Warm-up Strategies in Freestyle Snow Sports: Effects of Extremely Cold Environments on Performance

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Attestation of Authorship

I hereby declare that this submission is my own work and that to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which is to a substantial extent has been accepted for the qualification of any degree or diploma of a university or other institution of higher learning except where due acknowledgement is made.

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Ethical Approval

Ethical approval for this research was obtained from the AUT Ethics Committee (reference 16/215) on 28 June 2016 (Appendix 1),

Abstract

Background: The implementation of a dynamic warm-up is a widely accepted practice amongst athletes in many sports, but less common in freestyle snow sports (i.e. skiing and snowboarding). Moreover, in freestyle skiing and snowboard there are extended periods (transition phase = 10 to 15 min) of time following the warm-up where athletes are inactive and exposed to extremely cold temperatures (-30 to -10 ^{o} C). These transition periods exacerbate the issue of maintaining body temperature and physical readiness in the extreme cold. The literature regarding the effectiveness of a warm-up and its residual benefits during transition phases in cold temperatures is limited. ***Purpose:*** To examine the effects of a neuromuscular warm-up (NWU), dynamic re-activation (RA), and passive re-warming (PRW) on squat jump (SJ) in snow sport athletes under extremely cold environmental conditions. ***Methods:*** Nine freestyle snow sport athletes (age = 21.1 ± 5.0 years; Mean ± SD) volunteered to participate in this study. A randomised repeated measures cross-over design was used. Following the completion of a standardised NWU, participants sat inactive in a temperature controlled industrial freezer (-20 to -18 ^{o} C) wearing cold weather training clothing. At specified time points, participants completed a vertical SJ protocol as the performance measure. The participants completed both experimental conditions (RA or PRW) on separate occasions, where they performed a dynamic RA or PRW, 20 min following the NWU. Five SJ were performed at the following time points: 14 min (4 min post NWU), 18 min (8 min post NWU), 26 min (16 min post NWU), 39 min (4 min post RA or PRW), 43 min (8 min post RA or PRW), and 51 min (16 min post RA or PRW). ***Results:*** Jump height (JH), peak force (PF) and impulse (IMP) showed excellent inter-day reliability (ICC > 0.80; CV < 5.3 %) and were used to assess jump performance across the two conditions. *Small* to *moderate* significant reductions in JH

(ES > 0.2; P < 0.10) were observed at 26 min, 39 min, 43 min and, 51 min of cold exposure time under both conditions. *Small* significant reduction in PF (ES > 0.2; P < 0.10) were also observed at 51 min in both conditions. JH and PF decreased by 9 % and 5 %, respectively following 51 min of cold exposure. *Small* significant differences (ES > 0.2; P < 0.10) were observed between the PRW and RA at 4 min and 8 min post. The RA protocol had a *likely beneficial* effect on JH at these time points. ***Discussion****:* Participants had varying individual responses to the RA with some experiencing improvements in JH (6 to 12 %), while other had a poor response to RA, and JH continued to decline (0 to -7 %). A NWU appears insufficient to combat the effects of cold exposure during transition phases where athletes are inactive for short periods of time (4 to 16 min). The implementation of RA strategies may reduce the negative impact of cold by increasing tissue temperature and providing a post activation potentiation (PAP) stimulus. However, RA protocols need to be individualised, as negative or negligible responses may occur in some athletes. It is likely that decreasing muscle temperature plays a significant role in the decline JH and PF.

Chapter 1 Introduction

1.1 Thesis background

Warm-up is a well-established component of physical preparation in sport and has a large body of research supporting the underlying mechanisms for engaging in this practice (Bishop 2003; Bishop 2003a). A recent systematic review of warm-up research revealed that 79 % of the studies reviewed indicated that warm-up leads to improved physical performance (Fradkin, Zazyrn, & Smolgia, 2010).

