense joint position, movement and force to discriminate movements of their limbs (Riemann & Lephart, 2002). A decrease in proprioception acuity and/or diminished knee joint proprioception has previously been linked to rendering the knee less sensitive to potentially damaging forces and possibly at an increased risk for ligament injury (Baker et al., 2002). Despite a number of authors suggesting no detriment in joint position sense (JPS) following cryotherapy (LaRiviere & Osternig, 1994; Thieme et al., 1996; Uchio et al., 2003; Dover & Powers, 2004; Wassinger et al., 2007),
it is possible that the application of cold may decrease proprioception and predispose an individual to injury due to decreases in nerve conduction velocity, muscle force production, proprioceptive afferent information or a combination of these factors (Hopper et al., 1997; Surenkok et al., 2008; Oliveira et al., 2010). The importance, for clinicians and sportspeople alike, of increasing the awareness of the potential effects of cryotherapy on proprioceptive acuity in healthy individuals has been highlighted previously (Oliveira et al., 2010). Several studies (Uchio et al., 2003; Dover & Powers, 2004; Wassinger et al., 2007; Surenkok et al., 2008; Oliveira et al., 2010) and a systematic review (Costello & Donnelly, 2010) have highlighted previously the limited research available on the effects of locally applied cryotherapy (the application of an ice pack to a joint or muscle group or the immersion of a joint(s) in cold water) on proprioceptive acuity. Further controlled and empirical studies are required to address this brevity of research, and also in the area of WBC.

Many sporting organizations, clinicians, coaches and athletes are currently using WBC, despite the limited number of publications in the area, and the current study aimed to address this deficit in the literature. To our knowledge, the effects of WBC on knee JPS, muscle force reproduction, recovery after muscle damaging exercise or tympanic temperature ($T_{TY}$) have yet to be investigated. There were two distinct aspects to the current study, Experiment 1 focused on proprioceptive function and $T_{TY}$, while Experiment 2 on recovery from eccentric muscle damage. Therefore, the purpose of this study was (1) to evaluate the immediate effects of WBC on proprioception and $T_{TY}$ and (2) to evaluate the effectiveness of WBC in the treatment of muscle soreness and function following eccentric exercise damage.

Experimental overview

The current study was a single-blinded randomized controlled trial with two independent variables. In Experiment 1 of the study (proprioceptive acuity following WBC), these variables were time (baseline, immediately post and 15 min post-intervention application) and treatment groups (3 min of WBC and a control). Concealed, random allocation was used to assign participant treatment group after baseline measurements. In Experiment 2 of this study (the effects of WBC on muscle force recovery following eccentric exercise), a convenience sample of 18 volunteers (nine in each group) was recruited from the original 36 participants. Similarly, there were two independent variables for this component of the study including time (baseline, 24, 48 and 72 h post-treatment) and treatment group (3 min of WBC and a control). The main outcome measures of Experiment 1, based on the right limb, were knee JPS, maximal voluntary isometric contraction (MVIC) and muscle force reproduction of the right knee extensors and $T_{TY}$. The main outcome measures of Experiment 2, where 18 subjects underwent an eccentric muscle damaging protocol on their contralateral left limb 24 h before treatment, were MVIC (on the left knee extensors), muscle soreness and peak power output (PPO) recorded during repeated sprints on a cycle ergometer.

WBC protocol

Participants were exposed, in pairs, to either a cold or a control treatment in a cryogenic chamber at the Shannon Cryotherapy Clinic in Ennis, County Clare, Ireland. For the cold group, WBC exposures were administered in a specially built, temperature-controlled unit (Zimmer Elektromedizin, Germany), which consists of two rooms ($-60^\circ\text{C}$ and $-110^\circ\text{C}$). 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. Subjects entered and stood in the first room ($-60 \pm 3^\circ\text{C}$) for 20 s before entering the second room ($-110 \pm 3^\circ\text{C}$) for 3 min. The duration and temperature of the cold chamber were similar to that utilized elsewhere (Westerlund et al., 2003, 2006, 2009; Klimek et al., 2010). Subjects 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. For the control group, the subject followed the very same procedures as the cold group except both chambers were set at a temperature of $15 \pm 3^\circ\text{C}$. The exposure and females wore crop tops or sports bras. Glasses, contact lenses and all jewelry and piercings were removed before entry to the chamber.

Materials and methods

Subjects

The study population, for Experiment 1, consisted of 36 healthy participants [age, mean $\pm$ standard deviation (SD), 26.0 $\pm$ 1.2 years, height 177.0 $\pm$ 4.8 cm and body mass 76.0 $\pm$ 7.9 kg]. Subjects were recruited from the University of Limerick’s student population. The study was conducted in accordance with the Declaration of Helsinki and approved by The University of Limerick’s Research Ethics Committee (ULREC: 09/47). After providing informed written consent, participants were randomly assigned, using a random number generator, to a cold group (WBC, six women and 12 men) or a control group (six women and 12 men). Participants completed a pre-test questionnaire and were excluded if they had a history of lower limb injuries in the past 12 months, ear or vestibular conditions or if they had any contradiction to cryotherapy including Reynaud’s disease. They were also instructed to refrain from consuming alcohol or caffeine 24 h before testing commenced.

All subjects repeated the treatment (either $-110 \pm 3^\circ\text{C}$ or $15 \pm 3^\circ\text{C}$), after a lapse of 2 h. After the first visit to the chamber, the subjects were randomly chosen to complete either knee JPS or MVIC and force-reproduction assessments. The remaining tests (either knee JPS or MVIC and force reproduction) were completed after the second visit to the chamber. The order of the testing for each subject was randomized. Baseline tests (knee JPS or MVIC and force reproduction) were completed immediately before exposure to the chamber and post-tests followed immediately after each
exposure (within 2–3 min) and again 15 min later. Approximately 2 h after the first exposure, participants completed the remaining pre-tests and again entered the chamber. This time lag of 2 h between treatments has been recommended by the manufacturers and used extensively by the operators of the chamber in Ennis.

**Experiment 1**

**Knee JPS**

Active ipsilateral limb repositioning of the right knee was assessed after passive positioning, using an electrogoniometer placed at the lateral aspect of knee joint (Panics et al., 2008). This measurement has been validated as reliable in the clinical setting and has been suggested as the most appropriate test for determination of JPS in clinical studies (Olsson et al., 2004). This device used was Biometrics™ electrogoniometer (Biometrics Ltd, Cwmfelinfach, Gwent, UK) with an ADU301 angle display unit. This device has been validated previously with an accuracy of ±0.5° (Rowe et al., 2001). To reduce the contribution of vestibular and visual input, participant wore blind-folds and headphones, over which white noise was played during the testing procedures. Before commencing testing, all participants were familiarized with the procedures by explanation, demonstration and at least three practice repetitions a minimum of 24 h pre-testing and again on the day of testing, immediately before the pre-testing. Subjects were positioned in a seated position where the leg was resting at approximately 90° of flexion and the popliteal fossa did not touch the edge of the seat (Panics et al., 2008). The limb was then extended by the examiner at a slow steady speed (~10°/s) to a randomly assigned index angle between 10°, 30°, 60° or 90° of flexion. The examiner asked the subjects to hold this position for ~5 s (Olsson et al., 2004), which the subject was asked to remember with particular emphasis on the knee joint, and then the examiner returned the leg to it starting position at the same angular velocity. This 5-s time period enables the subject to become aware of the position of their limb. Subjects were then asked to actively reproduce the predetermined target angle with the ipsilateral limb. Subjects attempted to actively replicate the predetermined angle three times and the average was recorded. After the assessment of each angle, subjects were asked to leave the chair and walk around briefly. This assisted the subjects to concentrate on the new test angle and not the previous angle.

**MVIC**

MVIC of the right knee extensors was recorded in a seated position using a Tornvall Chair. The subject was seated in an upright position with their right knee flexed at 90°. A strap placed around the ankle was connected to a pre-calibrated load cell (Novatech, Hastings, UK), attached by an inextensible bolt to the chair. An analogue signal from the load cell was digitized using a recording system (Powerlab 4/25T, ADInstruments, Oxfordshire, UK) and recorded on a PC running Chart™ 5 software (ADInstruments). Participants were seated with arms crossed against the chest, and the hips were tied down to isolate the knee extensors. Participants were counted down from three and then asked to maximally contract their right leg for 3 s. The subjects performed the test three times with a minimum of 1-min rest between each repetition. The maximum value of the three trials was recorded as the result. The subjects were given constant verbal encouragement and received visual feedback from a monitor throughout for all MVIC tests. All participants were familiarized with these procedures as described previously.

**Force reproduction**

Force-reproduction testing was performed with the subject seated and positioned in the same position as for MVIC testing immediately before entering the chamber, after the cryotherapy treatment (within 3 min) and again 15 min later. A modified procedure based on that used by Dover and Powers (2003) was used in the current study. A target force equivalent to 25% and 50% of the MVIC was used for all subjects. To begin the force-reproduction measurement, the subject attempted to extend their knee with sufficient force, while receiving visual and verbal feedback, until the target force being produced (either 25% or 50% randomly assigned) was reached. A computer screen was positioned on the desk in front of the subjects so that they could easily see the screen and the forces they produced during the entire length of the trial (Rubley et al., 2003). Each volunteer’s individual target force (25%/50% of their MVIC) was displayed as a horizontal line (in black). A second line (in red) represented the instant output of the volunteer’s isometric force. Volunteers were instructed to match the force output line with the target line. Visual feedback was then removed and the subjects were instructed to reproduce the force after 10 s. When the subject verbally indicated that he or she had achieved the target force, T1 was recorded for 3 s. The measurement was repeated two more times for a total of three trials at both angles. The error score for each trial was calculated as the mean absolute difference between the target force and the reproduced force (Dover & Powers, 2003). All participants were again familiarized with this procedure as described previously.

**Tympanic temperature.** A Braun ThermoScan ear thermometer (model PRO 4000, Braun, Kronberg, Germany) was used to measure tympanic temperature. The ear was tugged and the probe was placed snugly into the external auditory canal of the right ear (Dzarr et al., 2009). The probe remained in this position briefly (1–2 s) until the machine beeped to signal a recording had been taken. Tympanic temperature was recorded before entry to the chamber and 3, 8, 15 and 20 min after exiting the chamber. The same experimenter recorded all tympanic temperatures.

**Experiment 2**

**Subjects**

In addition to participating in Experiment 1, a convenience group of 18 subjects (age, mean ± SD, 21.2 ± 2.1 years, height 177.5 ± 5.1 cm and body mass 77.2 ± 9.6 kg), sourced from the original 36 subjects, voluntarily agreed to participate in the second component of the study. Nine subjects participated from both the cold (two women and seven men) and control groups (two women and seven men). For these 18 subjects who participated in Experiment 2, the exposure commenced 24 h following eccentric exercise.

**Eccentric exercise protocol**

Immediately after the pre-tests on day one, the volunteers completed an eccentric exercise bout consisting of 100 high-force maximal eccentric contractions of the left knee extensors. We used an eccentric muscle damaging protocol used previously in a similar study (Mackey et al., 2004). These contractions were performed on an isokinetic dynamometer...
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(Con-Trex MJ; CMV AG, Diübendorf, Switzerland) set at an angular velocity of 1.57 rad/s. The 100 contractions were divided into 20 sets of five repetitions, with a minimum rest period of 1 min between sets. Participants were in a seated position with strapping isolating movement of the knee joint around the chest and opposite leg. The left leg in all subjects was tested and was strapped securely to the lever arm of the isokinetic system. The volunteers were required to maximally resist the forced lengthening of their quadriceps through a range of motion, from almost full extension to almost full flexion (Mackey et al., 2004). The subjects were given a standardized visual and verbal encouragement throughout the duration of the protocol.

### MVIC

The 18 subjects participating in Experiment 2 completed the same MVIC protocol, as described earlier, except the contractions were performed on their contralateral left limb.

### PPO (maximal cycling repeated-sprint test)

The maximal cycling repeated-sprint test used in this study is similar to that used elsewhere (McGawley & Bishop, 2006). This test was conducted on day 1 (approximately 24 h before the first visit to the chambers) and again 24, 48 and 72 h following exposure. The reliability of this outcome measure in terms of work and power has been established previously by McGawley and Bishop (2006). All trials were performed at the same time of day, and subjects were instructed not to undertake strenuous exercises throughout the duration of the testing. Following a standardized 5 min warm-up at a self-directed pace, each subject performed a 5 × 6 s maximal cycle repeated-sprint test on a Monark cycle ergometer (874E, Vansbro, Sweden) that was dynamically calibrated. The 5 × 6 s cycle test comprised of five 6-s maximal sprints departing every 30 s. During the 24-s recovery period between sprints, subjects were permitted to turn the pedals at a self-selected pace. Subjects received a countdown before each sprint and performed the sprints in the standing position while receiving a standardized verbal encouragement. Like all the previous outcome measures, participants were familiarized with this procedure.

### Muscle soreness questionnaire

Muscle soreness was also assessed in the days following eccentric exercise with the aid of a questionnaire that has been used elsewhere in which a similar exercise protocol were used (Mackey et al., 2004). Soreness was measured by palpation of the knee extensors at eight specified sites, corresponding to the proximal and distal regions of the knee extensors and flexors. Soreness was rated on a visual analogue soreness scale, ranging from 1 (normal, no pain) to 10 (very, very sore), and total soreness was calculated as the sum of the eight values (Mackey et al., 2004).

### Statistical analysis

The Statistical Package for the Social Sciences (SPSS) for windows (v16.0, SPSS Inc., Chicago, Illinois, USA) was used for statistical analysis. For each JPS trial, the actual error was calculated by subtracting the reproduced angle from the target angle. A positive angle represents an overestimation and a negative value represents an underestimation. For the purpose of this study, the absolute mean error (the average error in the three trials ignoring the direction of the error), relative error (the average of the errors in the three trials taking into account the direction of the error) and variable error (the standard deviation of the three relative error measurements) were analyzed were calculated (Olsson et al., 2004). In Experiment 1, the results were then analyzed using a mixed-design analysis of variance for repeated measures (ANOVA) to determine whether differences existed between control and cold application sessions (between subject), pre- and post-treatment (within subject) and the five sectors of movement (within subject). Pre-test PPO, MVIC (Experiments 1 and 2) and force reproduction data were normalized to 100% and analyzed similar to JPS. The current study had an 80% power to detect a 1° difference in JPS error, a 7% difference in MVIC and a 0.2 °C difference between cold and control cold conditions. Data are presented as means and standard deviation. For all analysis, statistical significant was set at α = 0.05. All data are presented as mean ± SD.

### Results

#### Experiment 1

### Effects of WBC on proprioception

Comparisons of absolute, variable and relative angle errors for the two groups are displayed in Table 1. There was no significant between group differences for absolute ($F_{2,34} = 0.36$, $P = 0.36$, $1 - \beta = 0.22$), relative ($F_{2,34} = 1.1$, $P = 0.34$, $1 - \beta = 0.24$) or variable ($F_{2,34} = 2.91$, $P = 0.062$, $1 - \beta = 0.55$), error over time. There was no significance differences in MVIC between groups following treatment ($F_{2,34} = 2.01$, $P = 0.89$, $1 - \beta = 0.4$). Similarly, participants’ ability to reproduce either 25 or 50% of their MVIC was significantly better with visual and verbal feedback than without. However, there was no between group time differences ($F_{2,34} = 0.05$, $P = 0.95$, $1 - \beta = 0.06$).

### Tympanic temperature ($T_{TY}$)

$T_{TY}$ initial baseline values for the cold and control groups were 36.9 ± 0.3 °C and 36.8 ± 0.3 °C, respectively. The comparison of the change from baseline for both the cold and the control group revealed a significant difference in tympanic temperature, 3 and 8 min following exposure to the cold chamber ($P < 0.001$, Fig. 1). The lowest $T_{TY}$, 36.6 ± 0.4 °C, was recorded in the cold group 8 min after leaving the chamber. Twenty-two minutes post-treatment $T_{TY}$ for the cold group returned to 36.8 ± 0.4 °C. $T_{TY}$ for the control group did not change significantly over time.

#### Experiment 2

### Effects of WBC on muscle recovery following eccentric exercise

MVIC significantly declined from 806 ± 138 to 483 ± 122 N immediately after the damaging protocol ($F_{1,16} = 121.54$, $P < 0.001$, $1 - \beta = 0.99$, Fig. 2) and recovered thereafter to 98.7 ± 12.3% of pre-exercise values on day 5. The WBC treatment did
**Effects of whole-body cryotherapy**

Table 1. Comparison of absolute, relative and variable knee joint position angle errors of the right limb

<table>
<thead>
<tr>
<th></th>
<th>Pre-test (n = 18)</th>
<th>3 min post (n = 18)</th>
<th>20 min post (n = 18)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cold</td>
<td>Control</td>
<td>Cold</td>
</tr>
<tr>
<td>Absolute error</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10–30°</td>
<td>2.1 ± 2.2</td>
<td>2.1 ± 1.3</td>
<td>2.7 ± 1.7</td>
</tr>
<tr>
<td>30–60°</td>
<td>4.4 ± 3.0</td>
<td>3.0 ± 2.0</td>
<td>5.2 ± 2.4</td>
</tr>
<tr>
<td>60–90°</td>
<td>3.9 ± 2.0</td>
<td>2.4 ± 2.4</td>
<td>3.7 ± 2.5</td>
</tr>
<tr>
<td>Relative error</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10–30°</td>
<td>1.5 ± 2.6</td>
<td>−0.4 ± 2.4</td>
<td>2.0 ± 2.5</td>
</tr>
<tr>
<td>30–60°</td>
<td>4.0 ± 3.5</td>
<td>1.9 ± 3.1</td>
<td>5.2 ± 2.4</td>
</tr>
<tr>
<td>60–90°</td>
<td>3.4 ± 2.6</td>
<td>1.6 ± 3.0</td>
<td>3.5 ± 1.1</td>
</tr>
<tr>
<td>Variable error</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10–30°</td>
<td>1.0 ± 0.7</td>
<td>1.1 ± 0.7</td>
<td>1.0 ± 0.7</td>
</tr>
<tr>
<td>30–60°</td>
<td>1.9 ± 0.8</td>
<td>2.5 ± 0.9</td>
<td>1.7 ± 0.9</td>
</tr>
<tr>
<td>60–90°</td>
<td>1.6 ± 1.1</td>
<td>1.3 ± 0.8</td>
<td>1.4 ± 0.9</td>
</tr>
</tbody>
</table>

Values are means ± SD for cold (n = 18) and control (n = 18). A negative value (−) represents an under estimation.

Fig. 1. Tympanic temperature calculated as change from baseline in degrees Celsius. Values are means ± SD for cold (n = 18) and control (n = 18). Cold group significantly different from control group (P < 0.001, using a repeated measures analysis of variance and 95% confidence intervals) at 3 and 8 min after the climatic chamber.

Fig. 2. Normalized maximal voluntary isometric contraction (MVIC) of the left knee extensors before and after eccentric muscle contractions (0 h) and in the days following treatment administered at 24 h. Values are mean ± SD for both the cold (n = 9) and control (n = 9) groups. *Both groups MVIC reduced significantly following eccentric exercise, P < 0.05 using a repeated measures analysis of variance and 95% confidence intervals.

Fig. 3. Normalized rating of muscle soreness measured on a visual analogue scale, before (0 h) and after eccentric muscle damage and in the days following treatment administered at 24 h. Values are mean ± SD for both the cold (n = 9) and control (n = 9) groups. *Both groups muscle soreness increased when compared with baseline, P < 0.05 using a repeated measures analysis of variance and 95% confidence intervals.

not effect MVIC ($F_{3,48} = 0.88, P = 0.49, 1 – β = 0.23$; Fig. 2) when compared with the control treatment in the days following treatment. PPO was also unaffected by the treatment ($F_{1,16} = 1.41, P = 0.24, 1 – β = 0.21$). Similarly, there were no significant changes in the visual analogue scale between groups over time ($F_{4,64} = 0.3, P = 0.88, 1 – β = 0.11$; Fig. 3).

**Discussion**

The purpose of this study was to assess the immediate effects of WBC on knee JPS, MVIC of the knee extensors, knee submaximal force sensation and tympanic temperature (Experiment 1). This study, in Experiment 2, also aimed to assess the effectiveness of WBC in treating indices of muscle soreness and function, in the days following an eccentric
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exercise bout. The results of the current study suggest that despite a significant reduction in $T_{TV}$, there are no detrimental effects (in terms of proprioceptive acuity) of using WBC before exercise. This may have a future impact on the use of WBC before athletic participation or between training sessions. The results of this study also suggest that cold air cryotherapy, administered 24 h after an eccentric muscle damaging protocol, is ineffective in the treatment of muscle soreness or indices of muscle damage.

WBC and proprioceptive acuity

Despite the widespread use of cryotherapy before, during and after athletic participation, there are conflicting results regarding the effect of cold therapy on joint stability, neuromuscular and proprioceptive acuity (Costello & Donnelly, 2010). Any impairment in proprioceptive acuity could result in an increased predisposition to knee injury. Our findings demonstrate that knee JPS remained unaltered following the recommended exposure to WBC. These results support that of other published material using other forms of cryotherapy (LaRiviere & Osternig, 1994; Thieme et al., 1996; Uchio et al., 2003; Dover & Powers, 2004). Despite the significant reduction in tympanic temperature reported in this study and the significant reduction in core and skin temperature reported in other studies (Taghawinejad et al., 1989; Westerlund et al., 2003), it appears that a healthy individual’s ability to derive knee JPS is capable of withstanding the degree of cooling experienced in this cooling protocol. Because a methodology commonly used by sports people was utilized in the current study, it does not exclude the possibility that a different protocol, using a different duration or temperature would reduce knee JPS.

This is also the first controlled study that has assessed force loss after WBC. Similar to the results ascertained from JPS, no significant between group differences were recorded for MVIC following the cold exposures. Previous studies have assessed MVIC in the hand follow cryotherapy applications with contradicting results (Coppin et al., 1978; Douris et al., 2003; Westerlund et al., 2009). Both Douris et al. (2003) and Coppin et al. (1978) have reported previously a significant reduction in isometric grip strength follow cold water immersion (10 ºC). However, mirroring our results, Westerlund et al. (2009) have found wrist flexion MVIC following both a single bout and repeated bouts of WBC was not significantly altered. It must be acknowledged that a potential explanation for the contrasting findings of the current study and those of Westerlund et al. (2009) to that of Douris et al. (2003) and Coppin et al. (1978) is the cryotherapy modality used. These results suggest the existence of a disparity in the degree of muscle and joint cooling that occurs during both the locally applied cryotherapy and standardized −110 ºC WBC. Also, individuals can remain in cold water for longer durations than in cold air chambers, up to 30 min at 14 ºC; it is possible that greater reductions in skin, joint and muscle temperature are experienced in the water. This would be expected as a direct result of the greater thermal conductivity of water compared to air.

The relationship between a component of proprioception, force matching or force reproduction, in the knee joint, and cryotherapy is poorly understood. Force reproduction in the present study involved the use of a reference force, 25% and 50% of a subjects’ MVIC of the right knee extensors, and attempting to replicate that force. Research encompassing cryotherapy and force reproduction is severely limited, with only two studies to date having assessed the effects of cooling on submaximal force reproduction (Tremblay et al., 2001; Rubley et al., 2003). Both Rubley et al. (2003) and Tremblay et al. (2001) found separate cryotherapy applications to have no effect on force matching. Rubley et al. (2003) addressed the relationship between cryotherapy, in the form of a 15-min ice bath immersion (10 ºC), from 1 in. (2.54 cm) proximal to the medial epicondyle to the distal end of the fingers, and submaximal isometric force variability in the finger and thumb. They concluded that the application of ice had little effect on motor control of the digits, by stating that cryotherapy does not increase isometric targeting error or mean force standard deviation. Similarly, Tremblay et al. (2001) also found no influence on proprioceptive acuity in the quadriceps muscles after cooling in the form of a crushed ice application for a period of 20 min. Nonetheless, they concluded that care must be taken in return to participation, as performance is believed to be affected after cryotherapy.

Peripheral signals of cutaneous and muscle origin are very likely to be reduced after cooling, but skin afferent reductions have less implication on proprioceptive acuity than muscle afferents (Tremblay et al., 2001). An explanation to why weight discrimination (force proprioception) may not be affected according to LaRiviere and Osternig (1994) may be that inputs from joint receptors may be able to compensate for the reduction in muscle and skin afferents, which were reduced during cooling.

WBC and tympanic temperature

It has been reported previously that tympanic membrane thermometry is in good agreement with rectal thermometry (Dzarr et al., 2009). Scant data are available about thermal responses to WBC (Westerlund
et al., 2003). Taghawinejad et al. (1989) found a slight decrease of 0.38 °C in oral temperature, indicating that 90 s at −100 °C does not affect core temperature. Unfortunately, these authors did not report any values before or after the WBC. Westerlund et al. (2003) reported no significant decrease in rectal temperature following exposure to −110 °C for 2 min. This is the first study that has investigated $T_{TY}$ after a 3-min exposure to −110 °C, preceded by 20 s standing in −60 °C, with the results suggesting that it takes up to 15 min for it to return to baseline levels (Fig. 1). A potential explanation to why these results are in contrast to that of Westerlund et al. (2003) is the modality of core temperature recorded ($T_{TY}$ and rectal) and the duration of the exposure (3 and 2 min). However, despite the use of similar thermometers in similar conditions, the reliability of the $T_{TY}$ recording (Ganio et al., 2009) may not give an accurate recording of core temperature.

**WBC and recovery from eccentric exercise**

Despite the wealth of literature on cold water-based rehabilitation techniques, published data on WBC are scarce (Banfi et al., 2009, 2010; Klimek et al., 2010) and the scientific principals are often based on pilot studies (Banfi et al., 2010). Previous research in the area of WBC has successfully examined the effect of the treatment on other measures such as skin temperature (Westerlund et al., 2003), neuromuscular adaptations (Westerlund et al., 2009), serum mediators of inflammation and serum muscle enzymes (Banfi et al., 2009) and hematological values in athletes (Banfi et al., 2008). However, there is limited evidence to support the use of WBC in the recovery of exercise-induced muscle damage. To our knowledge, this is the first controlled study that has assessed muscle force recovery following eccentric muscle damage.

The current study shows a reduction of approximately 40% in knee extensor MVIC immediately after eccentric exercise and returned to baseline approximately 96 h after the exercise. However, there was no significant differences between groups (cold or control) throughout the duration of the study. The MVIC results of the current study are supported by others using cold water immersion (Goodall & Howatson, 2008) and ice application (Howatson et al., 2005). However, these results are in conflict with those of another study using a different cryotherapy protocol (Vaile et al., 2008). As this is the first controlled study that has aimed to assess WBC as a rehabilitative therapy following eccentric exercise, we cannot directly compare our finding with any other WBC study.

An individual’s ability to repeatedly produce short, maximal efforts with brief recovery periods is an important fitness requirement of team sport athletes. Improving the repeated-sprint ability of athletes has become a focus of training and indeed rehabilitative programs for many sports (McGawley & Bishop, 2006). The repeated cycling sprint test utilized in the current study is similar to that used elsewhere (McGawley & Bishop, 2006). The results of the current study suggest that two 3-min bouts of WBC (−110 °C) are ineffective in altering PPO following this specific eccentric muscle damaging protocol, when compared with a cold group. However, the results of the current study did not show any decrease, in either the control or the cold group, following eccentric exercise. A potential explanation for this is that either the subjects had sufficiently recovered 48 h after eccentric exercise, as PPO was not assessed at 24 h, or that eccentrically exercising one leg did not reduce PPO during the two-legged cycling protocol.

Soreness is the most commonly measured marker of eccentric muscle damage (Warren et al., 1999). The most commonly used method for determining soreness is by palpation with a self-reported questionnaire or visual analogue scale (Warren et al., 1999). However, the limitation with self-reported assessments is that the measures are subjective, and therefore a comparison between subjects in studies is not the most reliable method of assessment. The application of cold for relieving pain and acting as an analgesic is common practice in clinical, medical and sports fields. This most likely reflects the potential of cold treatments to reduce the inflammatory response and consequent secondary muscle damage. As WBC has been shown previously to limit the increase of muscular enzymes creatine kinase (Wozniak et al., 2007; Banfi et al., 2009) and lactate dehydrogenase (Banfi et al., 2009), induce an increase of anti-inflammatory cytokines IL-10 (Banfi et al., 2009) and IL-6 (Lubkowska et al., 2010) and a decrease of pro-inflammatory cytokine IL-2, chemokine IL-8 and prostaglandin E2 (Banfi et al., 2009), it is possible that this treatment may reduce muscle soreness after eccentric exercise. Different modalities of cryotherapy, including ice therapy (Howatson et al., 2005), cold water immersion (Goodall & Howatson, 2008), contrast water therapy (Vaile et al., 2008) and a combination of these treatments (Vaile et al., 2008) have been studied with conflicting results regarding muscle soreness recovery. The results of the current study suggest that two 3-min bouts of WBC (−110 °C) is ineffective in alleviating subjective assessments of muscle soreness following this specific eccentric muscle damaging protocol. These findings are supported by others using different modalities of cryotherapy (Howatson et al., 2005; Goodall & Howatson, 2008).
Methodological considerations

The eccentric exercise bout used in this study may not accurately reflect the soreness and damage experienced during participation in other exercise. In addition, further controlled studies are required to assess the effect of WBC on muscle soreness, muscle function and PPO administered at a different time point other than that used in the current study (24 h post-exercise) and in different populations, including an athletic population. The current study did not record skin, muscle or joint temperature and further research is required to prove whether WBC alters these temperatures. Also, using aural measurement of core temperature when the ears are exposed to cold may give unreliable results, and therefore the T_{\text{TY}} data need to be treated with caution.

When compared with a control temperature, the major findings of this investigation are WBC significantly reduces T_{\text{TY}}; WBC does not deteriorate JPS, MVIC or force production and finally WBC, administered 24 h following eccentric exercise, is ineffective in alleviating muscle soreness or improving recovery. To our knowledge, this study is the first to report the effects of WBC on T_{\text{TY}}, knee JPS, MVIC and force reproduction. This is also the first controlled study to assess the effect of WBC, administered 24 h after an eccentric muscle damaging protocol, on indices of muscle soreness and function (MVIC, PPO and subjective assessments of muscle soreness measured by questionnaires). Although we have reported no improvements following eccentric muscle damage, these findings suggest that a healthy individual’s ability to perform MVIC of the knee extensors or proprioceptive-related tasks is unaltered, following WBC.

Perspectives

Performing eccentric contractions is a fundamental part of athletic performance and often leads to a delayed onset of muscle soreness. This relatively novel modality of cryotherapy (WBC) has been advocated a means of recovery following athletic participation. Similarly, the use of WBC has been supported either before or between sporting activities for various reasons. The results of the current study suggest that although WBC does not increase the risk of proprioceptive related injury, it is ineffective in improving recovery if administered 24 h after eccentric exercise. Data presented here can only be applied when WBC is administered 24 h after exercise and do not exclude the potential positive effects of using a different treatment regimen or using WBC as a prophylactic treatment.

Key words: eccentric exercise, joint position sense, maximal voluntary contraction, muscle soreness.

Acknowledgements

The authors would like to acknowledge the undergraduate student researchers Linda Coughlan, Stephen Kelleher and Barry Keogh who assisted in the data collection and Shannon Cryotherapy Clinic, Ennis, Co. Clare, Ireland, for the use of their cryotherapy chamber.

References


Effects of whole-body cryotherapy


The use of thermal imaging in assessing skin temperature following cryotherapy: a review

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ABSTRACT

Background: Cryotherapy is used in various clinical and sporting settings to reduce oedema, decrease nerve conduction velocity, decrease tissue metabolism and to facilitate recovery after exercise induced muscle damage. The basic premise of cryotherapy is to cool tissue temperature and various modalities of cryotherapy such as whole body cryotherapy, cold spray, cryotherapy cuffs, frozen peas, cold water immersion, ice, and cold packs are currently being used to achieve this. However, despite its widespread use, little is known regarding the effectiveness of different cryotherapy modalities to reduce skin temperature.

Objectives: To provide a synopsis of the use of thermal imaging as a method of assessing skin temperature following cryotherapy and to report the magnitude of skin temperature reductions associated with various modalities of cooling.

Methods: Three electronic databases were searched using keywords and MESH headings related to the use of thermal imaging in the assessment of skin temperature following cryotherapy. A hand-search of reference lists and relevant journals and text books complemented the electronic search.

Summary: Nineteen studies met the inclusion criteria. A skin temperature reduction of 5–15°C, in accordance with the recent PRICE (Protection, Rest, Ice, Compression and Elevation) guidelines, were achieved using cold air, ice massage, crushed ice, cryotherapy cuffs, ice pack, and cold water immersion. There is evidence supporting the use and effectiveness of thermal imaging in order to access skin temperature following the application of cryotherapy.

Conclusions: Thermal imaging is a safe and non-invasive method of collecting skin temperature. Although further research is required, in terms of structuring specific guidelines and protocols, thermal imaging appears to be an accurate and reliable method of collecting skin temperature data following cryotherapy. Currently there is ambiguity regarding the optimal skin temperature reductions in a medical or sporting setting. However, this review highlights the ability of several different modalities of cryotherapy to reduce skin temperature.

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1. Overview

Cryotherapy, the therapeutic use of cold, is applied in various clinical, rehabilitative and sporting settings to reduce edema, decrease tissue metabolism and provide analgesia (Knight, 1995). The basic premise of cryotherapy is to cool tissue temperature (Bleakley and Hopkins, 2010); various modalities such as whole body cryotherapy, cold water immersion, ice, and cold packs are currently used to achieve this. Each of these cooling modalities has a different thermal property and therefore a different skin cooling potential (Bleakley and Hopkins, 2010). Skin temperature is a very important physical attribute and is used as a diagnostic parameter in various medical and sporting settings (Cholewka et al., in press). The magnitude of skin tissue cooling achieved in cryotherapy determines the treatment’s ability to simultaneously achieve a meaningful analgesic effect and avoid adverse effects. Recent guidelines suggest that skin temperature reductions to less than 12°C are optimal for achieving analgesia (Bleakley et al., 2011, Bleakley and Hopkins, 2010). An optimal or safe lower limit for skin temperature is less clear however. Several instances of ice burn and even amputation are reported in the literature following prolonged or inappropriate cooling (Selife et al., 2007). Other adverse events associated with excessive cooling include: nerve damage (Heiness et al., 1998; Moeller et al., 1997), cold urticaria (Dover et al., 2004), and compartment syndrome (Khajavi et al., 2004).

There are a significant number of cold modalities available to practitioners and athletes; knowledge of their cooling capacity is central to clinical safety and effectiveness. Non-contact thermal imaging (TI) is a safe non-invasive method of collecting real time Skin Temperature (Tsk) data (Sherman et al., 1996, Hildebrandt et al., 2010). Infra red TI has been used in medicine since the early 1960’s (Ring and Ammer, 2000) and utilises the phenomenon that living and non living objects all emit infrared radiation to some extent. When the emissivity, the relative ability of a surface to emit energy by radiation, is known the intensity of infrared radiation can be used for calculation of the temperature of the emitting object. The technology is a sophisticated way of receiving the electromagnetic radiation and converting it into electrical signals (Hildebrandt et al., 2010). These signals are finally displayed in gray shades or colours which represent temperature values (Hildebrandt et al., 2010). An example of an infrared thermal image of the anterior human body is displayed in Fig. 1. TI is widely used in medical settings such as cancer research (Head and Elliot, 1995) and fever screening (Hewlett et al., 2011) to detect and locate thermal abnormalities characterized by an increase or decrease found at the skin surface (Hildebrandt et al., 2010). Selife et al. (2006) and Kennet et al. (2007) have previously highlighted the effectiveness and the reliability of the use of TI to measure Tsk. The use of TI has recently become a popular method of assessing skin temperature following cryotherapy such as cold air cryotherapy, cold water immersion, ice cubes or cold packs in humans to assess skin temperature. TI has been advocated in cryotherapy research primarily because it allows temperature data over the whole of the cooled area to be collected as opposed to a spot measurement obtained with a thermocouple (Hardaker et al., 2007).

Despite the significant number of original research studies and reviews assessing the effects of cryotherapy on Tsk, the optimal Tsk reductions in a clinical or sporting setting remains to be fully established (Bleakley et al., 2011, Bleakley et al., in press). Consequently, answers to questions such as “what method of cryotherapy is the most effective in reducing skin temperature?”, “is thermal imaging a reliable method of assessing skin temperature following cryotherapy?” and “what reduction in skin temperature is safe?” remain to be fully elucidated. Therefore the objectives of this current review was to determine (a) the effectiveness of TI in assessing skin temperature following cryotherapy and (b) the effect of different modalities on reducing skin temperature.

2. Research methods

We searched Medline, Pubmed, and Science Direct search engines to identify studies that assessed skin temperature following a cryotherapy application using infrared thermal imaging.

Fig. 1. An example of an anterior and posterior image of a subject in the anatomical position using infrared thermography. The inert markers, used to create regions of interest, are visible on the acromion, anterior superior iliac spine, posterior superior iliac spine, at the level of the olecranon, the popliteal fold, and 5 cm above and below the patella. The white frame, using the inert makers, creates a region of interest in the thigh.
Keywords used included “thermal imaging and cryotherapy”, “thermal imaging and cooling”, “thermology and cryotherapy”, “skin temperature and cryotherapy”, “skin temperature and cooling”, and “thermology and cooling”. No restrictions were made on study design or comparison group. Due to the advent of digital technology which has revolutionised the field of thermal imaging original papers published in the last decade were preferentially considered. The inclusion criteria for study selection were (1) the literature was written in English, (2) participants were human, (3) skin temperature assessed following a cryotherapy application, and (4) infrared thermal imaging was used to assess skin temperature. Articles were excluded if the title or abstract did not meet the inclusion criteria. Potentially relevant articles were also obtained by physically searching the bibliographies of included studies to identify any study that may have escaped the original search.

3. Magnitude and duration of skin tissue cooling

Physiotherapists, coaches, athletic trainers, and clinicians administer cryotherapy for numerous reasons, including the reduction of pain and swelling, to relieve muscle spasm, and to facilitate movement (Costello and Donnelly, 2011; Costello et al., in press). It has previously been suggested that cold application may relieve pain by numerous mechanisms including altered nerve conduction velocity (NCV), inhibition of nociceptors, a reduction in muscle spasm and/or a reduction in metabolic activity (Algafly and George, 2007; Airaksinen et al., 2003). The magnitude of tissue cooling following cryotherapy is therefore critically important as nerve conduction velocity is significantly and progressively reduced concomitantly with skin temperature following cold application (Algafly and George, 2007).

Of the 19 reviewed studies, which satisfied the inclusion criteria, 6 (Cholewka et al., 2004; Cholewka et al., 2006; Cholewka et al., 2010; Cholewka et al., in press; Gong et al., 2011; Klimek et al., 2011) assessed skin temperature following Whole Body Cryotherapy (WBC), 5 utilised a cryotherapy cuff (Selfe et al., 2010; Selfe et al., 2006; Robinson et al., 2010; Karki et al., 2004; Selfe et al., 2009), 4 after crushed ice (Kennett et al., 2007; Hardaker et al., 2007; Herrera et al., 2010; Selfe et al., 2009), 4 after cold water (Kennett et al., 2007; Fushimi et al., 1992; Herrera et al., 2010; Rasmussen and Mercer, 2004), 2 after gel pack (Kennett et al., 2007, Ring et al., 2004a), 2 cooling gel (Ring et al., 2004a, Ring et al., 2004b), 1 ice massage (Herrera et al., 2010; Rasmussen and Mercer, 2004) on skin temperature following the application of ice massage (Herrera et al., 2010). However, larger reductions in skin temperature may cause injury (Bleakley and Hopkins, 2010). Fig. 2 displays the maximum skin temperature reduction recorded by TI following the different cryotherapy modalities. Skin temperature of less than 12 °C were achieved using ice massage, cold air, crushed ice, cryo cuff, ice pack, and cold water immersion (Fig. 2). WBC, cold air, gel packs, cryo cuff, cold water immersion, ice packs, and frozen peas were all effective in reducing skin temperature by more than 5 °C at various locations. WBC did not reach the PRICE guidelines, with reductions of less than 5 °C at the hands, chest, and forehead. However, it must be noted that during WBC in order to protect the face and extremities against the extreme cooling, subjects have to wear a mask, ear protection, socks, shoes, and gloves and this attire may explain why these skin temperatures were not as significantly reduced as other regions. Similarly, a 10 min application of Deep Freeze Cooling Gel and a 3 min application of a cryo cuff were ineffective at reducing skin temperature in the back and knee respectively. Of the 19 included studies the lowest absolute skin temperature reported was 3.98 °C, a mean reduction of 27.6 (±1.32) °C following the application of ice massage (Herrera et al., 2010). However, it must be noted that Malone et al. (1992) have previously stated that if the peripheral nerve is cooled below 10 °C or if skin temperature is cooled to between 0 and 5 °C, cryotherapy can disturb function and cause motor/sensory loss.

In both a clinical and sporting setting, what happens to the temperature of the skin in the recovery period subsequent to the removal of the cold modality is of interest. In addition to reported skin temperature measurements immediately after the removal of the cryotherapy application, eleven of the reviewed studies reported follow up assessments of skin temperature. An interesting finding in all of these studies was that subjects’ skin temperature, during follow up data collection, did not return to baseline levels after cryotherapy. In one study skin temperature still had not returned to baseline levels 120 min after exposure to cold air (Kim et al., 2002). In another study skin temperature 35 min after cold water immersion remained 11 °C lower than baseline (Kennett et al., 2007). Furthermore, Klimek and colleagues (2011) utilising a WBC protocol have reported significant reduction in thigh surface temperature 90 min following exposure in both males and females. It is common practise that cold is applied intermittently with periods of application and removal. The time period following removal of the cold modality should therefore be considered an important part of cryotherapy treatment sessions to achieve full therapeutic benefit (Hardaker et al., 2007). Clinicians must therefore be aware that during these cycles skin temperature may not have returned to baseline levels and need to be cognisant of the potential for cold induced injury.

As cryotherapy is often applied to treat muscle injuries it is also important to consider the relationship between skin and intramuscular temperature. The reporting of skin temperature...
has been criticised as being of limited value when observing the influence of cooling on subcutaneous tissues, with a number of studies suggesting there is no relationship between skin and muscle temperature. However, Hardaker et al. (2007) have reported that a strong negative quadratic relationship exists between intramuscular and skin temperature. These authors (Hardaker et al., 2007) report that the amount of heat an object can hold is directly proportional to its volume and therefore the temperature of the muscle may be derived using the dispersion in the underlying tissue volume and the surface area of the skin that is being cooled. Interestingly as the skin temperature increases following the removal of the cryotherapy application intramuscular temperature decreases as the superficial tissues draw heat from the deeper tissues (Hardaker et al., 2007). Therefore, this is why the maximum reduction of muscle temperature is often recorded after the removal of cold, when the skin temperature has increased.