Implementation and content of warm-up practices varies greatly across sports that take place in vastly differing environmental conditions. It is generally accepted that a physiological and neuromuscular warm-up (NWU) is important from an injury prevention and performance enhancement perspective (Bishop, 2003; Fradkin et al., 2010; Sugimoto, Meyer, Foss, & Hewett, 2014). However, little research has been completed examining the effects of warm-up on dynamic neuromuscular function under extremely cold conditions (-30 to -10 ^{o}C). To date, research investigating the impact of cold has largely come from varying forms of external application of cooling on isolated body parts (Crowley, Garg, Lohn, Van Someren, & Wade, 1991; Dixon et al., 2010; Richendollar, Darby, & Brown, 2006; Schmid, Moffat, & Gutierrez, 2010). While this may be useful to speculate what may occur in a whole body cooling environment, there are obvious shortcomings to this approach. The ability to draw definitive conclusions from these studies is limited as these interventions do not represent the true environmental cooling conditions, such as experienced in snow sports (Comeau, Potteiger & Brown, 2003).

Freestyle skiing and snowboarding training and competition often take place in cold (-8 to 5 °C) to extremely cold (-30 to -10 °C) temperatures. The athletes may spend between 170 to 230 days training and competing on snow each year. Each training session on snow may vary in length from 1 to 4 hours per day and include multiple runs through the halfpipe or slopestyle course. A typical "run" through the half pipe may involve 5 to 6 tricks or "hits" involving a multitude of movements including explosive concentric, eccentric and isometric muscle actions (Noonan, 2018; Turnbull, Keogh and Kilding, 2011). Half pipe runs typically last between 25 to 30 s and are followed by 3 to 15 mins recovery periods as athletes ride lifts or snowmobiles back to the top of the pipe. A "run" through a slopestyle course will normally involve 3 rail sections and 3 jumps and last between 45 to 60 s followed by similar recovery periods to half pipe. As with half pipe, slopestyle athletes also engage in high force concentric (jumping), eccentric (landing), and isometric (resisting compression into kickers) muscle actions as they make their "run" through the course (Noonan, 2018). Some differences in physical demands exist between training and competition days. On snow training sessions and competition are often interspersed with extended transition phases of inactivity for chair lift rides, long queues between runs, pauses for TV commercials, athlete crashes and injuries, course preparation and weather interference. During these transition periods athletes may be standing in small enclosed areas with multiple athletes, coaches and support staff, limiting what they can do from a warm-up and/or muscle temperature maintenance perspective. Competition days are therefore characterised by longer transition periods and more likely to see athletes experience significant cooling.

There is a growing body of literature examining the effects of these transition phases and means of reducing the impact on performance through active and passive means (Kilduff, West, Williams, & Cook., 2013; Lovell, Barrett, Portas, & Weston, 2013; Mohr, Krustrup, Nybo, Nielsen, & Bangsbo, 2004; Russell et al., 2015). However, few studies have investigated the effects of extremely cold temperatures on physical performance under controlled environmental conditions (Faulkner *et al.*, 2013; Kilduff *et al.*, 2013; Mohr et al., 2004; Raccuglia *et al.*, 2016; Russell *et al.*, 2015; Spitz, Kenefick, & Mitchell, 2014; Suzuki, Ohya, Ito, Matsumoto, & Kitagawa, 2014). Furthermore, no studies to date have investigated the effects of extremely cold conditions and warm-up strategies on the physical performance of snow sports athletes (Hilfiker, Hubner, Lorenz, & Marti, 2007; Sporer, Cote, & Sleivert, 2012; Suzuki *et al.*, 2014). A critical aspect of warm-up practice is the practicality, athlete buy-in and adherence to a given warm-up strategy, if it is to ultimately make an impact on performance (Cook, Holdcroft, Drawer, & Kilduff, 2013). In their study with elite Skeleton Racers Cook *et al.* (2013) found that athletes ultimately chose a warm up protocol which did not produce the best physical performance but rather one they preferred, and subjectively felt better.