4. Technical issues with the methodology of thermal imaging following cryotherapy

Hardware and analysis software produced by Flir Systems (Danderyd, Sweden) was the most commonly used in this review. In terms of the area thermographed the knee (Selfe et al., 2010; Selfe et al., 2009; Selfe et al., 2007; Kim et al., 2002; Karki et al., 2004) was the most common with five studies focusing on that joint. Other studies focused the ankle (Kennet et al., 2007), chest (Cholewka et al., in press), thigh (Hardaker et al., 2007), and back (Cholewka et al., in press, Cholewka et al., 2006; Cholewka et al., 2004) following a cryotherapy application. While Cholewka et al. (2004) reported skin temperature information from the head, anterior and posterior view of the maximum skin temperature reduction following the different cryotherapy modalities. Air = Localised Cold Air, (A)(P)CC = Analogue/Pump Cryo Cuff, IM = Ice massage, CI = Crushed Ice, CWT = Cold Water Immersion, DF = Deep Freeze Cooling Gel, FP = Frozen Peas, GP = Gel Pack, WBC = Whole Body Cryotherapy (Cold Air). The superscripted numbers after the modality abbreviation indicate the relevant study where information was extracted. Cholewka et al. (2004)1, Cholewka et al. (2006)2, Cholewka et al. (in press)3, Hardaker et al. (2007)4, Herrera et al. (2010)5, Karki et al. (2004)6, Kennet et al. (2007)7, Kim et al. (2002)8, Rasmussen and Mercer (2004)9, Ring et al. (2004a)10, Ring et al. (2004b)11, Robinson et al. (2010)12, Selfe et al. (2007)13, Selfe et al. (2009)14, Selfe et al. (2010).15

Three further components to consider during thermal imaging is the distance the camera is from the area or region being thermographed, the room temperature of the laboratory where the TI took place (Ring and Ammer, 2000) and the emissivity factor. A limitation with the majority of the studies in this review was the failure to report either of these. The distance the area being thermographed is from the camera lens will affect the pixel resolution and has potential to alter the robustness of the data. It has also been suggested that a range of temperatures from 18 to 25°C should be used during TI (Ring and Ammer, 2000). If the temperature range is below thermoneutral, the subject is likely to shiver, and above 25°C room temperature is likely to cause sweating, which will affect the reading (see Table 1). In addition, during the analysis of skin temperature following the use of TI an emissivity of 0.97–0.98 has been recommended and used regularly in the literature (Stekete, 1973; Cholewka et al., in press). However, a number of the reviewed studies have again failed to report what emissivity factor was used during data collection. This is perturbing as the use of an incorrect emissivity would lead to an erroneous recoding of skin temperature.

5. Advantages and limitations of infrared imaging following cryotherapy

A number of methods and devices of recoding skin temperature following the application of cryotherapy have been reported in the literature including thermocouples (Merrick et al., 2003),...
Table 1
Studies assessing skin temperature following cryotherapy using thermal imaging.

<table>
<thead>
<tr>
<th>Author</th>
<th>Population N (M:F)</th>
<th>Treatment</th>
<th>Methodology</th>
<th>Immediate effects</th>
<th>Duration of effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cholewka et al. (2004)</td>
<td>(a) N=22 (17:5) LBP, Age=47.1 ± 10.1</td>
<td>WBC (−120 °C w/−60 °C)</td>
<td>– r=−N/A</td>
<td>– Back</td>
<td>N/A</td>
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<td></td>
<td>(b) N=8 (7:1) Healthy, Age=25 ± 4.1</td>
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<td></td>
<td>– Pre &amp; immediately post Rx</td>
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<td>– $T_{room}=n/a$</td>
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<tr>
<td>Cholewka et al. (2006)</td>
<td>(a) N=16 (10:6) LBP, Age=25.6 ± 3.9</td>
<td>WBC (−120 °C w/−60 °C)</td>
<td>– r=−2 min (1st session), 3 min (2nd &amp; 3rd session)</td>
<td>– T1/T2 to L5/S1</td>
<td>N/A</td>
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<tr>
<td></td>
<td>(b) N=30 (23:7) Healthy, Age=41.9 ± 12</td>
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<td>– Pre &amp; immediately post Rx</td>
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<td>– $T_{room}=21.5 ± 1 °C$</td>
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<tr>
<td>Cholewka et al. (2010)</td>
<td>(a) N=18 (18:0) Ankylosing spondylitis, Age=50.6 ± 8</td>
<td>WBC (−120 °C w/−60 °C)</td>
<td>– r=3 min</td>
<td>– T1/T2 to L5/S1</td>
<td>N/A</td>
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<tr>
<td></td>
<td>(b) N=15 (13:2) Sciatica, Age=44.7 ± 7.6</td>
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<td>– Pre &amp; immediately post Rx</td>
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<td></td>
<td>(c) N=6 (6:0) Spondylarthrosis, Age=46 ± 11.7</td>
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<td></td>
<td>– d=1.2–1.5 m</td>
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<td></td>
<td>(d) N=11 (11:0) Healthy, Age=34 ± 7.9</td>
<td></td>
<td></td>
<td>– $T_{room}=22.1 ± 1 °C$</td>
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<tr>
<td>Cholewka et al. (in press)</td>
<td>Healthy, age=47.1 ± 10.1 22 (17:5)</td>
<td>WBC (−120 °C w/−60 °C)</td>
<td>– r=3 min</td>
<td>– Whole body by summation feet, shank, back, chest, arms, hands, head</td>
<td>N/A</td>
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<td>– Pre &amp; immediately Post Rx</td>
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<td>– d=1.0–1.5 m</td>
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<td></td>
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<td></td>
<td>– $T_{room}=23 ± 1 °C$</td>
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<tr>
<td>Gong et al. (2011)</td>
<td>Cervical disk herniation</td>
<td>WBC (−110 °C w/−60 °C)</td>
<td>– r=60 s (−60 °C), 2.5 min (−110 °C), 30 sec (−60 °C)</td>
<td>– Upper trapezius, biceps brachii, triceps brachii</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>(a) N=10 (3:7) Control, Age=35.1 ± 5.8</td>
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<td>– Pre &amp; post Rx</td>
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<td></td>
<td>(b) N=10 (2:8) WBC, Age=34.8 ± 4.2</td>
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<td>– $T_{room}=23–24 °C$</td>
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<tr>
<td>Hardaker et al. (2007)</td>
<td>Healthy, age=27.8 9 (9:0)</td>
<td>CI</td>
<td>– Thigh</td>
<td>– Thigh</td>
<td>16 °C&lt;sup&gt;b&lt;/sup&gt;</td>
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<td></td>
<td></td>
<td></td>
<td>– r=15 min</td>
<td>– Pre &amp; immediately Post Rx (image/min for 40 mins)</td>
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<td></td>
<td>– $T_{room}=22 °C$</td>
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<tr>
<td>Herrera et al. (2010)</td>
<td>Healthy, age=20.5 ± 1.9 36 (18:18)</td>
<td>CI, Ice massage CWI</td>
<td>– Shank</td>
<td>– Shank</td>
<td>CI=24.43 °C&lt;sup&gt;b&lt;/sup&gt;, Ice massage=27.6 °C&lt;sup&gt;b&lt;/sup&gt;, CWI=18.23 °C&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>– Pre &amp; post Rx</td>
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<td>– d=as close as possible</td>
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<td>– $T_{room}=24 ± 0.08 °C$</td>
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<tr>
<td>Karki et al. (2004)</td>
<td>Healthy</td>
<td>CC</td>
<td>– Patella</td>
<td>– Patella</td>
<td>(a) 1.0 °C&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td></td>
<td>(a) N=19 (19:0), Age=25.2</td>
<td></td>
<td></td>
<td>– Pre &amp; post Rx (1 image/min for 25 mins)</td>
<td>(b) 1.1 °C&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td></td>
<td>(b) N=20 (0:20), Age=25.6</td>
<td></td>
<td></td>
<td>– $T_{room}=20.2–23.3 °C$</td>
<td></td>
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<tr>
<td>Kennet et al. (2007)</td>
<td>Healthy, age=24 ± 4.6</td>
<td>CI, GP, FP, CWI</td>
<td>– Lateral aspect of the ankle</td>
<td>– Pre &amp; immediately Post Rx (1 mage/min FP=14.59 ± 4.22 °C, CWI=16.99 ± 2.76 °C&lt;sup&gt;b&lt;/sup&gt;)</td>
<td>CI did not return to baseline $T_{sk}$ after 35 min (remained 11.8 °C lower)</td>
</tr>
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Table 1 (continued)

<table>
<thead>
<tr>
<th>Author</th>
<th>Population N (M:F)</th>
<th>Treatment</th>
<th>Methodology</th>
<th>Immediate effects</th>
<th>Duration of effects</th>
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<td>Kim et al. (2002)</td>
<td>Healthy, age=33.8±12.7 20 (15:5)</td>
<td>Cold Air</td>
<td>− K &amp; J, lateral aspect</td>
<td>− 12 Yes, Post Rx (1 image/30 s) &amp; Post Rx (1 image/min for 10 min+ 5 min for 120 min)</td>
<td>− T${\text{room}}$=26–28°C</td>
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<tr>
<td>Rasmussen and Mercer (2004)</td>
<td>Healthy</td>
<td>CWI</td>
<td>− Hand &amp; Foot</td>
<td>− i) Hands and (ii) Feet</td>
<td>− T${\text{room}}$=N/A</td>
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<tr>
<td></td>
<td>(a) N=12 (12:0) Young, Age=24.8±3</td>
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<td></td>
<td>(b) N=12 (12:0) elderly, Age=76.9±1</td>
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<td></td>
<td>24 (24:0)</td>
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<tr>
<td>Ring et al. (2004a)</td>
<td>Healthy</td>
<td>DFCG &amp; IP</td>
<td>− Lumbar Spine</td>
<td>− Pre &amp; post Rx (1 image/3 min for 1 hr)</td>
<td>− DFCG=4.5°C, IP=6°C</td>
</tr>
<tr>
<td></td>
<td>N=4 (4:0), Age=26.5</td>
<td></td>
<td>− Lumbar Spine</td>
<td>− d=0.7 m</td>
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<tr>
<td></td>
<td>N=2 (0:2), Age=32 &amp; 26</td>
<td></td>
<td>− Lumbar Spine</td>
<td>− T${\text{room}}$=22°C</td>
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<tr>
<td></td>
<td>6 (n/a)</td>
<td></td>
<td>− Lumbar Spine</td>
<td>− Pre &amp; post Rx (1 image/3 min for 1 hr)</td>
<td>− DFCG=6°C</td>
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<td>− T${\text{room}}$=23±1°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>− DFCG2 - rubbed in</td>
<td>− T${\text{room}}$=23±1°C</td>
</tr>
<tr>
<td>Robinson et al. (2010)</td>
<td>Carpel tunnel syndrome, age=54.7</td>
<td>CC</td>
<td>(i) 2nd digit</td>
<td>PreOp Hand-i=6.2°C</td>
<td>− DFCG did not return to baseline Tsk after 60 min (remained 6°C lower)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(ii) 5th digit</td>
<td></td>
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<tr>
<td></td>
<td>14 (6:8)</td>
<td></td>
<td>− Pre &amp; Post Rx (1 image/3 min for 20 min)</td>
<td>− T${\text{room}}$=20.2–23.3°C</td>
<td>− DFCG=6°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>− T=3 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>− Pre &amp; Post Rx (1 image/min for 20 min)</td>
<td>− d=0.8 m</td>
<td>− T${\text{room}}$=N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>− T=3 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Selle et al. (2006)</td>
<td>Anterior knee pain 9 (n/a)</td>
<td>CC</td>
<td>-Knee</td>
<td>N/A</td>
<td>− PreOp Finger-ii=9°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Pre &amp; Post Rx (1 image/3 min for 20 min)</td>
<td>− T${\text{room}}$=20.2–23.3°C</td>
<td>− DFCG=6°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- d=0.8 m</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>- T=3 min</td>
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</tr>
</tbody>
</table>
thermists (Gregson et al., 2011), and other wireless sensors such as an iButton (Lichtenbelt et al., 2006). The greatest advantage of TI over these other methods of assessing skin temperature is the fact this it is non-invasive and portable. TI does not have to be in contact with the skin, an obvious advantage for measurement, especially in a clinical context. Skin thermistors and thermocouples often consist of a thin metallic foil which serves as a heat spreader backed by a foam insulation pad. This has the potential of creating a layer of insulation over the area of skin being assessed and therefore significantly degrades the accuracy of the measured temperature (Boetcher et al., 2009). This artefact of testing, recording, and reporting erroneous skin temperature data is therefore troublesome, especially if the temperature of the skin is being assessed during (or after) a cryotherapy treatment. The prime advantage that TI has over thermistors is the wealth of data that TI collects. Temperature variation over large areas of skin can be quantified quickly and accurately, with high resolution rendering each image the equivalent of hundreds or thousands of individual thermistor readings.

With the ability to create a ROI (see Fig. 1), using anatomical landmarks or inert markers as reference points, TI also allows an investigator to study a number of different (and larger) skin temperature sites. As a result the clinician can be confident that it is the actual temperature of the area of interest and is not confined to the spot measurements like the other techniques. In addition, of particular interest following cryotherapy or thermotherapy applications, TI has the capability to record the maximum, minimum, and average skin temperature at any site. An ability to record the minimum skin temperature may be useful in future research on potential cold induced injury, which the minimum skin temperature rather than the average is pertinent. Furthermore, TI allows you to record, store, and prints print images. This may be useful if recorded data needs to be retrospectively revisited, viewed or realanalysed.

In order to collect and report robust skin temperature data, clinicians and researchers alike face a number of challenges. In essence skin temperature data collection is inherently difficult to standardise due primarily to intrinsic and extrinsic factors. Intrinsic variables describe factors relating to the individual subject/patient and include caffeine/alcohol consumption, smoking, recent physical activity, circadian rhythm, and gender. The influence of draughts, environmental temperature, heat sources (e.g. sun, radiators), acclimation period and clothing are some examples of extrinsic variables that may also have a significant effect on TI data. The majority of these variables can be relatively well controlled through effective protocol planning and communication with the subject prior to the commencement of TI but clinicians and researchers should be cognisant of these variables and endeavour to reduce their contribution. Although these intrinsic and extrinsic variables are not isolated to skin temperature assessments via TI, individually or collectively these factors could have a significant physiological effect and alter skin temperature recordings. Consequently, any protocol that included skin temperature assessment requires a great deal of planning and consistency.

One of the major limitations of TI is that to date, no standardised framework has been established (Ammer, 2008). Compared to other techniques that can assess skin temperature data, such as thermocouples or thermists, TI can be expensive. Additionally, as moisture emits radiation, in order to use TI the skin surface must be completely dry. Any excess water on the skin (which is likely to occur following cold water immersion or any ice application) needs to be removed. Finally, compared to thermocouples or thermists which could utilise a hand held battery operated devise, a computer with specialised software is usually required for TI and often a power source is required. This may
reduce the effectiveness of TI as a technique of assessing skin temperature outside or in a field based study, as we have previously highlighted the potential effects varying ambient temperature or draughts may have on skin temperature.

6. Conclusion

Thermal imaging is a safe and non-invasive method of collecting skin temperature. Although further research is required, in terms of structuring specific guidelines and protocols, thermal imaging appears to be an accurate and reliable method of collecting skin temperature data following cryotherapy. Despite the ambiguity regarding optimal skin temperature reductions in a clinician or sporting setting, this review highlights the ability of several different modalities of cryotherapy, including WBC, cold air, gel packs, cryo cuff, cold water immersion, ice packs, and frozen peas, to reduce skin temperature in accordance with the recent PRICE guidelines.

Conflict of interest statement

The authors declare they have no conflict of interest on the content of this paper.

References


Should Athletes Return to Sport After Applying Ice?
A Systematic Review of the Effect of Local Cooling on Functional Performance

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3 Sports Institute Northern Ireland, University of Ulster, Newtownabbey, County Antrim, Northern Ireland

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Abstract

Applying ice or other forms of topical cooling is a popular method of treating sports injuries. It is commonplace for athletes to return to competitive activity, shortly or immediately after the application of a cold treatment. In this article, we examine the effect of local tissue cooling on outcomes relating to functional performance and to discuss their relevance to the sporting environment. A computerized literature search, citation tracking and hand search was performed up to April, 2011. Eligible studies were trials involving healthy human participants, describing the effects of cooling on outcomes relating to functional performance. Two reviewers independently assessed the validity of included trials and calculated effect sizes. Thirty five trials met the inclusion criteria; all had a high risk of bias. The mean sample size was 19. Meta-analyses were not undertaken due to clinical heterogeneity. The majority of studies used cooling durations >20 minutes. Strength (peak torque/force) was reported by 25 studies with approximately 75% recording a decrease in strength immediately following cooling. There was evidence from six studies that cooling adversely affected speed, power and agility-based running tasks; two studies found this was negated with a short rewarming period. There was conflicting evidence on the effect of cooling on isolated muscular endurance. A small number of studies found that cooling decreased upper limb dexterity and accuracy. The current evidence base suggests that athletes will probably be at a performance disadvantage if they return to activity immediately after cooling. This is based on cooling for longer than 20 minutes, which may exceed the durations employed in some sporting environments. In addition, some of the reported changes were clinically small and may only be relevant in elite sport. Until better evidence is available, practitioners should use short cooling applications and/or undertake a progressive warm up prior to returning to play.

1. Introduction

Applying ice or other forms of topical cooling is a popular method of treating acute sports injuries. In competitive sport, this may occur during a game, pitch-side or at half time. The premise is usually to provide cold-induced analgesia,[1] and athletes will often return to competitive activity shortly or immediately after the application of a cold treatment. In addition to providing pain relief, local cooling has the potential to produce concomitant effects on many other physiological systems. A recent systematic review by Costello and Donnelly[2] found limited equivocal evidence on the effect that joint cooling has on proprioception (joint positional sense); as such, the authors advised caution when individuals are returning to competition immediately after cooling.

Although the analgesic effects of cooling are well established,[1] these must be balanced with any potential adverse effects to make clear recommendations for its use. Currently, there is little evidenced-based consensus on how cooling may affect other physiological systems relevant to sports and exercise; a large magnitude of effect...
could implicate sporting performance and injury risk. Our aim was to undertake a systematic review to examine the effect of tissue cooling on outcomes relating to functional performance, and to discuss their relevance to the sporting community.

2. Literature Search Methodology

2.1 Search Strategy

We searched MEDLINE, the Cochrane Central Register of Controlled Trials (CCTR) and EMBASE. Eighteen MeSH or keywords were combined. Results were limited to human participants, and subject headings were modified for use in CCTR and EMBASE. Each database was searched from their earliest available record up to April, 2011. We also searched Current Controlled Trials and the WHO International Clinical Trials Registry for ongoing and recently completed trials and undertook a related articles search on PubMed, and read reference lists of all incoming articles. English language restrictions were applied.

2.2 Inclusion Criteria

No restrictions were made on the study design or comparison group. Studies must have involved human participants treated with a local cooling intervention. Whole-body cooling interventions, e.g. cold water immersion above the waist or whole-body cryotherapy using an environmental chamber, or other forms of cold air cooling, were excluded. Studies must have reported at least one outcome relating to functional performance (e.g. muscle strength, power, speed, agility, accuracy movement) that was measured both before and after a cooling intervention. Studies measuring strength or force production during evoked muscle contractions were not considered.

2.3 Selection of Studies

Two authors (CB, PG) independently selected trials for inclusion. The titles and abstracts of publications obtained by the search strategy were screened. All trials classified as relevant by either of the authors were retrieved. Based on the information within the full reports, we used a standardized form to select the trials eligible for inclusion in the review. Disagreement between the authors was resolved by consensus, or third-party adjudication (JC).

2.4 Data Extraction and Management

Data were extracted independently by two review authors (CB, JC) using a customized form. This was used to extract relevant data on methodological design, eligibility criteria, interventions (including detailed characteristics of the cooling protocols), comparisons and outcome measures. Any disagreement was resolved by consensus, or third-party adjudication (PG). To perform intent-to-treat analysis, where possible, data were extracted according to the original allocation groups, and losses to follow-up were noted. There was no blinding to study author, institution or journal at this stage.

2.5 Measures of Treatment Effect

For each study, mean differences (MD) or standardized mean differences (SMD) and 95% confidence intervals (CIs) were calculated for continuous outcomes using the Cochrane Collaboration’s software RevMan version 5.1. Treatment effects (MD, SMD) could be based on between-group comparisons (ice vs control) using follow-up data, and/or within group comparisons (pre-ice vs post-ice). When standard deviations were missing from continuous data, studies were scanned for any other statistics (CIs, standard errors, t-values, p-values, f-values) that allow for its calculation. There were no cases where large numbers of standard deviations were missing.

2.6 Risk of Bias

For all included studies, methodological quality was assessed by two authors independently (CB, JC), using the Cochrane risk-of-bias tool.[3] Each study was graded for the following domains; sequence generation, allocation concealment, blinding (assessor) and incomplete outcome data. For each study, the domains were described as reported in the published study report (or if appropriate based on information from related protocols, or published comments) and judged by the review
authors as to their risk of bias. They were assigned ‘low’ if criteria for a low risk of bias are met or ‘high’ if criteria for a high risk of bias are met. If insufficient detail of what happened in the study was reported, or if what happened in the study was known, but the risk of bias was unknown, then the risk of bias was deemed ‘unclear’ for that domain. Disagreements between authors regarding the risk of bias for domains were resolved by consensus.

2.7 Subgroup Analysis

Differences in study quality and details of the treatment intervention (e.g. duration of cooling, time period between cooling cessation and follow-up assessment), were regarded as a potential source of bias and considered for subgroup analysis.

3. Results

Figure 1 summarizes the search strategy and selection process based on included and excluded studies.

3.1 Included Studies

Characteristics of included studies are summarized in table I. There were 35 eligible studies[4–38] comprising a total of 665 healthy participants. The average sample size was 19 with the largest study based on 89 participants. Participants tended to be young and mean ages ranged from 19[19] to 32 years[126] one study[36] included a subgroup of elderly participants (aged >70 years).

Twenty-seven studies (n = 3 randomized controlled trials, and n = 24 crossover trials) incorporated a cooling group and a resting control condition. In crossover studies, the time between conditions ranged from 1 to 14 days. The duration of cooling ranged between 3 and 45 minutes. All but seven studies[13,22,25,26,29,34] applied cooling for at least 20 minutes, two[25,34] included a comparison of different cooling durations and three[7,21,36] cooled until pre-determined intramuscular temperature reductions were reached (~30°C intramuscular temperature). A total of 15 studies recorded the tissue temperature reductions associated with cooling. Eight recorded skin temperature[4,7-9,12,21,36] with the lowest values reported in individual studies ranging from ~11.9°C[38] to 22.5°C[13] and seven recorded intramuscular temperatures[4,7-9,12,21,36] with the lowest values ranging between 23°C[7] and 30.4°C.