1.2 Aim of the thesis

The aim of this thesis was to explore the impact of cold exposure, warm-up & reactivation strategies, and, transition phases of varying durations on squat jump (SJ) performance in snow sport athletes. The assessment of jump performance to measure the effects of an intervention on ground based athletes is now common practice (Cronin, Hing, & McNair, 2004; Hori *et al.*, 2009; Taylor, Cronin, Gill, Chapman, & Sheppard, 2010). Jumping is a complex and dynamic motor pattern associated with quick force production, a quality often required for successful athletic performance in a variety of sports including freestyle skiing and snowboarding. When developing a jump protocol to assess changes in performance as a result of an intervention, it is critical to determine that the changes seen are greater than those which could be expected to occur by chance (Taylor *et al.*, 2010). In addition, it is necessary to show that these changes can be detected both within a testing session and when sessions are separated by greater periods of time such as hours, days or weeks (Argus, Mitchell, & Chapman, 2014; Hori *et al*., 2009; Sheppard, Cormack, Taylor, McGuigan, & Newton, 2008; Taylor *et al*., 2010). The measurement of jump variables using force plates and ground reaction forces (GRF) has been shown to be particularly reliable (Hori *et al*., 2009). Therefore, a critical first step in the current study is to establish within session and inter-day reliability of the SJ protocol used. By examining the factors above, it may be possible to make recommendations to improve the performance of snow sport athletes training and competing in extremely cold climates. This topic represents an aspect of athlete preparation that may offer competitive advantage for those looking to maximise their performance under extremely cold environmental conditions.

1.3 Purpose statement

The purpose of this thesis was to

(i) Assess the within session and inter-day reliability of a freestyle ski and snowboard specific SJ protocol.

(ii) Assess the effects of extremely cold temperatures and exposure duration on SJ performance.

(iii) Assess the effects of passive re-warming and re-activation strategies on SJ performance following exposure to extremely cold conditions.

(iv) Examine individual SJ performance responses to warm-up, cold exposure, re-warming and re-activation.

(v) Provide practical recommendations for optimising performance in extremely cold environments.

1.4 Significance of research

Warm-up plays an integral role in the preparation of the body for physical training and competition. Warm-ups are known to enhance performance at critical times, as well as contributing to injury prevention. Strategically designed warm-ups for individual snow sports that are performed in extremely cold climates have the potential to provide an even greater impact on performance. Freestyle snow sports athletes have traditionally been perceived to have poor warm-up strategies. Practitioners involved in optimising performance of freestyle athletes in training and competing are interested in identifying strategies that will prevent or combat performance decrements, which have previously been identified in athletes exposed to cold environments. Determining the effectiveness of current warm-up practices and assessing the impact of re-warming and re-activation protocols on physical performance in cold climates, may assist coaches and support staff in providing guidelines for optimising preparation practices to further enhance athlete performance and reduce injury risk.

1.5 Structure of thesis

This thesis is compiled in a traditional format (see Figure 1.1). The first section (Chapter 1) outlines the overall structure and significance of the research. The second section is comprised of a literature review (Chapter 2) addressing warm-up guidelines, impact of warm-up on performance, the underlying physiological and biomechanical mechanisms of warm-ups, and environmental factors (i.e. logistics of the sport and temperature) that effect the warm-up process. The third section, firstly assesses the reliability of the SJ protocol and, secondly investigates the effects of warm-up on SJ performance under extremely cold conditions (Chapters 3, 4 and 5). The fourth and final section (Chapter 6) summarises the main findings, provides practical recommendations and, directions for future research.