3.2 Details of Outcome

Twenty-five studies recorded muscle strength,[4–9,11–15,18,20–24,26–30,35,36,38] the majority used an isokinetic dynamometer to measure peak force (N) or torque (Nm) at isolated body
<table>
<thead>
<tr>
<th>Study (type)</th>
<th>Intervention</th>
<th>No. of participants; age (y)</th>
<th>Tissue temp</th>
<th>Duration of effects</th>
<th>Interventions, etc.</th>
<th>Outcomes recorded (follow-up)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edwards et al. [4]</td>
<td>Observational</td>
<td>10 healthy; 25.3</td>
<td>CWI, at a range of temps (10–44°C)</td>
<td>45 min (leg up to ischial tuberosity)</td>
<td>Lowest IM temp 22.5°C</td>
<td>Isometric knee ext strain gauge: 1. endurance (time to fatigue, sec) [immediately post Rx]</td>
</tr>
<tr>
<td>Johnson and Leider [5]</td>
<td>Crossover</td>
<td>12 healthy; NR</td>
<td>CWI, 30 min (forearm immersion); rest, 30 min</td>
<td>NR</td>
<td>Handgrip dynamometer: 1. grip strength [immediately, every 20 min for 4 h post-Rx] 1 decreased between 80–240 min post-Rx</td>
<td></td>
</tr>
<tr>
<td>Coppin et al. [6]</td>
<td>RCO</td>
<td>13 healthy, 9 M, 4 F; 2–52°C</td>
<td>CWI at 10°C, 30 min (left forearm immersion); CWI at 10°C, 30 min (right forearm immersion); rest 30 min</td>
<td>Skin temp measured but changes NR</td>
<td>Handgrip dynamometer: 1. grip strength (kg) [immediately post-Rx] 1 decreased to baseline after 40 min</td>
<td></td>
</tr>
<tr>
<td>Bergh and Ekblom [7]</td>
<td>RCO</td>
<td>5 healthy M; 4–29°C</td>
<td>CWI at various IM temps induced (30–39°C)</td>
<td>Lowest IM temp ~30°C</td>
<td>Isokinetic dynamometer knee ext conc (0, 90, 180/°C, 1 sec): 1. peak torque (Nm) 2. power (W) 3. vertical jump (height, cm) 4. sprint performance cycle (time, sec)</td>
<td></td>
</tr>
<tr>
<td>Oliver et al. [8]</td>
<td>RCO</td>
<td>20 healthy, 8 M; 9.2, 12 F; 25.1°C</td>
<td>CWI at 10–12°C, 30 min (lower leg immersion); rest 30 min</td>
<td>Skin temp 25.5°C (at IM depth = radius of muscle cross-sectional area)</td>
<td>Ankle isometric PF, cable tensiometer: 1. peak force (kg) [immediately post-Rx 30, 60, 90, 120, 180 min post-Rx] No significant findings 1 increased between 60–180 min post-Rx</td>
<td></td>
</tr>
<tr>
<td>Petrofsky and Lind [9]</td>
<td>Crossover</td>
<td>10 healthy, 5 M; 24–31.9°F; 11.5–17.7°F</td>
<td>CWI 10°C, 20°C, 30°C and 40°C at 30 min each and forearm immersion</td>
<td>Lowest IM temp ~23°C</td>
<td>Handgrip dynamometer: 1. strength (kg) 2. endurance (grip hold sec at 15–70% of MVC) [immediately post-Rx]</td>
<td></td>
</tr>
<tr>
<td>Barter and Freer [10]</td>
<td>Crossover</td>
<td>12 healthy M; 18–25</td>
<td>CWI at 18°C, 30 min; HWI at 45°C, 30 min; neutral immersion at 37°C, 30 min; all (hand and forearm immersion)</td>
<td>NR</td>
<td>Handgrip dynamometer: 1. time to fatigue (at 70% of MVC sec) [immediately post-Rx] No significant differences (CWI vs controls)</td>
<td></td>
</tr>
<tr>
<td>Ranatunga et al. [11]</td>
<td>Crossover</td>
<td>4 healthy; NR</td>
<td>CWI at 25–45°C (hand immersion)</td>
<td>Skin temp &lt;20°C</td>
<td>Index finger: ABD, tension transducer: 1. primary tension % baseline [immediately post-Rx]</td>
<td></td>
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</tbody>
</table>

Note: HWI significantly decreased 1 vs neutral

Continued next page
<table>
<thead>
<tr>
<th>Study (type)</th>
<th>No. of participants; age (y)</th>
<th>Intervention</th>
<th>Tissue temp</th>
<th>Outcomes recorded [follow-up]</th>
<th>Summary of significant effects</th>
<th>Duration of effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sargeant[12] (crossover)</td>
<td>4 active but untrained, 1 F; 24, 3 M; 27.67±5.51</td>
<td>CWI at 12°C, 18°C and 44°C (to the level of the gluteal fold), 45 min; no immersion, room temp</td>
<td>Muscle temp reduced by 7.7°C in 12°C water compared with no immersion condition</td>
<td>Isokinetic cycle ergometer (20 sec maximum sprint at a constant rate of 95 crank revolutions/min): 1. peak force (N) 2. peak power (W) 3. maximal mean power (W) [immediately after Rx]</td>
<td>1, 2 and 3 decreased (vs no immersion)</td>
<td>NA</td>
</tr>
<tr>
<td>Mattacola and Perrin[14] (RCO)</td>
<td>16 healthy, 5 M, 11 F; 22.1</td>
<td>CWI at 15°C; 20 min (lower/leg immersion); rest 20 min</td>
<td>NR</td>
<td>Ankle PF (ROM 0–50°); isokinetic dynamometer: 1. peak torque (Nm) 2. average power (Nm) 3. total work (Nm) [immediately post-Rx]</td>
<td>1, 2 and 3 decreased</td>
<td>NA</td>
</tr>
<tr>
<td>Howard et al.[15] (RCO)</td>
<td>10 physically active M; 22.9±2.2</td>
<td>CWI at 12°C; 45 min (lower limb immersion to gluteal fold); immersion at 35.5°C, 45 min (lower limb immersion to gluteal fold); nonimmersion, 45 min (room temp 22–23°C)</td>
<td>NR</td>
<td>Knee ext; isokinetic dynamometer: 1. peak torque 2. time to peak torque 3. angle of peak torque 4. average power 5. total work (velocities of 0°, 30°, 180°, 300° and 400°/sec randomly chosen) 6. peak torque isometric (45° angle) [immediately post-Rx]</td>
<td>1, 4, 5 and 6 decreased (at 180°, 300° 400°/sec) [vs neutral immersion and nonimmersion]</td>
<td>NA</td>
</tr>
<tr>
<td>Evans et al.[16] (RCO)</td>
<td>24 healthy; 22.4±2.1</td>
<td>CWI at 1°C; 20 min (lower limb immersion up to 8 cm above malleolus); rest 20 min</td>
<td>NR</td>
<td>Lower limb; time to complete test (sec): 1. shuttle run 2. co-contraction agility 3. catoca-run agility [immediately post-Rx]</td>
<td>No significant findings</td>
<td>NA</td>
</tr>
<tr>
<td>Lakie et al.[17] (crossover)</td>
<td>6 healthy, 5 M, 1 F; 24.8</td>
<td>CWI at 10°C; 30 min (forearm only); HWI at 44°C; 30 min (forearm only); control, no immersion</td>
<td>Skin temp 22.5°C</td>
<td>Shooting performance, accelerometer: 1. tremor (frequency, size and power) 2. final score (.200) [immediately post-Rx]</td>
<td>1 decreased (vs control and HWI)</td>
<td>NA</td>
</tr>
<tr>
<td>Catlau et al.[18] (crossover)</td>
<td>16 healthy, 8 M, 8 F; 20.4±1.2</td>
<td>Cryocuff, 20 min (thigh; no ice</td>
<td>NR</td>
<td>Knee ext; isokinetic dynamometer: 1. ECC peak torque 2. conc peak torque (velocities of 25–200° sec) [immediately post-Rx]</td>
<td>1 decreased (at 175° and 200° sec)</td>
<td>NA</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Study (type)</th>
<th>No. of participants; age (y)a</th>
<th>Intervention</th>
<th>Tissue temp b</th>
<th>Outcomes recorded [follow-up]c</th>
<th>Summary of significant effectsd,e</th>
<th>Duration of effectsf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross et al.[19] (RCT)</td>
<td>20 healthy; 19.3 – 1.2</td>
<td>CWI at 13°C, 20 min (lower limb immersion up to fibular head, with water turbulence); rest, 20 min</td>
<td>NR</td>
<td>Lower limb: 1. hop test (time to complete, sec) 2. vertical jump height (cm) 3. shuttle run (time to complete, sec) [immediately post-Rx]</td>
<td>2 decreasedf and 3 increasedf</td>
<td>NA</td>
</tr>
<tr>
<td>Kimura et al.[20] (RCO)</td>
<td>22 healthy, 11 M, 11 F; 23.8 ± 3.5</td>
<td>CWI at 10°C, 30 min (lower limb immersion to mid thigh); rest 30 min</td>
<td>NR</td>
<td>Ankle PF ECC; isokinetic dynamometer: 1. peak torque (Nm) 2. total work (Nm) [immediately post-Rx]</td>
<td>2 increasedf</td>
<td>NA</td>
</tr>
<tr>
<td>Zhou et al.[21] (observational)</td>
<td>3 healthy M; 31</td>
<td>Ice bag applied until thigh IM temp reached 30°C</td>
<td>30°C (at 30 mm IM depth)</td>
<td>Knee ext isometric: 1. peak force (N) [immediate post Rx]</td>
<td>1 decreasedf</td>
<td>NA</td>
</tr>
<tr>
<td>Sanya and Bello[22] (observational)</td>
<td>60 healthy, 30 M; 23.43 ± 1.89, 30 F; 22.63 ± 1.71</td>
<td>Ice-towel application at 3–6°C, 5 min (included liquid paraffin, applied to the anterior aspect of the thigh)</td>
<td>NR</td>
<td>Adapter cable tensiometer: 1. Isometric quadriiceps strength (kgf) 2. endurance index (sec) [immediately, 10 min post-Rx]</td>
<td>1 increased 2 increased (male only)</td>
<td>1 remained increased at 10 min post-Rx</td>
</tr>
<tr>
<td>Hatzel and Kaminski[23] (observational)</td>
<td>20 healthy; 19.6 ± 1.3</td>
<td>CWI at 10°C, 20 min (lower limb immersion to tibial plateau)</td>
<td>NR</td>
<td>Ankle ECC and conc isokinetic dynamometer: 1. peak torque (Nm): a) PF, b) INV, c) EV, d) DF; [immediately post-Rx]</td>
<td>1 conc decreasedf</td>
<td>NA</td>
</tr>
<tr>
<td>Hopkins and Stencil[24] (RCT)</td>
<td>30 healthy, 16 M, 14 F; 21 ± 3</td>
<td>1.5 L of crushed ice, 30 minutes (lateral ankle joint); rest, 30 min</td>
<td>Final skin temp –16°C</td>
<td>Ankle PF conc; isokinetic dynamometer: 1. Peak torque (Nm) [immediately post-Rx]</td>
<td>1 increasedf</td>
<td>NA</td>
</tr>
<tr>
<td>Cheung et al.[25] (crossover)</td>
<td>16 healthy, 11 M, 15 F; 24.8 ± 9.4</td>
<td>CWI at 10°C, (immersion to lateral epicondyle), 30 sec, 120 sec and 300 sec; no immersion</td>
<td>Final skin temp 15 ± 0.4°C</td>
<td>Hand dexterity testing: 1. buckle test (time to complete, sec) 2. fine dexterity [immediately post-Rx]</td>
<td>1 increasedf (120 sec and 300 sec vs control) 2 decreasedf (300 sec vs control)</td>
<td>NA</td>
</tr>
<tr>
<td>Douris et al.[26] (crossover)</td>
<td>16 healthy; 32 ± 6.3</td>
<td>CWI at 10°C, 5 min (elbow, forearm and hand immersion);</td>
<td>NR</td>
<td>Hand dynamometer: 1. grip strength, isometric (lbs) [immediately 15 min post-Rx]</td>
<td>1 decreasedf 1 remained decreasedf at 15 min post-Rx</td>
<td>NA</td>
</tr>
<tr>
<td>Thornley et al.[27] (RCO)</td>
<td>9 healthy M; 22 ± 3</td>
<td>Hot pack, 55°C; warm pack, 34°C; neutral pack, 22°C; cold pack, 17°C; all 30 min, anterior thigh</td>
<td>Skin temp 12.4 ± 2.8</td>
<td>Knee ext isometric: 1. peak torque (Nm) 2. time to fatigue (sec) [immediately post-Rx]</td>
<td>2 increasedf (vs hot and warm pack)</td>
<td>NA</td>
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</table>

Continued next page
Table I. Contd

<table>
<thead>
<tr>
<th>Study (type)</th>
<th>No. of participants: age (y)</th>
<th>Intervention</th>
<th>Tissue temp</th>
<th>Outcomes recorded [follow-up]</th>
<th>Summary of significant effects</th>
<th>Duration of effects</th>
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<td>NR</td>
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<tr>
<td>Borgmeyer et al. [28] (RCO)</td>
<td>11 healthy M; 23.9 ± 1.1</td>
<td>Ice massage, 10 min (biceps); rest, 10 min</td>
<td>NR</td>
<td>Elbow flex conc; isokinetic dynamometer: 1. peak torque (Nm) immediately post-Rx</td>
<td>No significant findings</td>
<td>NA</td>
</tr>
<tr>
<td>Hamzat and Fatudimu [29] (observational)</td>
<td>89 healthy, 49 M, 40 F; 19-30</td>
<td>Ice-towel application, 10 min (applied to the forearm muscles, temp not stated)</td>
<td>NR</td>
<td>Hand dynamometer: 1. grip strength, isometric (kgf) 2. endurance index (sec) [immediately, 5 and 10 min post-Rx]</td>
<td>2 increased</td>
<td>2 still increased from baseline at 5 and 10 min</td>
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<tr>
<td>Kubo et al. [30] (RCO)</td>
<td>8 healthy M; 26 ± 2</td>
<td>CWI at 5°C, 30 min (lower limb immersion up to head of fibula); HWI at 42°C, 30 min (lower limb immersion up to head of fibula)</td>
<td>NR</td>
<td>Ankle PF isometric, dynamometer: 1. peak force (Nm) [immediately post-Rx]</td>
<td>1 decreased</td>
<td>NA</td>
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<tr>
<td>Richendollar et al. [31] (RCO)</td>
<td>24 healthy M; 21.3 ± 3.3</td>
<td>Rest only, 20 min; warm-up only, 20 min; ice, 20 min followed by rest 20 min; ice 20 min followed by warm up 20 min. (Ice = 1.4 kg of crushed ice in plastic bag, secured with compression wrap over anterior thigh)</td>
<td>NR</td>
<td>Lower limb: 1. single leg vertical jump (cm) 2. shuttle run agility (time to complete, sec); 3. 36.5 m sprint (time to complete, sec) [20 min post-Rx]</td>
<td>No immediate follow-up recorded</td>
<td>1, 2 and 3 worse (20 min ice followed by 20 min rest vs 20 min rest only) There were no significant findings when 20 min ice was followed by a 20 min warm up</td>
</tr>
<tr>
<td>Wassinger et al. [32] (observational)</td>
<td>22 healthy, 14 M, 8 F; 21.6 ± 2.4</td>
<td>Ice cubes, 20 min (secured with standardized elastic bandage to centre of bag over the tip of acromion)</td>
<td>NR</td>
<td>Upper limb: 1. throwing accuracy (number of throws to hit a target and number of throws in 30 sec) [immediately post-Rx]</td>
<td>1 decreased</td>
<td>NA</td>
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<tr>
<td>Patterson et al. [33] (observational)</td>
<td>21 healthy, 7 M, 13 F; 19.8 ± 1.2</td>
<td>CWI at 10°C, 20 min (lower leg immersion with water turbulence)</td>
<td>NR</td>
<td>Lower limb: 1. countermovement jump [peak power and average power (W)] 2. 1-test agility (time to complete, sec) 3. 36.5 m sprint (time to complete, sec) [immediately and at 5 min intervals up to 30 min]</td>
<td>1 decreased, 2 and 3 increased</td>
<td>1 worse at 30 min post-Rx (20 min ice followed by 20 min rest vs 20 min rest only) 2 worse for up to 5 min post-Rx 3 worse for up to 20 min post-Rx</td>
</tr>
<tr>
<td>Study (type)</td>
<td>No. of participants; age (y)*</td>
<td>Intervention</td>
<td>Tissue temp†</td>
<td>Outcomes recorded (follow-up)</td>
<td>Summary of significant effects**</td>
<td>Duration of effects **</td>
</tr>
<tr>
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</tr>
<tr>
<td>Fischer et al.<a href="crossover">34</a></td>
<td>42 healthy, 25 F; 22 ± 0.5, 17 M; 23 ± 0.5</td>
<td>Cubed ice, 3 min and 10 min (hamstring muscle belly, secured with plastic wrap); rest</td>
<td>NR</td>
<td>Lower limb: 1. co-contraction (agility test, sec) 2. shuttle run (time to complete, sec); single leg vertical jump (cm) [immediately, 20 min post-Rx]</td>
<td>2 increased* and 3 decreased* after 10 min of ice. No significant findings reported after 3 min ice</td>
<td>2 worse at 20 min post-Rx*</td>
</tr>
<tr>
<td>Chen et al.<a href="observational">35</a></td>
<td>24 healthy, 12 M, 12 F; ~25</td>
<td>CWI in 11°C, 40 minutes (immersion of hand and forearm)</td>
<td>Skin temp 12.5°C</td>
<td>Upper limb: 1. gross dexterity 2. fine dexterity [1 and 2: after 2, 10, 18, 26, 34 and 40 min of CWI. Outcome 3 recorded after 40 minutes of CWI only] 3. Grip strength, gauge with load cell (kg/W) [immediately post Rx]</td>
<td>1, 2 and 3 all decreased*</td>
<td>NA</td>
</tr>
<tr>
<td>Dewhurst et al.<a href="RCO">36</a></td>
<td>27 healthy F: young subgroup (n = 15); 21.5 ± 2.2, old subgroup (n = 12); 73.6 ± 3.2</td>
<td>Cold, 30°C IM temp; control, 34°C IM temp; warm, 38°C IM temp; all: quad, 1 cm below subcutaneous fat; ice and hot packs used to regulate temp</td>
<td>IM temp 30°C</td>
<td>Knee ext; isokinetic dynamometer: 1. isometric peak torque 2. conc peak torque (velocities of 30°, 60°, 90° and 120° sec) [immediately post-Rx]</td>
<td>2 decreased** (vs control). Note: in young subgroup only</td>
<td>NA</td>
</tr>
<tr>
<td>Dixon et al.<a href="RCO">37</a></td>
<td>9 M athletes; 22.1 ± 1.5</td>
<td>CWI at 12°C, 45 min followed by no warm up; CWI 12°C, 45 min followed by warm up; standing control, 45 min followed no warm up; standing control, 45 min followed by warm up [bladder immersion of lower limbs up to the gluteal fold]</td>
<td>NR</td>
<td>Lower limb: 1. countermovement jump: [power output: W] [immediately, 15 min post-Rx]</td>
<td>1 decreased** [after both CWI protocols compared with both ambient temperature protocols]</td>
<td>In group using CWI without active warm, 1 remained worse at 15 min post- Rx** (vs all groups)</td>
</tr>
<tr>
<td>Pereir et al.<a href="RCT">38</a></td>
<td>18 healthy, 11 M, 7 F; 22 (SE 1)</td>
<td>Crushed ice pack, 30 min (anterolateral surface of lower limb, secured with elastic wrap); rest, 30 min</td>
<td>Skin temp 11.9 (SE 0.7°C)</td>
<td>Ankle DF isometric; strain gauge: 1. peak force (N) [immediately 5, 15, 30 and 60 min post-Rx]</td>
<td>1 decreased**</td>
<td>Immediate only</td>
</tr>
</tbody>
</table>

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**a Data for ages are presented in whole y, means, means ± SDs or SEs, and ranges or not reported where stated.

**b Tissue temperature immediately post-ice.

**c Different outcomes are numbered from 1 to 6 throughout the studies. Outcome 1 in the Hatzel and Kaminski[23] study is made up of multiple outcomes denoted by a,b,c and d.

**d Summary of significant effects of cooling at immediate follow-up.

**e p < 0.05 vs pre-treatment.

**f p < 0.05 vs control group.

| **ABD** | Abduction |
| **conc** | Concentric |
| **CWI** | Cold water immersion |
| **DF** | Dorsiflexion |
| **ECC** | Eccentric |
| **ext** | Extension |
| **EV** | Eversion |
| **F** | Female |
| **HWI** | Hot water immersion |
| **IM** | Intramuscular |
| **INV** | Inversion |
| **kgf** | Kg force |
| **M** | Male |
| **MVC** | Maximum voluntary contraction |
| **NA** | Follow ups not measured beyond the immediate stages post Rx |
| **PF** | Plantar flexion |
| **RCO** | Randomized crossover trial |
| **RCT** | Randomized controlled trial |
| **ROM** | Range of movement |
| **SE** | Standard error |
| **temp** | Temperature |
regions: knee extension, elbow flexion and ankle (all movements). The remainder used a cable tensiometer[8,22] or a strain-gauge device or load cell,[4,11,35,38] with one[21] failing to specify the recording device. Eight studies[5,6,9,10,13,26,29,35] measured grip strength using a handgrip dynamometer and three further studies measured isolated finger strength[14] or hand dexterity.[25,35] Nine studies assessed endurance, based on the total work[14,15,20] or time to fatigue[4,9,10,22,27,29] undertaken during multiple exercise repetitions.