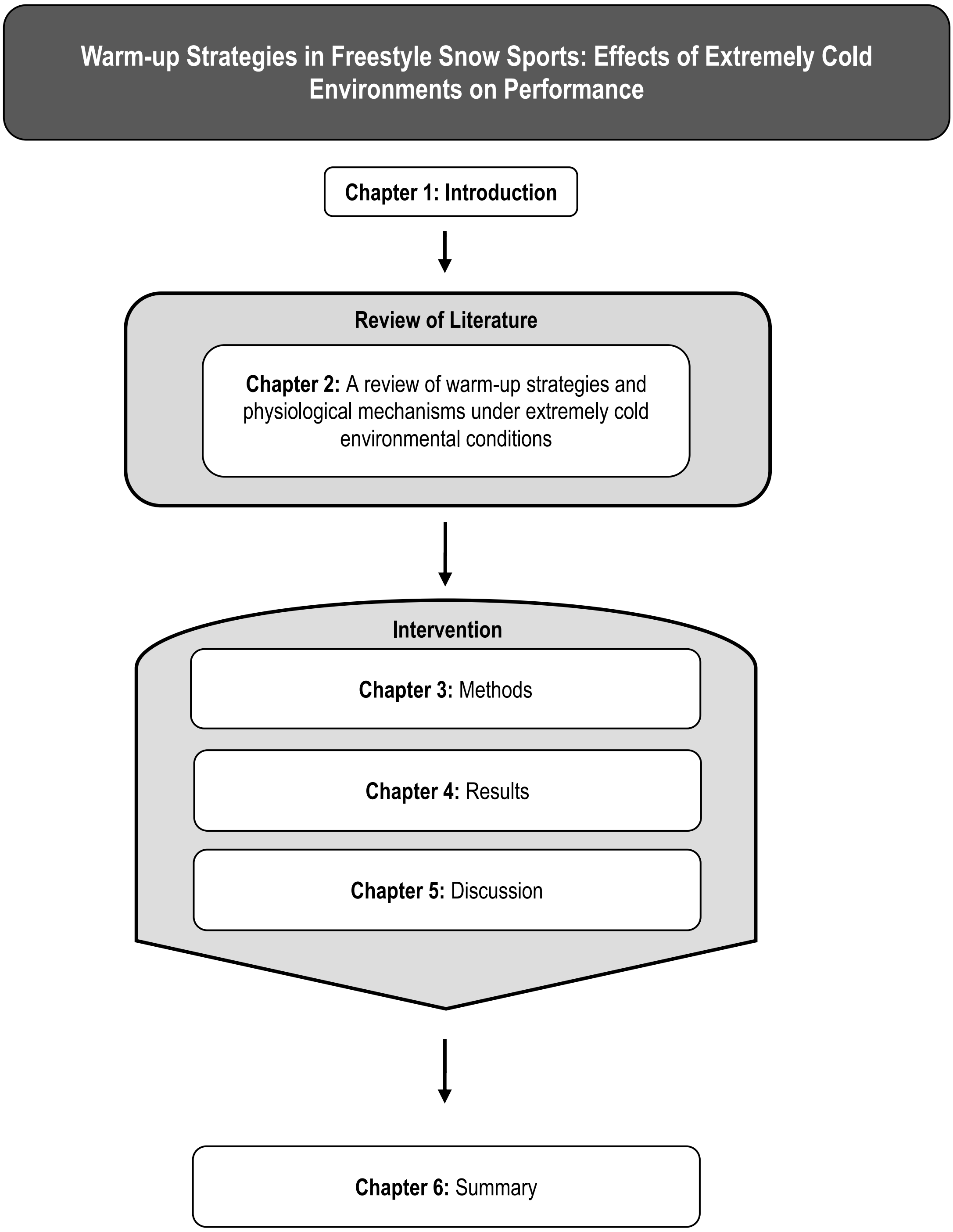

Figure 1.1 Thesis structure

Chapter 2: Review of Literature

2.1 Introduction

To date there has been little research undertaken investigating the warm-up practices of snow sport athletes, in particular freestyle athletes competing in ski and snowboard halfpipe and slopestyle. Due to the frequency and magnitude of forces experienced during landing, these athletes are at an increased risk of lower limb injuries with approximately 18 % of all injuries in elite snowboarders occurring at the knee (Major, Steenstrup, Bahr, & Nordsletten, 2014). Furthermore, freestyle skiing and snowboarding often takes place at high altitudes (1000 to 3000m) and in extremely cold temperatures (-30 to 10 ^{o}C) offering a unique challenge for athletes, support staff and coaches when implementing warm-up strategies. Therefore, the goal is to enhance the timing, content, duration, intensity, and warm-up modality from an injury prevention and performance enhancement perspective.

Following the initial warm-up, these snow sport athletes may have to wait for extended periods of time (10 to 45 min) riding in cars, ski lifts and/or in confined areas (i.e. starters' tent) before competing in their event. Additionally, within training sessions and competitions, athletes may be inactive or resting for 10 to 15 min due to travel time on ski lifts, waiting for their turn to "drop", course maintenance, removal of injured athletes, and/or reviewing video. This period between the completion of warm-up and onset of training or competition has been termed the transition phase. No research to date has considered optimal means of maintaining warmth or readiness during these transition phases in snow sport athletes. Therefore, the literature review will address key topics important to performance preparation, enhancement, and maintenance in extremely cold environments. The following topics specific to warm-up for snow sport athletes are discussed in detail; i) performance enhancement and injury minimisation strategies, ii) environmental factors impacting on performance, iii) strategies for maintaining performance in cold environments, and iv) optimal practice warm-up strategies for snow sport athletes.

2.2 Search strategies

The database searches gathered information on i) the impact of cold exposure on dynamic neuromuscular function, ii) the effect of varying length of transition phase on neuromuscular performance, iii) strategies of retaining the positive effects of a warm-up during the transition phase and iv) current warm-up practices in snow sports athletes. Research studies were identified using the following electronic data bases: SPORT Discus, PubMed, Google Scholar. The following key words and phrases were used to identify potential articles: warm-up, activation, re-activation, cold exposure, and neuromuscular function, thermoregulation of athletes, snow sport athletes. Screening criteria was initially limited to elite and high level athletes, performance enhancements, cryotherapy, and snow sports athletes. Due to the paucity of literature, the search criteria were expanded to include developmental and trained recreational athletes, injury prevention, all forms of cryotherapy, and all sports examining the effects of cold exposure on performance.

2.3 Warm-up for performance enhancement and injury prevention

Although not specific to snow sports, a significant body of research exists examining the effects of warm-up and the underlying principles that guide an effective physical preparation strategy. An overview of this extensive research is outlined below.

Warm-ups are primarily performed to increase muscle and tendon suppleness, to stimulate blood flow to the periphery, and to increase muscle temperature for preventing injuries and enhancing performance (Fradkin *et al.*, 2010; Grooms, Palmer, Onate, Myer, & Grindstaff, 2013; Hübscher & Refshauge, 2013; Hübscher et al., 2010; Steffen, Bakka, Myklebust, & Bahr, 2008; Steffen *et al*., 2013; Sugimoto *et al*., 2014). Dynamic neuromuscular warm-ups (NWU) are believed to have a strong injury prevention function by enhancing joint position sense, improving joint stability and developing protective joint reflexes (Herman, Barton, Malliaras, & Morrissey, 2012; Hübscher & Refshauge, 2013; Mednis, 2009; Steffen, *et al*., 2013; Sugimoto, Myrer, Barber, & Hewett, 2015).

While there is an obvious indirect performance effect of maintaining injury free athletes, several studies have also reported warm-up to have a positive influence on sport performance tasks, such as agility, explosive force production, jumping ability, balance, strength, and power production (Altamirano, Coburn, Brown, & Judelson, 2012; Burkett, Phillips, & Ziuraitis, 2005; Fletcher, 2013; Fradkin *et. al*., 2010; Passanen, Parkkari, Passanen, & Kannus, 2009; Steffen *et al*., 2013; Young & Behm, 2003). A recent meta-analysis examining the impact of warm-up on physical performance parameters, showed that 79 % of the studies examined found improvements in performance following warm-up (Fradkin *et al*., 2010). Improvements were seen across a variety of activities including aerobic (running, cycling and swimming), anaerobic (vertical jump, broad jump, sprinting and kicking), and sport specific skills (softball, basketball and golf) (Fradkin *et al*., 2010).