Six studies examined the effect of cooling immediately prior to undertaking various types of whole-body exercise tests. These included vertical jump height[19,31] or power,[33,37] timed hop test,[19] sprint time[31,33] and the time taken to complete various running-based agility tests, e.g. carioca runs,[16] shuttle sprints,[16,19,31,34] T-shuttle[33] or a co-contraction test.[16,34] Two studies recorded performance accuracy during throwing (percentage of ball throws to hit a target in 30 seconds)[32] and shooting (total shooting score),[17] and two[25,35] measured hand dexterity.

3.3 Follow-Up


3.4 Risk of Bias

There was a high risk of bias across all studies as summarized in figure 2. Fifteen studies stated that participants were randomized into groups; however, only two[8,24] provided adequate details on how the random sequence was generated. There was further risk of selection bias as just one randomized study[24] adequately reported allocation concealment. Blinding of outcome assessor was not reported in any study. As a result of the nature of the intervention, we did not assess blinding of participants or caregivers. There was a high risk of attrition bias across all studies; only four studies[6,22,33,37] provided any information relating to dropouts, exclusions, missing data or approach to analysis.

3.5 Muscle Strength: Lower Limb (Thigh)

Eight studies focused on quadriceps strength. Howard et al.[15] found that a 45-minute cold water immersion resulted in significant strength reductions during knee extension, with the largest changes observed during high-speed isokinetic test speeds (180°/sec–400°/sec); peak torque, average power and total work were all reduced by up to 27% compared with baseline values. Three studies[7,21,36] recorded a number of knee extension strength outcomes after inducing a range of intramuscular temperature reductions. Zhou et al.[21] found peak knee extension force decreased when quadriceps muscle temperatures were cooled below 34°C, with further decreases when muscle temperatures of 30°C were reached.

![Fig. 2. Risk of bias summary.](image)
Effect of Tissue Cooling on Functional Performance

(MD 126.80 N [95% CI 1–1.38, 254.98] vs baseline). Dewhurst et al. [36] found that colder intramuscular temperatures (~30°C) were associated with lower isokinetic torques; however, this was only observed in a subgroup of younger participants. Bergh and Ekblom [7] reported that for every 1°C decrease in intramuscular temperature, both extension torque and power declined by around 5%.

A small study [12] found that compared with untreated control, a 45-minute cold water immersion (12°C or 18°C) involving the lower limbs decreased isokinetic cycling performance in terms of peak force (MD 143 N [95% CI 9–25.96, 30.96]) and peak power output (MD 278 W [95% CI 1–9, 565]). Others reported more moderate changes. Thornley et al. [27] found little to no differences in knee extension torque immediately after treatment, when groups were treated with hot and cold packs at a range of temperatures. Of note, the cold group had the largest reduction from baseline (MD 19 Nm [95% CI 1–25.96, 63.96]). In contrast, Sanya and Bello [22] found that long durations (>30 minutes) of upper limb cold water immersion, significantly decreased eccentric peak torque, in plantar flexion, dorsiflexion, eversion and inversion) before and after a 20-minute cold water immersion; however, the only significant finding was a decrease in concentric dorsiflexion immediately after cooling (MD 7.4 Nm [95% CI 1–0.13, 14.93] vs baseline). Hopkins and Stencil [24] found that a 30-minute ice-pack application to the lateral ankle joint induced small increases in plantar flexion peak torque, compared with a resting control. Using a similar design, Kimura et al. [20] also found that a 30-minute cold water immersion resulted in small increases in eccentric ankle plantar flexion peak torque (MD 3.93 Nm [95% CI 1–2.23, 20.09]).

3.5.2 Muscle Strength: Upper Limb

Borgmeyer et al. [28] found that 10 minutes of biceps cooling had little effect on concentric or isokinetic strength at the elbow (MD 0.4 Nm [95% CI 1–1.45, 2.25] vs control). Five studies found that long durations (>30 minutes) of upper limb cold water immersion, significantly decreased isolated finger [11] and handgrip strength [15,6,9,33]. There was sufficient data for each size calculation in just one of these studies (MD 4.10 kg [95% CI 9–6.66, 17.86] vs control), with one other stating that grip strength was reduced by 12%. Three further studies [13,26,29] were based on shorter periods of cooling (<10 minutes) of the hand and/or forearm; both Douris et al. [28] (MD 129 N [95% CI 121.16, 136.84]) and Vincent and Tipton [13] (decreased by 13–16%) found significant reductions in peak grip strength compared with pre-cooling values, whereas, Hamzat and Fatudimu [29] found little to no change in grip strength immediately following an ice-towel application (MD 0.36 N [95% CI 1–2.21, 2.93] vs baseline).

3.6 Muscle Endurance

Kimura et al. [20] reported that a 30-minute cold water immersion significantly increased plantar flexion endurance (total work during 100 repetitions) [MD 377.82 Nm (95% CI 1–158.03, 913.67)] compared with a resting control condition. Three studies also found that cooling significantly increased isometric endurance, based
on time to fatigue at the quadriceps[22,27] or handgrip muscles;[29] the magnitude of the changes were much larger in Thorley et al.[27] (MD 26.4 sec [95% CI −1.61, 54.41] vs heating) compared with both Sanya and Bello[22] (MD 4.08 sec [95% CI −0.88 to 9.04] vs baseline) and Hamzat and Fatudimu[29] (MD 5.04 sec [95% CI 1.08, 9] vs baseline).

In contrast, both Petrofsky and Lind[9] and Barter and Freer[10] found cold water immersion reduced time to grip strength fatigue compared with neutral water immersion; the magnitude of effects differed across each study (MD 293 sec [95% CI 132.96, 453.04])[9] and (MD 0.8 sec [95% CI −6.22, 7.82]).[10] Mattacola and Perrin[14] also reported reduced endurance after cooling ankle plantar flexors (MD 61 Nm [95% CI −6.67, 128.7] vs control); a small study by Edwards et al.[4] concluded quadriceps endurance was optimized at immersion in water at 26°C but tended to decrease after immersions at extreme temperature (either 10°C or 4°C). In a further study,[15] long durations (45 minutes) of cooling did not affect isokinetic quadriceps muscle work over a range of test speeds.

3.7 Vertical Jump, Sprint and Agility Performance

All studies[19,33,34,37] found that vertical jump performance was reduced immediately after cooling; this was observed after 10 minutes of crushed ice applied to the hamstrings (MD 1.10cm [95% CI −1.96, 4.16] vs baseline).[34] 20 minutes of lower limb cold water immersion in 13°C (MD 2.14cm [95% CI −3.54, 7.82] vs baseline)[19] or 20 minutes of lower limb cold water immersion in 10°C (MD 648 W [95% CI 10.91, 1285.09]).[33] The largest detriments in vertical jump performance were found following a 45-minute cold water immersion involving both lower limbs (MD 1165 W [95% CI 194, 2135.76] vs baseline).[37]

There was also a clear trend[19,31,33,34] that shuttle run time was worse immediately following cooling; the largest change from baseline was based on an MD of 0.63 seconds (95% CI 0.27, 0.99).[33] There was further evidence that after 10–20 minutes of lower limb icing, participants took longer to complete various running-based agility tests,[16,31,33,34] the largest reported MD from baseline was 1.38 seconds (95% CI 0.72, 2.04).[33]

3.8 Performance Accuracy

There was evidence from a single observational study[32] that 20 minutes of shoulder joint cooling, significantly reduced throwing accuracy (MD 7.11% [95% CI 2.29, 11.93] vs baseline). In contrast, a small study by Lakie et al.[17] found that compared with the control, isolated forearm immersion (30 minutes at 10°C) decreased tremor by 40% during a shooting performance and improved the scoring accuracy (SMD 0.89 [95% CI −0.32, 2.10]).

3.9 Upper Limb Dexterity

Cheung et al.[25] showed that short-duration (300 sec) immersions of the hand and forearm, significantly reduced hand dexterity in terms of time to complete a functional dexterity test (MD 9 sec [95% CI 2.89, 15.11] vs control) and a Purdue peg test (8.8 points [95% CI 3.93, 13.67] vs control). Chen et al.[35] also concluded that hand immersion reduced gross and fine finger dexterity by up to 55% (vs baseline).

3.10 Summary of Immediate Effects of Cooling

We were unable to combine studies for meta-analyses because of the heterogeneity relating to cooling time/dosage, body part and outcome measure. The overall trend was a reduction in performance immediately after cooling. This is evident in the forest plot graphs (SMD [95% CI]) presented in figure 3 and 4, which summarize the within (baseline vs post-ice) and between-group differences (ice vs control).

3.10.1 Duration of Effects Post-Cooling

Two studies[5,8] found that over a 2–4 hour period, post-cooling strength values steadily increased beyond baseline levels. The remainder of the studies noted that cold-induced detriments in performance lasted beyond the immediate stages after cooling, but for varying durations. Pereira
et al.[38] found that a 5-minute rest period was enough for ankle dorsiflexion strength to return to baseline; whereas, two studies[22,29] found that performance remained significantly changed for up to 10-minutes post-cooling. In another study,[26] the effects of cold on grip strength diminished with time; however, a 5.9% strength reduction (from baseline) remained 15-minutes post-cold water immersion. Coppin et al.[6] reported that grip strength remained below baseline values for up to 40-minutes post-immersion. Fischer et al.[34] found vertical jump performance was still below baseline values after a 20-minute recovery. Patterson et al.[33] also found that vertical jump, agility and sprint performance remained lower than baseline for up to 30 minutes following treatment. Similarly, Richendollar et al.[31] also found that vertical jump, agility and sprint performance were all reduced for 20 minutes after cooling. However, both Richendollar et al.[31] for vertical jump, agility and sprint performance; and Dixon et al.,[37] for countermovement jump, found these detrminents were negated after undertaking a progressive warm up for 6.5 and 15 minutes, respectively.

### 3.10.2 Cooling Dose

Two studies[25,34] incorporated different cooling durations. Fischer et al.[34] found that although 10-minute treatments reduced vertical jump and agility/speed performance, no effects were reported when treatment times were reduced to 3 minutes. In a comparison of three different cooling times (30, 120 or 300 sec), Cheung et al.[25] also found that longer durations induced larger detrminents to hand dexterity.

### 3.10.3 Adverse Effects

No study reported cold-induced complications or side effects relating to skin damage, nerve palsy or allergy. One participant suffered a hamstring strain during a baseline (pre-cooling) 40 m sprint test.[33]
4. Discussion

4.1 Quality of Evidence

There were large limitations within the current evidence base. Sample size was generally small, raising questions as to the power of individual trials. There was also a consistently high risk of bias across the studies, and we were unable to meaningfully subgroup studies into high and low quality. Few studies reported adequate sequence generation or allocation concealment. As some of the included studies were randomized crossover trials, there may also be risk of carry-over effects. Primarily, this could relate to a practice or learning effect during the outcome assessments. Additional carry-over effects may also have resulted from fatigue induced during the first treatment period; the length of time between crossover conditions varied from the same day,[25] up to 2 weeks[20] across studies. In a number of the crossover trials,[9,11-15,36] the length of time between treatment conditions was not stated.

It is acknowledged that based on the nature of cold treatment, stringent blinding of participants

<table>
<thead>
<tr>
<th>Study or subgroup</th>
<th>SMD IV, random, 95% CI</th>
<th>SMD IV, random, 95% CI</th>
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<td>0.09 [-0.71, 0.89]</td>
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</tr>
<tr>
<td>Borgmeyer et al., 2004</td>
<td>-0.17 [-1.01, 0.66]</td>
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<td>Catlaw et al., 1996</td>
<td>-2.33 [-3.25, -1.40]</td>
<td>-0.17 [-1.01, 0.66]</td>
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<tr>
<td>Cheung et al., 2003</td>
<td>1.00 [0.25, 1.74]</td>
<td>1.22 [0.46, 1.98]</td>
</tr>
<tr>
<td>Cross et al., 1996</td>
<td>0.34 [-0.54, 1.23]</td>
<td>-0.09 [-0.97, 0.78]</td>
</tr>
<tr>
<td>Evans et al., 1995</td>
<td>0.07 [-0.50, 0.63]</td>
<td>0.16 [-0.41, 0.72]</td>
</tr>
<tr>
<td>Fischer et al., 2009</td>
<td>0.35 [-0.08, 0.78]</td>
<td>0.27 [-0.16, 0.70]</td>
</tr>
<tr>
<td>Hopkins and Stencil, 2002</td>
<td>-0.03 [-0.75, 0.68]</td>
<td>-0.14 [-0.73, 0.45]</td>
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<tr>
<td>Kimura et al., 1997</td>
<td>-0.41 [-1.01, 0.19]</td>
<td>-0.89 [-2.10, 0.32]</td>
</tr>
<tr>
<td>Lakie et al., 1995</td>
<td>0.53 [-0.08, 1.15]</td>
<td>0.49 [-0.12, 1.11]</td>
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<td>Mattacola and Perrin, 1993</td>
<td>0.08 [-0.54, 1.23]</td>
<td>0.35 [-0.22, 0.92]</td>
</tr>
<tr>
<td>Pereira et al., 2010</td>
<td>0.10 [-0.88, 1.08]</td>
<td>0.67 [0.09, 1.25]</td>
</tr>
<tr>
<td>Petrofsky and Lind, 1980</td>
<td>1.54 [0.51, 2.56]</td>
<td>1.06 [-0.51, 2.63]</td>
</tr>
<tr>
<td>Richendollar et al., 2006</td>
<td>0.35 [-0.22, 0.92]</td>
<td>1.17 [-0.43, 2.77]</td>
</tr>
<tr>
<td>Sargeant et al., 1987</td>
<td>1.06 [-0.51, 2.63]</td>
<td></td>
</tr>
<tr>
<td>Thornley et al., 2003</td>
<td>-0.83 [-1.80, 0.14]</td>
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</tbody>
</table>

Fig. 4. Forest plot summarizing the immediate effect (SMD [95% CI]) of cooling on functional performance (ice vs control). CI = confidence interval; IV = inverse variance; random = randomized; SMD = standardized mean difference.

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and caregivers is difficult. Blinding of outcome assessors should be feasible but was not reported in any of the included studies. Equally, no studies adequately described missing outcomes or how these were managed. Overall, the consistently small sample sizes and poor quality of evidence mean that findings should be interpreted with caution.

4.2 Muscle Strength

Basic scientific evidence portends that cooling is detrimental to muscle performance based on cold-induced decreases to nerve conduction velocity, receptor firing rate, muscle spindle activity, myotatic stretch reflex and ion (Na\(^+\), K\(^+\), Ca\(^{2+}\)) diffusion at the motor end plate. It is also well accepted that enzymatic activity is reduced at lower temperatures, and there are further suggestions that cooling impairs Ca\(^{2+}\) release from the muscles’ sarcoplasmic reticulum, resulting in a decline in adenosine triphosphate availability and impaired cross bridge function.

The trend from the current evidence base was that cooling reduces muscle strength. However, the magnitude of these changes was variable. In some cases, large effects were reported based on strength reductions from a baseline of 13% to 27%, or peak torque losses of around 130 N. In others, cold-induced strength losses were less than 9 Nm; such changes may be less clinically relevant and may only be applicable to elite sport environments. Although a small number of studies found cold-induced increases in force output, the magnitude of these changes were consistently small. Interestingly, one of these studies applied ice directly onto the ankle joint; isolated joint cooling has previously been shown to enhance muscle recruitment based on Hoffmann-reflex and central-activation ratios at the ankle and knee.

4.3 Muscle Endurance

The effects of cooling on other components of muscle function were conflicting; there were some suggestions towards cold-induced increases in muscle endurance, with others showing an opposite effect. Some postulate that cooling muscle prior to intense exercise, decreases pain, minimizes metabolic by products or prevents excessive increase in muscle temperature. Furthermore, a recent review found that pre-cooling, using ice vests, ice collars or body immersions, improves aerobic performance during running and cycling. The theory is that pre-cooling prevents excessive increases in core body temperature during exercise. The effect of core temperature on our current findings is difficult to ascertain as no included studies measured core temperature. Of note, interventions in the current review used local muscle cooling or peripheral limb immersion; previous studies found that such localized cooling does not affect core temperature.

4.4 Vertical Jump, Sprint and Agility Performance

The lower limb performance outcomes recorded in some of the included studies may be better correlates of sports performance. Five studies found that cooling had a negative effect on at least one of the following outcomes: vertical jump, sprint or agility, with only Evans et al. reporting no changes. Vertical jump height was reduced by up to 2 cm in the immediate stages after cooling. The majority also found that sprint or agility time was reduced by around 0.2 seconds, with one study noting larger decreases of 1.4 seconds. The clinical relevance of these detrimental outcomes may again depend on the type of sport or performance level and how soon following treatment individuals return to participation.

A small number of studies recorded skill-based outcomes. There was a general trend that cooling decreased hand dexterity and throwing accuracy by approximately 7%. In contrast, a small study found that cooling enhanced shooting performance in novices; this was attributed to a cold-induced attenuation of physiological tremor (up to 40%), which was measured using an accelerometer.

4.5 Cooling Dose, Return to Sport and Warm Up

In this review, there is variation across studies in the cooling modes, durations and body areas treated. Overall, the cooling dosages were large,
with most studies using a minimum duration of 20 minutes. Indeed, many studies [4,7-9,12,21,36] induced intramuscular temperatures to less than 30°C. It is difficult to recommend an optimal tissue temperature reduction. Recent clinical guidelines[1] suggest that the cooling dose should be modified according to the patho-physiological objective. Longer bouts of cooling, such as those employed within the current review, may be most appropriate for targeting deep tissue and/or reducing local cellular metabolism. In contrast, local analgesia, which is often the objective prior to returning to sport, may be readily attained with shorter durations (<10 minutes).[1] The patterns in this review may, therefore, represent the largest potential changes associated with cooling.

We must also consider that during sport, very brief bouts of cooling (<1 min) are sometimes used during a break in play, where the rationale is to provide a counterirritant for pain, rather than to induce large/deep temperature reductions. Interestingly, one study[34] found that a 3-minute treatment did not affect vertical jump, agility or sprint performance.

We noted that the majority of studies in this review involved cold water immersion or muscle cooling. Localized joint cooling may have different effects on function; indeed, evidence exists that isolated joint cooling[44,45] has an excitatory effect on the surrounding musculature. This could have positive implications and future studies must consider the effect of isolated joint cooling on functional performance. Clinicians should also consider that outcome is affected by individual factors, such as adiposity, with higher levels acting to limit the magnitude and depth of cooling.[49]

It is important to note that intramuscular temperatures have been shown to decline for up to 10 minutes after the removal of an ice-pack.[50] In this review, many studies have found that performance remained below baseline for at least 15 minutes following treatment. In sport, athletes are often encouraged to undertake a warm-up period after finishing a cooling treatment and before returning to play. Previous studies have shown that light- or moderate-physical activity can significantly speed up intramuscular rewarming.[50,51] We also found evidence from two studies[31,37] that there were no performance detriments when participants undertook a 6.5- to 15-minute warm up (dynamic joint movements and jogging) between the end of a cooling treatment and returning to activity. Future study should ascertain whether this practice should be universally encouraged prior to returning to sport. Although it seems likely that the physiological effects of cooling can be reduced through use of a progressive warm up, again, we must consider that these studies applied cooling for 20[31] to 45 minutes.[37] The significance of a post-icing warm up may depend on the magnitude and depth of tissue cooling, and may be less important after short cooling durations.

4.6 Comparison to Other Reviews

Few reviews have systematically examined the effect of cooling on other physiological systems relevant to sporting activity. Costello and Donnelly[2] found equivocal evidence on the effect that joint cooling has on proprioception (joint positional sense) and, in conjunction with this review, the majority of included studies were of limited methodological quality. They did find some significant effects; absolute errors were found to increase (worsen) by 1–2°C immediately after cooling the ankle and shoulder joints. Again, the effect of these changes on performance and injury risk is difficult to determine.

Although this review focuses on a healthy population, other reviews[1,52] have noted a dearth of high-quality randomized studies into the therapeutic effect of cooling after soft-tissue injury. Quod et al.[53] and, more recently, Ranalli et al.,[47] have also reviewed the effects of pre-cooling before exercise on subsequent endurance performance in the heat and aerobic and anaerobic performance, respectively. Both reviews concluded that pre-exercise cooling seems to have a positive effect on aerobic performance, although the impact on anaerobic performance varied and did not provide the same positive effect.

4.7 Limitations and Future Study

We undertook an exhaustive search based on a comprehensive list of electronic databases and...
extensive supplementary searching. We acknowledge that other relevant studies may have been overlooked in the grey literature (e.g. Conference abstracts or other literature that is not formally published in books or journal articles). None of the included studies had a registered protocol and bias from selective reporting of results was, therefore, difficult to ascertain. There were a limited number of outcomes where summary values were extracted from graphs. Although this was undertaken by two independent reviewers, with inconsistencies checked through reviewer consensus and a third party, it still serves as an estimation of treatment effect. We were also unable to perform any paired analysis in the randomized crossover studies; instead, data were analysed as if these studies used a parallel group design. This approach may give rise to bias through a unit of analysis error; however, this is likely to be conservative, as the crossover studies tend to be under rather than over weighted.[54]

Future studies must incorporate larger sample sizes, and employ methods to limit selection, performance and attrition bias. Employing short-duration cooling may be more practically relevant; particularly, if applied in the middle of simulated play. This would better ascertain the influence of cooling when the physiological systems (eg. blood flow, neural activity, and metabolism) are functioning under competitive conditions. This review is limited to healthy subjects, whereas, in real sporting situations, ice is usually applied to athletes in pain relating to injury. Replicating painful circumstances in the laboratory may be more practically relevant and should be the touchstone for future studies. Finally, we have focused on important outcomes relevant to sporting performance; however, we acknowledge that other key correlates of performance exist. There is evidence that temperature can influence the visco-elastic properties of sensori-motor patterns[55] and soft tissues,[56] which should be systematically examined in future reviews.