Performance enhancements are attributed to physiological mechanisms, such as muscle temperature changes, musculo-tendon stiffness alterations, metabolic priming, improved neural conduction, and co-ordination, post activation potentiation (PAP), and improved neuromuscular efficiency (Bishop, 2003; Bishop, 2003a; Bridgeman, McGuigan, Gill, & Dulson, 2017; Hodgson, Docherty, & Robbins, 2005; Kof & Strojnik, 2007; Mednis, 2009;

Russell *et al*., 2015; Seitz & Haff, 2016). Although, a general dynamic NWU may provide a potentiating stimulus, sport-specific NWU are believed to provide greater physical benefits particularly with athletes in explosive sports (Bullock & Comfort, 2011; Chen, Wang, Peng, Yu, & Wang, 2013; Chiu *et al*., 2003; Fletcher, 2013; Hilfiker *et al*., 2007; Kilduff, Finn, Baker, Cook, & West, 2013 Maloney, Turner & Fletcher, 2014; Young & Behm, 2003). It is suggested that an athlete who begins a competition in a potentiated state may have an initial advantage that could prove to be the difference between winning or losing (Hilfiker *et al*., 2007; Maloney *et al*., 2014).

Historically PAP (Figure 2.1) has been induced using heavy resistance exercise, however less fatiguing PAP methods, such as plyometric exercises, have been effectively implemented (Bridgeman *et al*., 2017; Bullock & Comfort, 2011; Chen *et al*., 2013; Hilfiker *et al*., 2007; Kilduff *et al*., 2013; Maloney *et al*., 2014; Seitz & Haff, 2016).

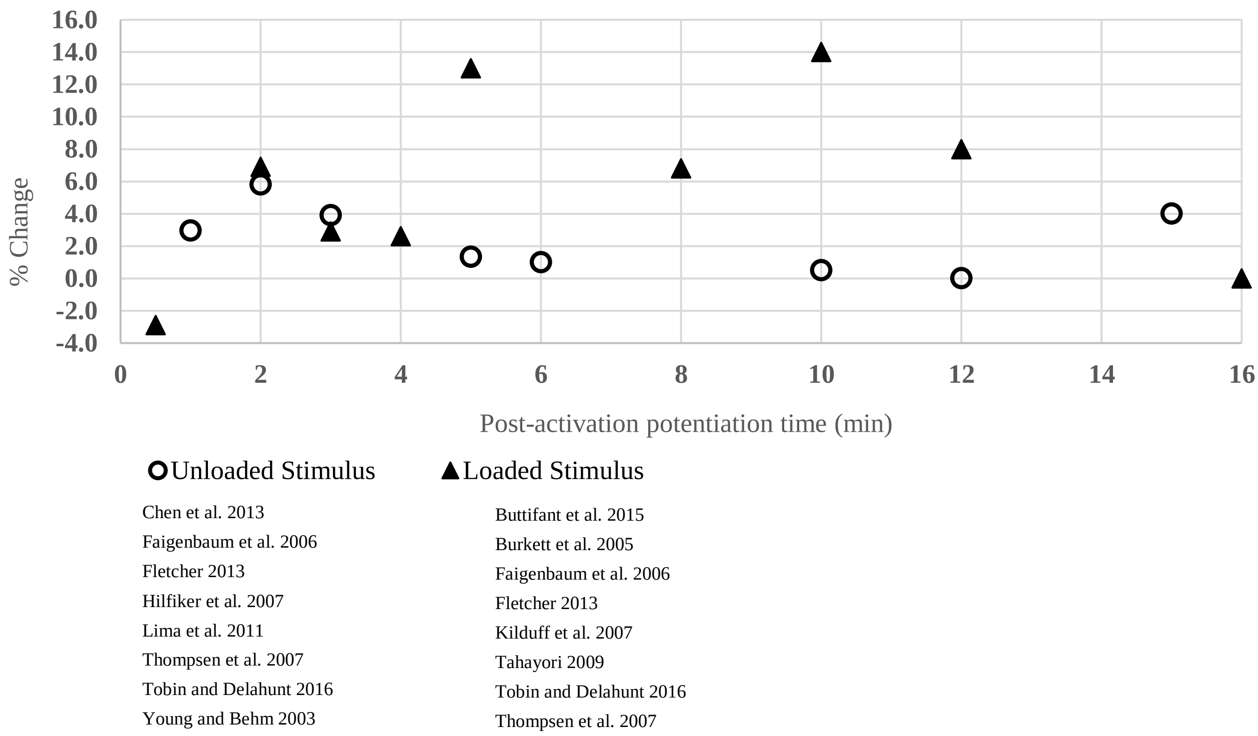

Figure 2.1. Time-course improvements in vertical jump following loaded and unloaded post-activation potentiation stimuli