5. Conclusion

The current evidence base suggests that the performance of athletes will probably be adversely affected should they return to activity immediately after cooling. We must consider that these findings are largely based on cooling durations of at least 20 minutes, which may exceed the dosages used on the sidelines or at half time during sport. There is preliminary evidence that cold-induced detrimental effects on performance can be reduced or prevented by using a shorter cold application and/or undertaking a progressive warm up prior to returning to play. Future studies in this area must incorporate larger sample sizes, and limit the risk of bias. The cooling dosages employed should be made more applicable to the sporting environment with potentially more focus on short-duration applications. Until better evidence is available, practitioners should use short cooling applications and/or undertake a progressive warm up prior to returning to play.

Acknowledgements

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Title: Do thermal agents affect range of movement and mechanical properties in soft tissues? A systematic review

Article Type: Systematic/Meta-analytic Reviews

Keywords: Cold Temperature; Hot Temperature; Joint Range of Motion; Muscle Stretching Exercises

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Abstract: OBJECTIVE: To examine the effect of thermal agents on the range of movement (ROM) and mechanical properties in soft tissue, and to discuss their clinical relevance.

DATA SOURCES: Electronic databases (Cochrane Central Register of Controlled Trials, MEDLINE, and EMBASE) were searched from their earliest available record up to May 2011 using subject headings (MeSH) and key words. We also undertook related articles searches and read reference lists of all incoming articles.

STUDY SELECTION: Studies involving human participants describing the effects of thermal interventions on ROM and/or mechanical properties in soft tissue. Two reviewers independently screened studies against eligibility criteria.

DATA EXTRACTION: Data were extracted independently by two review authors using a customised form. Methodological quality was also assessed by two authors independently, using the Cochrane risk of bias tool.

DATA SYNTHESIS: Thirty six studies, comprising a total of 1301 healthy participants, satisfied the inclusion criteria. There was a high risk of bias across all studies. Meta-analyses were not undertaken due to clinical heterogeneity, however effect sizes were calculated. There were conflicting data of the effect of cold on joint ROM, accessory joint movement, and passive stiffness. Acute cold applications may enhance the effects of stretching however further evidence is required. There was evidence that heat increases ROM, and a combination of heat and stretching is more effective than stretching alone.

CONCLUSION: Heat is an effective adjunct to developmental and therapeutic stretching techniques and should be the treatment of choice for enhancing ROM in a clinical or sporting setting. The effects of heat or ice on other important mechanical properties (eg. passive stiffness) remain equivocal, and should be the focus of future study.
Dear Professor JR Basford,
Editor of Archives of Physical Medicine and Rehabilitation

My co-author and I are very pleased to submit a review article entitled ‘Do thermal agents alter the ROM and mechanical properties of soft tissue? A systematic review’ to be considered for publication in ‘Archives of Physical Medicine and Rehabilitation’

This systematic review includes literature published up to May 2011, based on an extensive electronic and grey literature search. We hope that the findings will help physicians, physiotherapists and other allied health professionals involved in rehabilitation medicine make better informed decisions regarding the use of thermal agents in the clinic.

Many thanks for taking the time to consider this proposal.

Best wishes,

Chris Bleakley PhD BSc MCSP SRP
Corresponding author
Do thermal agents affect range of movement and mechanical properties in soft tissues? A systematic review

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Abstract

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List of abbreviations: range of movement (ROM); Cochrane Central Register of Controlled Trials (CCTR); Medline subject headings (MeSH); mean differences (MD); 95% confidence intervals (95% CI); standardised mean differences (SMD); hot water immersion (HWI); ultrasound (US); short wave diathermy (SWD); cold water immersion (CWI); straight leg raise (SLR)

The application of thermal agents such as heat or cold is popular in clinical and rehabilitative settings. Altering tissue temperature can have a range of therapeutic effects through changes in metabolism, nerve transmission, haemodynamics and mechanical properties.

Increasing soft tissue temperature prior to exercise is an accepted practice. This can involve active warm up, or local heat application using warm water immersion or hot packs. Heat is thought to alter the viscoelastic properties of muscles and other collagenous tissues, in preparation for physical activity or rehabilitation. Heat is also used as an adjunct to therapeutic or developmental stretching, and is often employed to treat restrictions in range of movement (ROM) due to injury or prolonged immobilisation.

Cryotherapy is the use of cold for therapeutic purposes. We have previously examined the evidence base for cryotherapy in acute injury management\textsuperscript{1} and post exercise recovery.\textsuperscript{2,3} Paradoxically, there is a growing trend of applying cold prior to exercise or rehabilitation.\textsuperscript{4} Pre-cooling (based on cold water immersion, ice packs or ice vests) has gained widespread
acceptance as a method of offsetting thermal strain and fatigue, and increasing aerobic and anaerobic capacity during competitive exercise. Others advocate application of cold prior to therapeutic rehabilitation exercises (Cryokinetics) to induce analgesia and increase volitional muscle activation around injured joints.

The benefits of using thermal interventions must outweigh any deleterious physiological effects. Recent systematic reviews advise caution with the clinical application of cryotherapy, due to short term but adverse changes to joint proprioception, muscle strength and neuromuscular performance. The biomechanical properties of collagenous tissue represent an important component of function. In vitro studies clearly show that the mechanical properties of ligament, tendon and muscle are significantly influenced by temperature; this may suggest that heat and cold should not be used interchangeably in a rehabilitation setting.

Our aim was to undertake a systematic review to examine the effect of thermal agents on the ROM and mechanical properties of soft tissue in vivo, and to discuss their clinical relevance.

Methods
Search Strategy
We searched the Cochrane Central Register of Controlled Trials (CCTR), MEDLINE, and EMBASE by combing a range of subject headings (MeSH) and key words [Cryotherapy; Cold Temperature; Ice; ice pack; cold pack; ice bath; cold water immersion; cold compress; thermotherapy; Hyperthermia, Induced; Hot Temperature; hot pack; Elasticity; extensibility; Biomechanics; mechanical properties; Stress, Mechanical; viscoelastic; Viscosity; Range of Movement, Articular; stretch; flexibility; Pliability]. Each database was searched from their earliest available record up to May 2011. We also undertook a related articles search using on
Pubmed (http://www.ncbi.nlm.nih.gov/pubmed) and read reference lists of all incoming articles. English language restrictions were applied.

**Inclusion criteria**

Studies must have involved human participants, undertaking thermal interventions (hot or cold) to soft tissues; interventions could be used with or without concomitant stretching exercises. No restrictions were made on the mode, duration or frequency of interventions.

Studies must have reported at least one outcome relating to ROM or mechanical properties of soft tissue eg. stiffness or other visco-elastic properties; these could be based on either active or passive movements. There were no restrictions made on study design or comparison group.

**Selection of studies**

Two authors independently selected trials for inclusion. The titles and abstracts of publications obtained by the search strategy were screened. All trials classified as relevant by either of the authors were retrieved. Based on the information within the full reports, we used a standardised form to select the trials eligible for inclusion in the review. If necessary, we contacted primary authors for clarification of study characteristics. Disagreement between the authors was resolved by consensus, or third party adjudication.

**Data extraction and measures of treatment effect**
Data were extracted independently by two review authors using a customised form. For each study, mean differences (MD) and 95% confidence intervals (95% CI) were calculated for continuous outcomes using RevMan software. For continuous outcomes that were pooled on different scales, standardised mean differences (SMD) were used. Treatment effects (MD, SMD) were based on between group comparisons (e.g., thermal vs control) and/or within group comparisons (pre thermal vs post thermal).

**Risk of bias**

For all included studies, methodological quality was assessed by two authors independently, using the Cochrane risk of bias tool. Each study was graded as having high, low or unclear risk of bias for the following domains; sequence generation, allocation concealment, blinding (assessor), and incomplete outcome data. For each study, the domains were described as reported in the published study report and judged by the review authors as to their risk of bias. Disagreements between authors regarding the risk of bias for domains were also resolved by consensus.

**Results**

**Included studies**

Figure 1 summarises the search strategy and selection process based on included and excluded studies. There were 36 eligible studies, comprising a total of 1301 healthy participants. The average sample size was 35.1 with the largest study based on 120 participants. Participants tended to be young, the mean ages reported in studies was between 20 and 30 years. Studies were sub-grouped based on primary treatment intervention.
In the majority of cases, the thermal intervention was applied in isolation to muscle tissue; the remainder immersed entire body parts in water, or targeted a joint region. Further methodological details of included studies are summarised in Table 1.

Details of thermal interventions

Heating interventions were classified as superficial agents: infra-red, hot packs, hot water immersion (HWI) or electric heating pads and deep heating agents: ultrasound (US) or short wave diathermy (SWD). The duration of treatments ranged between 30 seconds and 60 minutes. All but six studies applied heating for at least 10 minutes. One study heated until a pre-determined muscle temperature reduction was reached; no others recorded tissue temperature changes associated with heat application.

Cooling was undertaken topically, with the majority using ice cubes, cooling pads and cold water immersion (CWI), for durations between 10-60 minutes. A further two studies employed brief applications of vapo-coolant sprays. Skin temperature reductions were reported in four cases; three lowered to between 18°C and 23°C, with one study cooling to 10°C. Intra-muscular temperatures were reported in one study with reductions to 28.1°C.

Details of outcomes

Twenty-eight studies recorded ROM; sixteen measured active ROM (hip flexion/knee extension/ankle all movement) based on goniometric/inclinometer
measurements; three of these\textsuperscript{28,48,49} used active, weight-bearing ankle dorsiflexion and a single study\textsuperscript{29} recorded trunk flexion using a sit and reach test. Eleven\textsuperscript{19,23,31-35,37,41,43,45} measured passive ROM (hip flexion, ankle dorsiflexion, knee extension, shoulder external rotation), and in one study,\textsuperscript{25} it was unclear if the ROM tested was active or passive.

Six studies measured accessory joint movement (laxity) in response to anterior, posterior, valgus or varus passive forces at the knee joint, using an arthrometer\textsuperscript{20,21,46,47,52} or related device.\textsuperscript{38} Four studies\textsuperscript{36,40,44,52} measured passive tissue stiffness based on the relationship between joint torque and ROM. Two studies recorded passive tissue force/torque using an isokinetic dynamometer or similar device, during slow (3-5°/sec) passive movements of either the knee\textsuperscript{40} or ankle\textsuperscript{36} in the sagittal plane; in both cases real time ultrasonography was used to determine muscle fascicle length throughout the movements. Price & Lehmann\textsuperscript{44} used a motor driven foot plate and force transducer to measure passive ankle stiffness when small amplitude (5 degrees) oscillating forces (3-12 Hz) were applied, with stiffness outcomes dichotomised into elastic and viscous components.

\textit{Follow up}

All studies recorded outcomes before and immediately after the intervention. Several undertook additional outcome assessment at 5,\textsuperscript{50} 15,\textsuperscript{52} 20\textsuperscript{20} and 30\textsuperscript{33,42,47} minutes post intervention. When studies employed multiple interventions over a period of days or weeks, we focused on outcomes reported at the end of the entire treatment package; this was after 5 days,\textsuperscript{18,24,28-30,37} three\textsuperscript{19,23,43} four\textsuperscript{45} or six weeks of treatment.\textsuperscript{35}

\textit{Risk of bias}
There was a high risk of bias across all studies (Figure 2). Despite the majority of studies stating that some form of randomisation was employed, only three\textsuperscript{20,48,49} provided adequate details on sequence generation, and no study adequately reported allocation concealment. Blinding of outcome assessor was reported in six studies.\textsuperscript{26,34,35,45,48,49} Due to the nature of the intervention we did not assess blinding of participants or care givers. There was a high risk of attrition bias across all studies; just five studies\textsuperscript{19,38,42,45,46} were transparent in their reporting of drop outs, exclusions, missing data and approach to analysis.

Effect of Cold

*Hip Flexion ROM*

Three studies\textsuperscript{20,39,41} examined the immediate effect of topical cooling on hip ROM. One study\textsuperscript{20} found that 20 minutes of cooling over the hamstring muscle had little effect on active knee extension in supine (90 degrees hip flexion). In contrast, large increases in hip flexion straight leg raise (SLR) were recorded immediately after a 20 minute ice pack application (MD 11.78 degrees [8.82 to 14.73] versus baseline)\textsuperscript{39} and brief (5 sec x 6) sprays of vapocoolant (mean increase from baseline: 8.78 degrees [SD 4.97]).\textsuperscript{41}

*Ankle ROM*

Patterson et al.\textsuperscript{42} measured ankle ROM before and after a 20 minute CWI of the lower limb, with follow ups recorded every 5 minutes, for 30 minutes after treatment. The only significant findings were decreases in ankle dorsiflexion at 7 and 12 minutes versus baseline; there were insufficient data for effect size calculation.
Passive accessory ROM: Knee

This was assessed by four studies,\textsuperscript{20,21,38,52} but there were few significant findings. Two found anterior-posterior tibial displacement was reduced (MD from baseline) by 0.92mm [95% CI: 0.34, 1.50]\textsuperscript{20} and 1.00mm [95% CI: -0.59 to 2.59]\textsuperscript{52} immediately after cooling. Others found small effects in the opposite direction, with cooling immediately increasing knee joint displacement (MD 0.30mm [95% CI -0.42, 1.02] vs baseline)\textsuperscript{38} (MD 0.80mm [95% CI: -1.40 to 3.00 vs control]).\textsuperscript{21}

Passive stiffness

Uchio et al.\textsuperscript{52} found a cold induced increase in terminal stiffness during anterior to posterior tibial displacement at the knee joint (MD 22.10 Nm/mm [95% CI: 4.90 to 39.30] vs baseline). Price & Lehmann\textsuperscript{44} also found that both elastic (MD 0.52 Nm-sec/rad [95% CI -0.38 to 1.41]) and viscous tissue stiffness (MD 1.04 Nm-sec/rad [0.1 to 1.99]) around the ankle increased from baseline levels. There were conflicting results when passive tissue stiffness was measured during slow, lengthening physiological movements. Muraoka et al.\textsuperscript{40} found that cooling increased stiffness in the triceps surae muscle and tendon unit (MD 2.00Nm/mm [95% CI: -7.05, 11.05] vs baseline), whereas Kubo et al.\textsuperscript{36} found a small reduction in stiffness (MD 0.80 N/mm [95% CI: -11.06 to 12.66] vs baseline).

Effect of Heat

Hip Flexion ROM

Four studies found that hamstring heating increased knee extension\textsuperscript{26,31,50} or SLR ROM.\textsuperscript{39} The largest increase from baseline was a MD of 8.8 degrees (95% CI 4.77 to 12.83).\textsuperscript{26} This
study\textsuperscript{26} also reported significant increases in ROM compared to an untreated control (MD 7.8 degrees [95% CI 5.42 to 10.18]). Others found smaller effects in favour of heating when compared to icing [MD 2.3 degrees [95% CI -8.65 to 13.25],\textsuperscript{39} stretching (MD 2.6 degrees [-3.12 to 8.12])\textsuperscript{31} or untreated controls (MD 0.36 degrees [-4.87 to 5.59]).\textsuperscript{50}

**Ankle Dorsiflexion ROM**

In two studies,\textsuperscript{48,49} calf heating increased weight-bearing dorsiflexion ROM significantly more than untreated controls; heating was based on 15 minutes of SWD (MD 1.9 degrees [95% CI 1.04 to 2.76])\textsuperscript{48} or hot pack application [MD 2.68 degrees (95% CI 1.03 to 4.33)].\textsuperscript{49}

**Shoulder ROM**

Infra-red heating at the shoulder resulted in statistically significant increases in ROM compared to placebo (MD 11.5 degrees [95% CI 2.28 to 20.72]).\textsuperscript{27} Although Kain et al.\textsuperscript{34} found greater ROM after myofascial release compared to a 20 minute hot pack; between group differences were small and statistically insignificant.

**Passive accessory ROM: Knee**

Using a single group (before/after) design, Reed & Ashikaga\textsuperscript{46} found that 8 minutes of knee joint heating with US increased passive knee joint displacement from baseline. The largest change from baseline was an increased varus/valgus displacement (at 20 degrees of knee flexion) of 1.3 mm [95% CI -0.9 to 3.5]. In an RCT, Benoit et al.\textsuperscript{21} compared passive knee joint displacement, before and after either hot water immersion (HWI) or control; there was a
small trend that heating decreased displacement (MD 0.2mm [-1.73 to 2.13] vs control) but no significant within or between group differences.

Passive stiffness
Kubo et al. found heating resulted in slight reductions to tendon stiffness during slow, passive lengthening physiological movements (MD 0.4N/mm [-11.73 to 12.53] vs baseline).

Figures 3 and 4 are Forest plots summarising the within and between group effects for Cold and Heat.

Effect of Heat or Cold used in combination with stretching
A large number of studies compared the effects of stretching only, to stretching combined with either cold or heat interventions, with all studies reporting ROM. Figures 5 and 6 summarise the individual effect sizes reported in each study.

Cold & Stretching vs Stretching only (Single intervention)
Five studies found effects in favour of cold and stretching over stretching alone based on a single intervention. Brodowicz et al. recorded the largest increase in ROM [MD 22.6 degrees 95% CI (-17.1 to 62.3)], with others finding MD’s of 6.1 degrees [95% CI -1.43 to 13.63]) and 3.9 degrees (CI’s not available). Effect sizes in the remaining studies were small and statistically insignificant.
Cold & Stretching vs Stretching only (Multiple interventions)

Three studies used multiple interventions over periods of 5 days or four weeks. There were no significant differences in ROM at the end of each study; the largest between group differences were in favour of stretching only (MD 2.4 degrees [95% CI -1.7 to 6.5]).

Heat & Stretching vs Stretching only (Single intervention)

Eleven out of twelve studies reported larger increases in ROM after a single intervention of heating and stretching compared to stretching alone. Only two effects in favour of heat and stretching reached statistical significance (MD 2.9 degrees [95% CI 1.36 to 4.44]) (MD 5 degrees [95% 1.12 to 8.88]).

Heat & Stretching VERSUS Stretching only (Multiple interventions)

10 studies examined the effects of multiple interventions undertaken over periods of up to 5 weeks. Four studies found little differences in ROM between groups, at the end of the intervention package. The remaining six found effects in favour of stretching and heat, with four reaching statistical significance. The largest effect in favour of heating and stretching was reported by Draper et al. based on a MD of 10.9 degrees (95% CI 4.76 to 17.04 vs stretching alone).

Heating Dose

Few studies compared different modes of thermal interventions. Two studies found significantly greater increases in ROM based on a pulsed, dry heating device (pneumatherm).
compared to a moist heat pack. Interestingly, Sakulsriprasert et al.\textsuperscript{49} found that heating for 15 minutes resulted in larger increases in ankle ROM, than a 30 minute treatment duration (MD 2.52 degrees [95% CI 0.27 to 4.77]). One study\textsuperscript{35} compared combinations of hot pack and stretching with ultrasound and stretching; despite recording active and passive ankle ROM after 2, 4 and 6 weeks of treatment, there were no significant differences between groups.

### Duration of Effects

A small number of studies reported outcomes beyond the immediate stages after treatment. Despite reporting an immediate effect on knee stiffness, two studies found no significant differences at 15\textsuperscript{52} and 20 minutes\textsuperscript{20} after icing. Reed et al.\textsuperscript{47} and Henricson et al.\textsuperscript{33} found that heating and stretching combined, and stretching alone, both significantly increased knee joint ROM for up to 30 minutes after treatment, but there were no between group differences.

### Discussion

#### Summary of findings

This is the first review to systematically examine the in vivo effects of thermal interventions on ROM and biomechanical properties of soft tissues. There was a consistently high risk of bias across included studies, and we were unable to meaningfully sub-group studies into high and low quality. Few studies reported adequate sequence generation or allocation concealment. Equally, few studies undertook blinding of outcome assessors or adequately described missing outcomes or how these were managed. Overall, the poor quality of
evidence, and the small number of participants within many included studies, means that findings should be interpreted with some degree of caution.

There were conflicting data on the effect of cold on ROM, accessory joint movement, and passive stiffness. There was clearer evidence that heat increases ROM with a number of studies showing statistically and clinically significant effects. Both cold and heat seem to be effective adjuncts to stretching; however larger increases in ROM were attained using a combination of heat and stretch.

**Therapeutic heating**

Increasing soft tissue temperature prior to exercise is a popular practice. Heat is thought to alter the viscoelastic properties of collagenous tissues in preparation for physical activity. In accordance with current practice, we found clear trends that heating immediately increases ROM at a variety of joints. There was further evidence that heat improves the therapeutic effects of stretching; this was evident after a single treatment intervention in 11 out of 12 studies with two studies$^{18,37}$ reporting significant effects over stretching alone. Furthermore, cumulative increases in ROM were reported when heat and stretching were repeated over a period of days or months.

There may be a number of mechanisms underpinning the heat induced increases in ROM reported. In vitro research into the effects of temperature on tissue mechanics show explicit patterns with human supraspinatus,$^{12}$ canine patellar tendon$^{15}$ and porcine hamstring tendon$^{16}$ all showing reduced stiffness and greater viscous mechanical behaviour at higher temperatures. In contrast, cooling is associated with an increased force response in
ligaments,\textsuperscript{11} and increased muscle stiffness.\textsuperscript{13,14} Notwithstanding this, it is unlikely that the included human studies could replicate the large temperature changes induced within in vitro models. We also found conflicting evidence on the effect of temperature on related mechanical properties such as accessory joint movement, and passive stiffness. A more likely mechanism is that heat increased patients’ stretch tolerance based on sensory stimulation and analgesia. This aligns with the theory is that increased muscle extensibility after stretching is primarily due to modification of sensation rather than acute changes in tissue mechanics.\textsuperscript{54-56}

\textbf{Thermal dose}

The fundamental principle for thermal interventions is to transfer or extract heat energy from the body. The magnitude of energy transfer and the resultant temperature fluctuation is a key determinant of therapeutic effect. Studies in this review employed a range of thermal interventions, of which many were topical agents such as ice packs, hot packs or water immersion. Large temperature changes may be difficult to achieve with topical agents, due to the insulating effect of adiposity.\textsuperscript{57} In the current review, only two studies\textsuperscript{40,50} considered intramuscular temperature change, with the largest increase reported to be just 0.4°C.\textsuperscript{50} Previous studies confirm that deep thermal modalities such as US, can rapidly increase deep (3cm) tissue temperature by >4°C,\textsuperscript{58,59} perhaps suggesting a superior therapeutic effect. Direct comparison between deep and superficial heating agents was limited to two studies,\textsuperscript{26,48} with both finding larger increases in ROM with deep heating agents. Another interesting observation was that studies undertaking stretching and heating simultaneously,\textsuperscript{18,23,30,37,43} generally reported larger effects (over stretching alone), than those which initiated stretching shortly after heating.\textsuperscript{19,24,35} Tissue temperature has been shown to
drop rapidly after removal of a heating agent; and potentially, applying heat and stretching simultaneously can maximise its therapeutic effects.

Cooling and stretching

Heating and cooling agents are regarded as having opposing physiological effects in terms of temperature, blood flow and metabolism. Although the effect of cold on tissue stiffness and joint laxity was unclear, an interesting trend was that cold also enhanced the acute effects of stretching. In vitro findings suggest tissue compliance decreases at lower temperatures; however, we must acknowledge that topical cooling agents produce only moderate reductions to deep muscle temperatures in vivo. Again a more likely explanation for the observed increases in ROM due to concomitant cooling and stretching is that cold analgesia increased stretch tolerance, permitting stretching into more extreme ranges.

Cooling pre-exercise

Cold agents are often applied prior to sport or other physical activities. For example, athletes often apply short periods of cooling at the side line or during half time, before returning to sporting competition. A growing trend is the use of pre-cooling before exercising in the heat. Recent systematic reviews advise caution when undertaking physical activity immediately after cryotherapy; this is due to short term but adverse changes to joint proprioception and muscle strength. A related concern is often that cooling reduces tissue compliance and ROM; however this cannot be fully substantiated from the current evidence base. The effects of local cooling (without therapeutic stretching) on joint ROM were conflicting; the cold induced decreases in ROM reported were generally small and may only be relevant for competitive sporting situations requiring maximum ROM. Notwithstanding this, tissue
stiffness and compliance are important factors determining performance and injury risk \(^{61}\) and
the in vivo effect of temperature on these parameters remains unclear, and is an important
area for future study.

**Limitations and future study**

The majority of studies in the current review applied thermal agents to muscle. Tendons and
ligaments have unique mechanical properties and may respond differently to changes in
temperature. This is an important area for future research as tendon mechanics have an
important role in sporting performance. Indeed, different sports need different levels of
musculoskeletal compliance. Sports involving jumping or bounding carry a high volume of
stretch shortening demands and therefore favour a more elastic, compliant tendon whereas
less compliant tendon are suited to sports where isometric or concentric activity
predominates.\(^{62}\) An interesting concept may be the judicious use of thermal agents to
optimise tendon mechanics and force transmission prior to sport.

Our primary focus was on the effects of thermal interventions, and potential differences in
stretching techniques were not addressed. In studies comparing heat and stretch, or ice and
stretch versus stretch alone, the stretching dose was standardised across groups, in terms of its
mode, duration and frequency. Subsequent research should consider whether heating or
cooling complements certain stretching techniques or dosages.

Perhaps the most significant limitation is the high risk of bias across included studies. Future
studies should incorporate: a randomised controlled design with adequate sequence
generation and allocation concealment, and ensure effective and explicit blinding of outcome.
Conclusion

Thermal agents are commonly used in a variety of capacities throughout sport and rehabilitation and we must have strong rationale for their use. An inherent limitation in the current evidence base is the high risk of bias. The majority of studies have focused on effects of thermal agents on ROM. Although the effects of cold are conflicting, there was clearer evidence that heat increases ROM. This seems to provide a therapeutic window which ameliorates the effects of stretching interventions on ROM; and there was clear evidence that combined heat and stretching is more effective than stretching alone. These findings seem to support the use of heat an adjunct to developmental and therapeutic stretching techniques.

The effects of heat or ice on key mechanical properties such as passive stiffness remain equivocal, and should be the focus of future study.

References


43. Peres SE, Draper DO, Knight KL, Ricard MD. Pulsed shortwave diathermy and prolonged long-duration stretching increase dorsiflexion range of motion more than identical stretching without diathermy. J Athl Train 2002;37:43-50.


**Figure Legends**

Figure 1: Summary of search strategy and selection process based on included and excluded studies

Figure 2: Included studies: Risk of bias summary

Figure 3: Forest plot of within group comparisons (Pre Thermal treatment (Baseline) versus Post Thermal treatment)

Figure 4: Forest plot of between group comparisons (Thermal treatment versus Control)

Figure 5: Forest plot of between group comparisons (Ice & stretch versus Stretch only)

Figure 6: Forest plot of between group comparisons (Heat & stretch versus Stretch only)
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### Table 1

**Summary of Study Characteristics**

<table>
<thead>
<tr>
<th>AUTHOR (STUDY TYPE)</th>
<th>SUBJECT / INCLUSION CRITERIA</th>
<th>INTERVENTION [FINAL TISSUE TEMPERATURE REPORTED °C]</th>
<th>OUTCOMES RECORDED [FOLLOW UP]</th>
<th>SIGNIFICANT CHANGES WITHIN GROUPS</th>
<th>SIGNIFICANT CHANGES BETWEEN GROUPS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>COLD vs CONTROL</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Newton 41 RCT</td>
<td>N=84 healthy</td>
<td>-COLD: Fluori-Methane Spray</td>
<td>SPECIALLY DESIGNED TABLE</td>
<td>No significant findings</td>
<td>No significant findings</td>
</tr>
<tr>
<td></td>
<td>10 male, 74 female</td>
<td>-COLD: Isopropyl alcohol</td>
<td>1. Passive hip flexion</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aged: Collegiate age</td>
<td>-COLD: Ethyl chloride</td>
<td>[immediately post Rx]</td>
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<td></td>
<td></td>
<td>Each applied 6 times (5 sec each and 3 sec off) to the posterior aspect of the thigh</td>
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<td></td>
<td>-CONTROL: No intervention</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Price &amp; Lehmann 44</td>
<td>N=10 healthy</td>
<td>-COLD: Ice water pack 30 min (gastrocnemius)</td>
<td>1 and 2 increased [Immediate]</td>
<td>1 and 2 increased [Immediate]</td>
<td>N/A</td>
</tr>
<tr>
<td>Single group:</td>
<td>5 male, 5 female</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>before/after</td>
<td>Aged: 20-29 yrs</td>
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<tr>
<td></td>
<td></td>
<td>-COLD: Ice water pack 30 min (gastrocnemius)</td>
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<tr>
<td>Uchio et al 52</td>
<td>N=20 healthy</td>
<td>-COLD: Cooling pad 15 mins at 4°C (knee joint)</td>
<td>KNEE KT 2000 ARTHROMETER</td>
<td>1. Decreased [Immediate]</td>
<td>N/A</td>
</tr>
<tr>
<td>Single group:</td>
<td>10 male, 10 female</td>
<td>[skin temperature: 21.6°C]</td>
<td>1. Total joint displacement (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>before/after</td>
<td>Mean age: 21-28 yrs</td>
<td></td>
<td>2. Terminal stiffness (N/mm )</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>[immediately, 15 mins post Rx]</td>
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<tr>
<td>Melnyk et al 38</td>
<td>N=15 healthy</td>
<td>-COLD: Automatic water cooler 20 minutes (knee joint)</td>
<td>ACCELERATED PISTON APPLYING POSTERIOR TO ANTERIOR FORCE ON TIBIA</td>
<td>No significant findings</td>
<td>N/A</td>
</tr>
<tr>
<td>Single group:</td>
<td>Mean age: 25 (± 3.6 yrs)</td>
<td>[skin temperature: 10.1 (±1.5°)]</td>
<td>1. Tibial translation distance (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>before/after</td>
<td></td>
<td></td>
<td>2. Tibial velocity (mm / s-1)</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>[immediately post Rx]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muraoka et al 40</td>
<td>N=6 healthy males</td>
<td>-COLD: CWI 60 min at 5-8°C (lower leg)</td>
<td>ANKLE DYNAMOMETER / ULTRASONOGRAPHY / EMG</td>
<td>No significant findings</td>
<td>N/A</td>
</tr>
<tr>
<td>Single group:</td>
<td>Mean age: 27 (± 4 yrs)</td>
<td>[skin temperature:22.8 (±2.5°), intramuscular</td>
<td>1. Passive stiffness (N/mm2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>before/after</td>
<td></td>
<td>temperature:28.1 (±1.3°)]</td>
<td>2. Gastrocnemius muscle fasicle length (mm via US)</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>[immediately post Rx]</td>
<td></td>
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<tr>
<td>Patterson et al</td>
<td>N=21 healthy</td>
<td>-COLD: CWI 20 mins at 10°C (lower leg with water)</td>
<td>SELF REPORTED DOMINANT</td>
<td>1. Decreased [7 and 12 mins post]</td>
<td>N/A</td>
</tr>
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<tr>
<td>Study</td>
<td>Participants</td>
<td>Intervention</td>
<td>Outcome Measures</td>
<td>Findings</td>
<td></td>
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<tr>
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</tbody>
</table>
| Arguello 20 | N=14 | COLD: Cooling pad 20 mins (knee) [skin temperature: 18.26 (±2.3°C)]  
CONTROL: Room temperature pad 20 min (knee) | KNEE HAND HELD GONIOMETER  
1. Active ROM (degrees)  
KT 1000 ARTHROMETER  
2. Knee joint displacement (mm)  
[immediately, 20 min post Rx] | 2. Decreased in COLD [Immediate]  
2. COLD < CONTROL |
| Minton 39 | N=18 healthy  
Crossover | -COLD: Crushed ice secured with elastic wrap 20 mins (hamstring)  
-HEAT: Heating pads secured with elastic wrap 20 mins (hamstring) | HAMSTRING GONIOMETER (hand held)  
1. Active SLR (deg)  
[immediately post Rx] | 1. Increased in BOTH GROUPS [immediate]  
No significant findings |
| Benoit et al 21 | N=15 healthy  
Crossover (1 day between conditions) | -COLD: CWI 20 mins at 15°C (4 inches above patella)  
-HEAT: HWI 20 mins at 40°C (4 inches above patella)  
-CONTROL: No Intervention | KNEE KT 1000 ARTHROMETER  
1. Joint displacement with 89N (cm)  
2. Joint displacement with maximal force (cm)  
[immediately post Rx] | No significant findings  
No significant findings |
| Kubo et al 36 | N=8 healthy males  
Rand Crossover (separate days) | -COLD: CWI 30 mins at 5°C (to head of fibula)  
-HEAT: HWI 30 min at 42°C (to head of fibula) | ANKLE DYNAMOMETER / ULTRASONOGRAPHY / EMG  
1. Passive torque (Nm)  
2. Passive stiffness (N/mm)  
[immediately post Rx] | No significant findings  
No significant findings |
| Reed & Ashikaga 46 | N=25 healthy  
Single group: before/after | HEAT: Continuous US (1 MHz, 1.5 w/cm²), 8 minutes (knee) | GENUCOM ARTHROMETER ELECTROGONIOMETERS  
1. anterior-posterior drawer test at 90° of knee flexion,  
2. varus/valgus test at 0° of knee | 2-4. Increased [immediate]  
N/A |
<table>
<thead>
<tr>
<th>Study</th>
<th>Description</th>
<th>Methodology</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Funk et al 31</td>
<td>Rand Crossover (7 days between conditions)</td>
<td>N = 30 healthy males</td>
<td>Flexion (full extension), 3. varus/valgus at 20° of knee flexion, 4. the genu recurvatum test. [immediately post Rx]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-HEAT: Hot moist pack 20 minutes at 160°F (hamstring)</td>
<td>-GONIOMETER 1. Passive knee extension (deg) 2. Subjective assessment of both treatment (questionnaire) [immediately post Rx]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-STRETCH: 3 x 30 secs hamstring.</td>
<td>-1. HEAT &gt; STRETCH [immediate] 2. Subjects believed hot pack was less beneficial.</td>
</tr>
<tr>
<td>Sawyer et al 50</td>
<td>RCT (leg randomised to treatment or control)</td>
<td>N = 27 male (3 unable to complete) Mean age: 21.9 (± 6.3 yrs) (&gt; 20° from full knee extension with the hip flexed to 90°)</td>
<td>Heat: Hot pack applied until muscle temperature increased by 0.4°C (hamstring) Intramuscular temperature (2.54 cm below skin surface) increased by 0.4°C -CONTROL</td>
</tr>
<tr>
<td>Cosgray et al 26</td>
<td>Rand Crossover (24 hours between conditions)</td>
<td>N = 30 healthy males</td>
<td>Heat: Pneumatherm heating 20 mins (posterior thigh)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-HEAT: Moist heat pack 20 mins (posterior thigh)</td>
<td>-HAND HELD GONIOMETER 1. Active knee extension (deg) [immediately post, 4, 8 and 16 mins Rx]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-CONTROL: Dry terry cloths 20 mins</td>
<td>1. Increased in HEAT (pneumatherm) [immediate]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1. Heat (pneumatherm) &gt; CONTROL [immediate]</td>
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<tr>
<td>Robertson et al 48</td>
<td>Rand Crossover (36 hrs between conditions)</td>
<td>N = 24 healthy 12 male, 12 female Mean age: 21.5 (± 2.5yrs)</td>
<td>Heat: SWD 15 mins (calf)</td>
</tr>
<tr>
<td></td>
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<td>-HEAT: Hot pack 15 mins (calf)</td>
<td>-INCLINOMETER 1. Weightbearing ankle D/F (deg) [immediately post Rx]</td>
</tr>
<tr>
<td></td>
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<td>-CONTROL: no intervention</td>
<td>-1. HEAT (SWD) &gt; HEAT (hot pack); HEAT (SWD) &gt; CONTROL [immediate]</td>
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<tr>
<td>Demura et al 27</td>
<td>Rand Crossover (Time between conditions not clear)</td>
<td>N = 24 healthy 10 males, mean age 20.9 (± 3.1 yrs); 14 females, mean age 21.2 (± 1.7 yrs)</td>
<td>Heat: polarised infra-red light 10 mins (shoulder)</td>
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<td>-PLACEBO: Placebo heating, 10 mins (shoulder)</td>
<td>-HAND HELD GONIOMETER Active shoulder ROM (deg) 2. Shoulder extension 3. Total ROM [immediately post Rx]</td>
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<td>-LIGHT EXERCISE: 10 mins (shoulder)</td>
<td>1-3. Increased in HEAT [immediate] 1-3. HEAT &gt; PLACEBO [immediate]</td>
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<tr>
<td>Sakulsriprasert 49</td>
<td>RCT</td>
<td>N = 75 healthy 30 male, 45 female Aged: 18-25 yrs</td>
<td>Heat: Hot pack 15 mins at 45°C (calf)</td>
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<td>-HEAT: Hot pack 30 mins at 45°C (calf)</td>
<td>-INCLINOMETER 1. Weightbearing active ankle D/F (deg) [immediately post Rx]</td>
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<td>-CONTROL: No intervention</td>
<td>-1. HEAT (15 mins) &gt; CONTROL; HEAT (15 mins) &gt; HEAT (30 mins) [immediate]</td>
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<td>Kain et al 34</td>
<td>RCT</td>
<td>N = 31 healthy junior/senior college students</td>
<td>Heat: Hot pack 20 minutes (shoulder)</td>
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<td>-MYOFASCIAL RELEASE: 3 mins (shoulder)</td>
<td>-GONIOMETER被动ROM (deg) 1. Flexion 2. Extension 3. Abduction</td>
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<td>1-3. Increased in BOTH GROUPS [immediate] No significant findings</td>
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<td>Study</td>
<td>Participants</td>
<td>Intervention</td>
<td>Outcome</td>
</tr>
<tr>
<td>---------------------</td>
<td>--------------</td>
<td>-------------------------------------------------------------------------------</td>
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</table>
| Halkovich et al     | N=30 healthy | -COLD: Fluori-Methane spray, six applications, 5 sec on and 3 sec off (skin overlying the hamstring muscles when in a stretched position)  
-CONTROL: Held in a stretched position for 45 sec | SPECIALLY DESIGNED TABLE  
1. Passive hip flexion (side lying SLR) (deg)  
[immediately post Rx] | -            |
|                     | RCT          |                                                                 |         | 1. COLD >CONTROL [immediate] |
| Cornelius et al     | N=120 males  | -STRETCH ONLY: Passive stretch  
-COLD & STRETCH 1: PNF stretching with ice cubes 10 mins (posterior thigh)  
-COLD & STRETCH 2: Passive stretch with ice (ice cubes) 10 mins (posterior thigh) | LEIGHTON FLEXOMETER  
Hip flexion (deg)  
[immediately post Rx] | -            |
|                     | RCT          |                                                                 |         | No significant findings  |
| Rancour et al       | N=33 healthy | - COLD & STRETCH: Ice 10 min and hamstring stretch  
-STRETCH ONLY: Hamstrings  
Standardised Rx: Daily Rx for 4 weeks | HIP FLEXION  
DOUBLE ARM GONIOMETER  
1. Passive SLR (supine position)  
[weekly during Rx and for 4 weeks post Rx] | 1. Increased in BOTH GROUPS [immediate]  
1. Decreased in both groups [4 weeks after the final Rx] |
|                     | RCT          |                                                                 |         | No significant findings |
| Lentell et al       | N=92 U.S. healthy males  
Mean age: 24.3 (± 4.1 yrs) | -HEAT & STRETCH: Moist hot packs at ~66°C (shoulder) during stretch  
-COLD & STRETCH: Ice pack ~0°C (shoulder), during stretch  
-HEAT & STRETCH AND ICE: Moist heat and stretch followed by ice pack  
-STRETCH ONLY  
-CONTROL: No Intervention  
Standardised Rx: Three 40 mins Rx over a 5 day period. | SHOULDER  
UNIVERSAL GONIOMETER  
1. Passive external rotation (supine position)  
[immediately post Rx; 3 days following final Rx] | -            |
|                     | RCT          |                                                                 |         | 1. HEAT & STRETCH > STRETCH ONLY [immediate; 3 day after final Rx]  
1. HEAT & STRETCH > CONTROL [3 days after final Rx] |
| Taylor et al        | N=24 U.S. Army population  
12 male, 12 female  
Mean age: 25.46 yrs | - HEAT & STRETCH: Hot pack (77°C) 20 min (posterior thigh) followed by 1 min hamstring stretch.  
- COLD & STRETCH: Cold gel pack (~18°C) 20 min (posterior thigh) followed by 1 min hamstring stretch.  
- STRETCH ONLY. | ELECTRONIC INCLINOMETER  
Lying supine with the hip of the treated thigh flexed to 90°.  
1. Active knee extension  
[immediately post Rx] | -            |
| Rand Crossover      | (at least 7 days between conditions) |                                                                 |         | No significant findings |
| Brodowicz et al     | N=24 healthy male athletes  
Mean age: 20.7 (± 1.2 yrs) | -HEAT & STRETCH: Heat 20 mins (posterior thigh) during stretching  
-COLD & STRETCH: Ice 20 mins (posterior thigh) | HAMSTRING  
Leighton flexometer  
1. Active SLR (deg)  
[immediately post Rx] | -            |
<p>|                     | RCT          |                                                                 |         | 1. COLD &amp; STRETCH &gt; HEAT &amp; STRETCH: COLD &amp; STRETCH &gt; CONTROL [immediate] |</p>
<table>
<thead>
<tr>
<th>Study</th>
<th>Participants</th>
<th>Intervention</th>
<th>Outcome Measures</th>
<th>Results</th>
</tr>
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<tbody>
<tr>
<td>Burke et al 24 RCT</td>
<td>N=45 healthy (24 male, 21 female) Age range: 18-25 yrs</td>
<td>-HEAT &amp; STRETCH: HWI 10 mins at 44°C (up to gluteal fold) followed by PNF training -COLD &amp; STRETCH: CWI 10 mins at 8°C (up to gluteal fold) then PNF training -STRETCH ONLY: 10 min (standing) then PNF training Standardised Rx: PNF training to increase SLR, intervention every day for 5 days</td>
<td>GONIOMETER RIGHT HIP 1. Active ankle D/F (deg) [immediately post Rx]</td>
<td>1. Increased in ALL GROUPS [immediately]; increased in HEAT &amp; STRETCH [immediate, 30 mins post Rx] 2. Increased in HEAT &amp; STRETCH [immediate; 30 mins post Rx] 3. Increased in STRETCH ONLY [immediate; 30 mins post Rx] No significant findings</td>
</tr>
<tr>
<td>Henricson et al 33 RCT</td>
<td>N=30 healthy (15 male, 15 female) Mean age: 30 (± 0.5 yrs)</td>
<td>-HEAT &amp; STRETCH: Electric heating pad 20 mins at 43°C followed by the stretching -HEAT: Electric heating pad 20 mins at 43°C (lateral, medial and posterior portion of the thigh) -STRETCH ONLY: Stretching (SLR in supine position using a modified contract-relax technique)</td>
<td>GONIOMETER RIGHT HIP 1. Active ankle D/F (deg) [immediately post Rx]</td>
<td>1. Increased in HEAT &amp; STRETCH; STRETCH ONLY [immediate] 1. HEAT &amp; STRETCH &gt; CONTROL; HEAT &amp; STRETCH &gt; CONTROL [immediate] No significant findings</td>
</tr>
<tr>
<td>Wessling et al 53 Rand Crossover (7 days between treatment sessions)</td>
<td>N=40 healthy college students (18 male, 22 female) Mean age: 20.4 (± 2.5 yrs)</td>
<td>-HEAT &amp; STRETCH: Static stretch combined with US (1.5 W/cm²) 7 mins (triceps surae) -STRETCH ONLY: Static stretch 7 mins -CONTROL: No Rx</td>
<td>INCLINOMETER 1. Knee joint displacement (valgus and varus) (deg) [2.5, 17.5 and 32.5 mins post Rx]</td>
<td>1. Increased in BOTH GROUPS [17.5 and 32.5 mins post Rx] No significant findings</td>
</tr>
<tr>
<td>Draper et al 28 RCT</td>
<td>N=40 healthy college students (18 male, 22 female) Mean age: 20.4 (± 2.5 yrs)</td>
<td>-HEAT &amp; STRETCH: US 7 mins (3 MHz, 1.5 W/cm²) and stretching -STRETCH ONLY: Standardised Rx: Rx twice daily (&gt;3 hours apart) for 5 consecutive days.</td>
<td>HAND HELD GONIOMETER 1. Passive ankle D/F (deg) [2, 4 and 6 weeks follow up]</td>
<td>1. Increased in BOTH GROUPS [weeks 2 and 4] 2. Increased in HEAT (US) &amp; STRETCH [week 2] 2. Increased in EXERCISE [week 2] No significant findings</td>
</tr>
<tr>
<td>Reed 47 Rand Crossover (28 days between conditions)</td>
<td>N=21 healthy women Mean age: 31.5 (± 11 yrs)</td>
<td>-HEAT &amp; STRETCH: Continuous US (3 MHz, 1.25 W/cm² for 2.5 mins) during static valgus stretch (10 ft-lb) -SHAM HEAT &amp; STRETCH: Sham continuous US (0 W/cm² for 2.5 mins) and static valgus stretch (10 ft-lb)</td>
<td>GENUCOM ARTHROMETER ELECTROGONIOMETERS 1. Knee joint displacement (valgus and varus) (deg) [2.5, 17.5 and 32.5 mins post Rx]</td>
<td>1. Increased in BOTH GROUPS [17.5 and 32.5 mins post Rx] No significant findings</td>
</tr>
<tr>
<td>Knight et al 35 RCT</td>
<td>N=97 (38 male, 59 female Aged: 17-50 years (ankle D/F less than 20°)</td>
<td>-HEAT &amp; STRETCH: Moist hot packs 15 mins at 73.8°C (plantarflexors) followed by stretching (4 x 20 secs calf) -HEAT &amp; STRETCH: US 7 mins (1 MHz, 1.5 W/cm²) followed by stretching (4 x 20 secs calf) -STRETCH ONLY: Stretch (4 x 20 secs calf)</td>
<td>HAND HELD GONIOMETER 1. Active ankle D/F (deg) 2. Passive ankle D/F (deg) [2, 4 and 6 weeks follow up]</td>
<td>1. Increased in ALL GROUPS [weeks 2 and 4] No significant findings</td>
</tr>
<tr>
<td>Study</td>
<td>Design</td>
<td>Subjects</td>
<td>Interventions</td>
<td>Measured Outcomes</td>
</tr>
<tr>
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</tr>
<tr>
<td>Draper et al 29 RCT</td>
<td>N= 37 college students 11 male, 26 female Mean age: 20.46 (± 1.74 yrs) (SLR &lt;100°)</td>
<td>-HEAT &amp; STRETCH: PSWD 15 mins (hamstring) followed by stretching (3 x 30 secs hamstring) -SHAM &amp; STRETCH: Sham PSWD 15 mins (hamstring) followed by stretching (3 x 30 secs hamstring) -CONTROL: No Rx</td>
<td>SIT AND REACH BOX [immediately after Rx for 5 consecutive days; additional follow up 3 days after final Rx]</td>
<td>1. Increased in ALL GROUPS [immediate; 3 day follow up] No significant findings</td>
</tr>
<tr>
<td>Peres et al 43 RCT</td>
<td>N=60 healthy (44 completed study) 21 male, 23 female Aged: 22.5 (± 2 yrs)</td>
<td>-HEAT &amp; STRETCH: PSWD 20 mins (triceps surae) during stretch 10 mins (calf) -HEAT &amp; STRETCH &amp; ICE: PSWD 20 mins (triceps surae) and stretch 10 mins (calf) and ice 5 mins (triceps surae) -STRETCH ONLY: Stretch 10 mins (calf)</td>
<td>DIGITAL INCLINOMETER 1. Passive ankle D/F (deg) [immediately post Rx over consecutive 14 days; additional follow up 6 days after final Rx]</td>
<td>1. Increased in ALL GROUPS [immediate, 6 day follow up] 1. No significant findings</td>
</tr>
<tr>
<td>Draper et al 30 RCT</td>
<td>N=30 healthy 19 male, 11female Mean age: 21.5 yrs (&lt; 160° of knee extension with the hip at 90° of flexion).</td>
<td>-HEAT &amp; STRETCH: PSWD 15 mins (distal hamstrings) during stretch 10 mins (hamstrings) -SHAM HEAT &amp; STRETCH: Sham heating 15 mins (distal hamstrings) during stretch 10 mins (hamstrings) -CONTROL: No Rx</td>
<td>HAND HELD GONIOMETER 1. Active knee extension (deg) [immediately post Rx for 5 consecutive days; additional follow up 3 days after final Rx]</td>
<td>1. Increased in HEAT &amp; STRETCH; SHAM HEAT &amp; STRETCH [mean daily increase over 5 days] 1. HEAT &amp; STRETCH &gt; SHAM HEAT &amp; STRETCH [after 3,4 and 5 days of Rx; 3 days after final Rx] No significant findings</td>
</tr>
<tr>
<td>Brucker et al 23 RCT</td>
<td>N=23 Healthy college-age 8 male, 15 female Mean age: 22.7 (±2.1 yrs) 5 subjects dropped out: 3 were unavailable and 2 subjects did not report for the study.</td>
<td>-HEAT &amp; STRETCH: PSWD 20 mins during stretch -STRETCH ONLY: Stretch (low-load, prolonged, long-duration calf)</td>
<td>DIGITAL INCLINOMETER 1. Passive ankle D/F (deg) [immediately post Rx over 3 weeks; additional follow up at 3 and 17 days after final Rx]</td>
<td>1. Increased in BOTH GROUPS [Day 19, 24, 39] No significant findings</td>
</tr>
<tr>
<td>Akbari et al 19 RCT</td>
<td>N=50 Inactive boys Aged: 12-14 yrs (SLR &lt; 70°)</td>
<td>-HEAT &amp; STRETCH: US 5 mins followed by stretch (4 x 15 secs hamstring) -HEAT &amp; STRETCH: US for 5 mins followed by stretch (2 x 30 secs hamstring) -HEAT: US 5 mins (hamstring) -STRETCH ONLY: 4 x 15 secs hamstring -STRETCH ONLY: 2x 30 secs hamstring</td>
<td>GONIOMETER 1. SRL (passive knee extension) (deg) [after 3 weeks of Rx]</td>
<td>1. Increased in ALL GROUPS [after 3 weeks of Rx] No significant differences</td>
</tr>
<tr>
<td>Ajaz et al 18 RCT</td>
<td>N=30 healthy males Mean age: 24.13 (ankle D/F less than 20°)</td>
<td>-HEAT &amp; STRETCH: Static stretch (calf) and US (1MHz) applied to the plantar flexors for first 7 mins of 10 mins stretch protocol -STRETCH ONLY: Static stretch (calf) for 10 mins</td>
<td>HAND HELD GONIOMETER 1. Active ankle D/F (deg) [immediately after Rx for 5]</td>
<td>1. Increased in BOTH GROUPS [immediately after 5 days of Rx; 3 days after final Rx] 1. HEAT &amp; STRETCH &gt; STRETCH ONLY [immediately after 5 days of Rx; 3 days after final Rx] No significant differences</td>
</tr>
<tr>
<td>Standardised Rx: Rx once daily for 5 consecutive days.</td>
<td>consecutive days; additional follow up 3 days after final Rx</td>
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</tbody>
</table>