For example, the addition of depth jumps to warm-up have been shown to increase performance in strength based activities, jump performance, rate of force development, and maximal power production (Bullock & Comfort, 2011; Chen *et al*., 2013; Hilfiker *et al*., 2007; Kilduff *et al*., 2013; Young & Behm, 2003). A recent meta-analysis raised the question as to whether plyometric activities were more effective than heavy resistance exercises (Seitz & Haff, 2016). This assertion is based on mechanical and physiological stress-response of plyometric exercises. It is believed, that plyometrics have a preferential recruitment of type II motor units, create less fatigue, and require less recovery time to achieve a potentiating effect (Seitz & Haff, 2016). Furthermore, high intensity plyometrics requires little equipment or space and have been seen to potentiate performance in explosive tasks within 30 s to 4 min following the stimulus, making plyometrics a viable practical addition to any warm-up protocol (Hilfiker *et al*., 2007; Seitz & Haff, 2014). Previous research shows that warm-up has the potential to reduce injury rates, and enhance performance. However, not all warm-ups are created equal, and there is an abundance of evidence that suggests several factors must be considered when designing and implementing an effective NWU. These NWU factors include warm-up content, warm-up duration, warm-up specificity, recovery period and subsequent PAP response.

2.3.1 Warm-up content, duration, recovery, specificity and post-activation potentiation

Warm-ups that include dynamic stretching have demonstrated greater performance effects on agility, power, and explosive tasks in comparison to warm-ups using a static stretching component (Behm & Chaouachi, 2011; Holt & Lambourne, 2008; Mednis, 2009; Pearce, Kidgell, Zois, & Carlson, 2009; Ymaguchi, Ishii, Yamanaka, & Yasuda, 2008). In addition, NWU conducted 2 to 3 times per week for at least 20 min per session and containing elements of locomotion, jumping-landing, agility, balance, core, and lower body strength have been shown to be effective injury prevention and performance enhancement strategies (Dai, Herman, Liu, Garrett, & Yu, 2012; Herman *et al*., 2012; Hübscher *et al*., 2010; Hübscher & Refshauge, 2013; Passanen *et al.*, 2009; Steffen *et al*., 2013; Sugimoto *et al*., 2014). Furthermore, dynamic NWU with an added plyometric, ballistic, or heavy resistance exercise have been shown to enhance performance in tasks requiring explosiveness, power, and high rates of force development through PAP (Bullock & Comfort, 2011; Chen *et al*., 2013; Chiu *et al*., 2003; Faigenbaum, Bellucci, Bernieri, Bakker, & Hoorens, 2005; Fletcher, 2013; Hilfiker *et al*., 2007; Masamoto, Larson, Gates, & Faigenbaum, 2003; Seitz & Haff, 2016; Tillin & Bishop, 2009).

The duration of a warm-up should be sufficient to induce physiological and neural changes without producing undue or prolonged fatigue. The subsequent recovery period is also an important factor to consider. Both factors are also influenced by the training age and status of the athlete, as poorly conditioned athletes may fatigue easily, while older athletes may require a longer warm-up to produce the desired changes (Bishop, 2003; Lindblom, Walden, & Hagglund, 2012). More recently, the use of shorter, higher intensity warm-ups have been examined and shown to be effective in improving performance in explosive, short duration, intermittent activities, while being rated as less intense than longer, lower intensity warm-ups (Lovell *et al*., 2013; Zois, Bishop, Ball, & Aughey, 2011; Zois, Bishop, & Aughey, 2015).