EMG: Electromyography; deg: degrees; Rx: Treatment; N/A: Not applicable; CWI: Cold water immersion; HWI: Hot water immersion; ROM: Range of movement; PSWD: Pulsed Short wave diathermy; SLR: Straight leg raise; D/F: Dorsi Flexion; P/F: Plantar Flexion; US: Ultrasound; PNF: Proprioceptive Neuromuscular Facilitation
Electronic search

Medline / CCTR / EMBASE (n=1771 titles/abstracts)
Related articles pubmed (n=231 titles/abstracts)

FULL TEXT STUDIES SCREENED FOR ELIGIBILITY: N=53

Included (n=36)
- Cold (n=7)
- Heat (n=8)
- Cold vs Heat (n=3)
- Cold & Stretch / Heat & Stretch (n=18)

Excluded with reasons (n=16)
- Animal study (n=3)
- Review article (n=1)
- Treatment intervention not relevant (n=1)
- Outcomes not relevant (n=11)
Figure 3

<table>
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<th>Study or Subgroup</th>
<th>Std. Mean Difference</th>
<th>Std. Mean Difference</th>
</tr>
</thead>
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<tr>
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<td>IV, Fixed, 95% CI</td>
<td>IV, Fixed, 95% CI</td>
</tr>
<tr>
<td>1.1.1 Cold (immediate follow up)</td>
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<td></td>
</tr>
<tr>
<td>Arguello 2009</td>
<td>1.14 [0.33, 1.95]</td>
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<tr>
<td>Arguello 2009</td>
<td>0.00 [-0.74, 0.74]</td>
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<tr>
<td>Kubo 2005</td>
<td>-0.06 [-1.04, 0.92]</td>
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<tr>
<td>Melnyk 2006</td>
<td>0.29 [-0.43, 1.01]</td>
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<tr>
<td>Minton 1993</td>
<td>-0.31 [-0.96, 0.35]</td>
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<tr>
<td>Muraoka 2008</td>
<td>0.23 [-0.91, 1.37]</td>
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<tr>
<td>Price 1990</td>
<td>0.52 [-0.38, 1.41]</td>
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<tr>
<td>Price 1990</td>
<td>1.04 [0.10, 1.99]</td>
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<tr>
<td>Uchio 2003</td>
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<td>Uchio 2003</td>
<td>0.38 [-0.24, 1.01]</td>
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<td>1.1.2 Heat (immediate follow up)</td>
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<td>Cosgray 2004</td>
<td>-1.09 [-1.64, -0.55]</td>
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<tr>
<td>Cosgray 2004</td>
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<td>Kubo 2005</td>
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<td>Minton 1993</td>
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<tr>
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<tr>
<td>Sakulsripasert 2010</td>
<td>-0.42 [-0.98, 0.14]</td>
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Figure 4

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<th>IV, Fixed, 95% CI</th>
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</thead>
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<td>2.2.1 Cold (immediate follow up)</td>
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<tr>
<td>Arguello 2009</td>
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<tr>
<td>Benoit 1996</td>
<td>-0.25 [-0.97, 0.47]</td>
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<td>2.2.2 Heat (immediate follow up)</td>
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<td>Benoit 1996</td>
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<td>Demura 2006</td>
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<td>Funk 2001</td>
<td>-0.23 [-0.73, 0.28]</td>
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<td>Robertson 2005</td>
<td>-1.23 [-1.85, -0.61]</td>
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<td>Sakulsriprasert 2010</td>
<td>-0.89 [-1.47, -0.31]</td>
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<tr>
<td>Sawyer 2003</td>
<td>-0.04 [-0.60, 0.53]</td>
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</tbody>
</table>

Favours = Greater ROM
### Figure 5

3.1.5 Effect of single Rx on ROM
- Brodowicz 1996: -0.53 [-1.53, 0.47]
- Cornelius 1992: -0.26 [-0.98, 0.46]
- Cornelius 1992: -0.56 [-1.30, 0.17]
- Lentell 1992: -0.17 [-0.82, 0.49]
- Taylor 1992: -0.09 [-0.65, 0.48]

3.1.6 Effect of multiple Rx on ROM
- Burke 2001: 0.41 [-0.31, 1.13]
- Lentell 1992: -0.19 [-0.85, 0.46]
- Rancour 2010: -0.06 [-0.78, 0.67]

Favours = Greater ROM
### 4.1.1 Effect of single Rx on ROM

<table>
<thead>
<tr>
<th>Study or Subgroup</th>
<th>IV, Fixed, 95% CI</th>
<th>Std. Mean Difference</th>
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<tr>
<td>Aijaz 2007</td>
<td>-1.31 [-2.11, -0.51]</td>
<td></td>
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<tr>
<td>Brodowicz 1996</td>
<td>-0.19 [-1.17, 0.80]</td>
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<tr>
<td>Brucker 2005</td>
<td>-0.31 [-1.15, 0.54]</td>
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</tr>
<tr>
<td>Draper 1998</td>
<td>-0.34 [-0.97, 0.28]</td>
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</tr>
<tr>
<td>Draper 2002</td>
<td>-0.71 [-1.54, 0.12]</td>
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<tr>
<td>Hendricson 1984</td>
<td>0.00 [-0.88, 0.88]</td>
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<tr>
<td>Lentell 1992</td>
<td>-0.77 [-1.41, -0.12]</td>
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<td>Peres 2002</td>
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<td>Taylor 1995</td>
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<tr>
<td>Wessling 1987</td>
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### 4.1.2 Effect of multiple Rx on ROM

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**Favours = Greater ROM**
Appendix G: Ethics Confirmation for Chapter 3
University of Limerick

OLLSCOIL LUIMNIGH

University of Limerick Research Ethics Committee

C/o Vice President Academic and Registrar’s Office, University of Limerick

Tel: (061) 202022, Fax: (061) 330027, Email: VPAReg@staffmail.ul.ie

25 May 2009

Prof Alan Donnelly

PESS Dept

University of Limerick

Limerick

Re: ULREC No.09/11 The Effects of Water Immersion On Joint Repositioning Sense

Dear Prof Donnelly

The above revised application was considered by the University of Limerick Research Ethics Committee at its meeting on 14th May 2009.

The committee agreed to grant full approval to the revisions.

Yours sincerely

Dr Kevin Kelleher

Chairman

University of Limerick Research Ethics Committee
Prof Alan Donnelly
Dept of Physical Education & Sports Sciences
University of Limerick
Limerick

Re: ULREC No.09/47 The Physiological And Neuromuscular Effects Of Whole Body Cryotherapy

Dear Prof Donnelly

The above application was considered by the University of Limerick Research Ethics Committee at its meeting on 9th July 2009.

Full approval is hereby granted for this application.

Yours sincerely

Prof John Breen
Acting Chairman
University of Limerick Research Ethics Committee
Appendix I: Ethics Confirmation for Chapter 6
Date: 10-05-2011

Dear Alan, Joseph

Thank you for your Research Ethics Application which was recently reviewed by the Education & Health Sciences Research Ethics Committee. The recommendation of the Committee is outlined below:

**Project Title:** EHSREC10- 95 The Effect of Cryotherapy on Muscle, Core and Skin Temperature  
**Principal Investigator:** Alan Donnelly  
**Other Investigators:** Joseph Costello, James Selfe, Kevin Culligan  
**Recommendation:** Approved

Yours Sincerely

Anne O’Brien  
Administrator, Education & Health Sciences  
Research Ethics Committee
Appendix J: Copyright Agreement to Reprint Chapter 2
Date  December 23, 2010

To: Joseph Costello

I am writing to request permission to include this article as part of my PhD submission.
Author(s): Costello JT, Donnelly AE
Title: Date of publication: May-June 2010

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Title: Editorial Assistant
Date: December 23, 2010
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Appendix N: Copyright Agreement to Reprint Appendix A
Dear Joe,

Please find below the necessary acknowledgements for the re-use of data from the article you mention from *Sports Medicine*.

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Team Leader

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Appendix 0: Statement of Contribution of Others
Chapter 1

Chapter 1 was written solely by the candidate, with the final draft approved by the supervisor Prof. Alan Donnelly.

Chapter 2


Joseph Costello as lead author was responsible for 1) conception and design of the review, 2) systematic acquisition of data, 3) data analysis, 4) interpretation of data, 5) drafting the article and revising it critically for important intellectual content, 6) corresponding with the editor and staff of the Journal of Athletic Training, 7) responding to referees comments, 8) copy editing and 9) final approval of the version to be published.

Prof. Alan Donnelly 1) advised Joseph Costello in the design of the systematic review, 2) critically revised drafts of the article written by Joseph Costello, 3) advised the lead author in responding to referees comments, 4) revised the article for important intellectual content and 5) approved the final version to be published.

Chapter 3


Joseph Costello as lead author was responsible for 1) conception and design of the study, 2) writing the ethics application, 3) subject recruitment, 4) acquisition
of data, 5) data analysis, 6) interpretation of data, 7) drafting the article and revising it critically for important intellectual content, 8) corresponding with the editor and staff of the Journal of Sports Sciences, 9) responding to referees comments, 10) copy editing and 11) final approval of the version to be published.

Prof. Alan Donnelly 1) advised the lead author on the design of the study, 2) revised drafts of the ethics application, 3) revised drafts of the article prepared by Joseph Costello, 3) advised the lead author in responding to referees comments and 4) final approval of the version to be published.

Dr. Ian Kenny, (Lecturer in Biomechanics Department of Physical Education and Sport Science, University of Limerick) advised the lead author on the methodology.

Chapter 4


Joseph Costello as lead author was responsible for 1) conception and design of the study, 2) writing the ethics application, 3) subject recruitment, 4) acquisition of data, 5) data analysis, 6) interpretation of data, 7) drafting the article and revising it critically for important intellectual content, 8) corresponding with the editor and staff of the Scandinavian Journal of Medicine and Science in Sports, 9) responding to referees comments, 10) copy editing and 11) final approval of the version to be published.

Ms. Lynne Algar (Ph.D. Student, Department of Physical Education and Sport Science, University of Limerick) as second author was responsible for 1) assisting in the conception and design of the study, 2) helping the lead author with the ethics application, 3) revising drafts of the article and 4) final approval of the version to be published.
Prof. Alan Donnelly was responsible for 1) advising the lead author in the design of the study, 2) revising drafts of the ethics application, 3) revising drafts of the article, 3) advising the lead author in responding to referees comments and 4) final approval of the version to be published.

Fourth year Sport and Exercise Science (2010) undergraduate students Linda Coughlan, Stephen Kelleher and Barry Kehoe, although not list as authors in this study, assisted in subject recruitment and data collection.

Chapter 5


Joseph Costello as lead author was responsible for 1) conception and design of the review, 2) systematic acquisition of data, 3) data analysis, 4) interpretation of data, 5) drafting the article and revising it critically for important intellectual content, 6) corresponding with the Journal of Athletic Training editor and staff, 7) responding to referees comments, 8) copy editing and 9) final approval of the version to be published.

Mr. Ciaran McInerney assisted in 1) data extraction, 2) data analysis and 3) approved the final version to be published.

Prof. James Selfe (Prof. of Physiotherapy in the Department of Allied Health Professions at University of Central Lancashire), Prof. Alan Donnelly and Dr. Chris Bleakley (Research Associate at the Health and Rehabilitation Sciences Research Institute, University of Ulster) assisted in 1) revising drafts of the article, 2) revising the article for important intellectual content and 3) final approval of the version to be published.
Chapter 6


Joseph Costello as lead author was responsible for 1) conception and design of the study, 2) writing applications for equipment funding, 3) writing applications for research internships to assist with the study, 4) writing the ethics application, 5) subject recruitment, 6) acquisition of data, 7) data analysis, 8) interpretation of data, 9) drafting the article and revising it critically for important intellectual content and 10) corresponding with the editor and staff of Medicine and Science in Sport and Exercise.

Dr. Kevin Culligan (M.D., Senior House Office, Mid-Western Regional Hospital, Dooradoyle) was responsible for 1) the insertion and removal of the intramuscular probe via an indwelling cannula and 2) revising drafts of the article.

Prof. James Selfe was responsible for 1) advising the lead author in the protocol for obtaining skin temperature data, 2) loaning the thermal imaging equipment to the University of Limerick and 4) revising drafts of the article.

Prof. Alan Donnelly was responsible for 1) advising the lead author in the design of the study, 2) revising drafts of the ethics application, 3) revising drafts of the article, 3) revising responses to the referees’ comments, 4) revising responses to referees comments and 5) final approval of the version to be published.

Sport and Exercise Science graduate (2011) Ciaran McInerney, although not list as author in this study assisted in subject recruitment and data collection. Ciaran was funded on a research internship post by the Faculty of Education and Health Science. Similarly, Sport and Exercise Science undergraduate Grainne Hayes, funded by the Physiological Society, assisted in subject recruitment and data collection.
Prof. of Biomechanics in the Department of Allied Health Professions at University of Central Lancashire Jim Richards Professor although not listed as an author advised the lead author on statistical analysis.

Chapter 7

Chapter 7 was written solely by the candidate, with final draft approved by the supervisor Prof. Alan Donnelly.

Appendix A


Dr. Chris Bleakley as lead author was responsible for 1) conception and design of the review, 2) systematic acquisition of data, 3) data analysis, 4) interpretation of data, 5) drafting the article and revising it critically for important intellectual content, 6) corresponding with the editor and staff of Sports Medicine, 7) responding to referees comments, 8) copy editing, 9) final approval of the version to be published and 10) sourcing funding for the study.

Joseph Costello was responsible for 1) conception and design of the review, 2) systematic acquisition of data, 3) data analysis, 4) interpretation of data, 5) drafting the article and revising it critically for important intellectual content, 6) advising Dr. Bleakley when responding to referees comments, 7) copy editing and 8) final approval of the version to be published.
Appendix B


Dr. Chris Bleakley as lead author was responsible for 1) conception and design of the review, 2) systematic acquisition of data, 3) data analysis, 4) interpretation of data, 5) drafting the article and 6) revising it critically for important intellectual content.

Joseph Costello was responsible for 1) conception and design of the review, 2) systematic acquisition of data, 3) data analysis, 4) interpretation of data, 5) drafting the article and 6) revising it critically for important intellectual content,