Performance potentiation may also be achieved through a well-planned warm-up. Athletes with lower training ages may require reduced volume and a less intense stimulus (60-85 % 1RM), while more experienced athletes may require greater intensities and volumes particularly to produce PAP effects (Hilfiker *et al*., 2007; Wilson *et al*., 2013). For a warm-up to induce a PAP response, the intensity of the preceding activity needs to be sufficiently demanding on the neuromuscular system (Maloney *et al*., 2014). Although, percentage of maximum heart rate (%MHR), oxygen consumption or percentage of 1RM have been used as indicators of intensity, rating of perceived exertion (RPE) may also be used to assess and establish the intensity of warm-up as well as to quantify internal load; and in turn, enhance the warm-up (Zois *et al*., 2011).

The optimal recovery time between warm-up and the physical performance task is also a critical factor and has yet to be identified, although studies suggest this timing is somewhere between 1 and 20 min depending on the individual, event, and warm-up protocol used (Hilfiker *et al*., 2007; Lovell *et al*., 2013; Seitz & Haff, 2016; Spitz *et a*l., 2014). While sufficient recovery is required for the regeneration of short term energy supplies, an extended recovery may lead to a loss of warm-up specific benefits (i.e. muscle temperature, elevated oxygen consumption, nerve conduction rates, and PAP) (Bishop, 2003; Buttifant & Hrysomallis, 2015; Chiu *et al*., 2003; Gouvêa, Fernandes, Cesar, Silva, & Gomes, 2013; Maloney, Tillin & Bishop, 2009; Wilson *et al*., 2013). It is believed that a 5 min recovery period is sufficient to replenish short-term energy supplies, whereas, muscle temperature is thought to decrease significantly 15 to 20 min following the cessation of exercise/activity depending on the environmental conditions (Bishop, 2003; Lovell *et al*., 2013). In the literature, there appears to be a range of recovery durations for optimising performance. It seems that recovery periods of between 30 s and 18.5 min allows for the dissipation of fatigue and regeneration of short term energy supplies (see Figure 2.1); which are dependent on the training status of the athlete and the warm-up content (i.e. volume and intensity of the stimulus) (Buttifant & Hrysomallis, 2015; Fletcher, 2013; Gouvêa *et al*., 2013; Hilfiker *et al*., 2007; Maloney *et al*., 2014; Seitz & Haff, 2016; Tillin & Bishop, 2009; Wilson *et al*., 2013). Therefore, as the content of a warm-up also plays a critical role in potentiating the physical performance task, it is important to give this due consideration.

Utilising a warm-up that includes the performance task often leads to a greater improvement in the targeted activity (i.e. principle of specificity) through the priming of the neuromuscular system and energy systems specific to the performance task (Burkett *et al*., 2005). Specificity of movement is also thought to provide injury prevention benefits through enhanced lower limb mechanics, particularly in sports where jumping and landing tasks are performed frequently (Aerts *et al*., 2015; Passanen, *et al*., 2009). Therefore, jump landing tasks are an important and recommended part of warm-ups in sports where landing mechanics are critical to success (Hilfiker *et al*., 2007; Hewett *et al*., 2005; Kristianslund & Krosshaug, 2013; Noyes, Barber-Westin, Fleckenstein, Walsh, & West, 2005; Stensrud, Myklebust, Kristianslund, Bahr, & Krosshaug, 2010; Turnbull, Keogh, & Kilding, 2011). Hilfiker *et al*. (2007) have demonstrated improvements in power and performance in explosive athletes, when tasks similar to their sport are used as a pre-conditioning activity during warm-up. They found elite freestyle ski and snowboard athletes' vertical jump (CMJ and SJ) performance improved when the jumps were preceded by a drop jump specific warm-up (Hilfiker *et al*., 2007). For example, they fund CMJ power was significantly improved by 2.2 % when drop jumps were added to the warm up protocol. Furthermore, Turnbull *et al.* (2011), also suggest that drop jump training has the potential to play a significant role in injury prevention in landing sports. They state that drop jump training as a stimulus provides the correct muscle activation timing and joint range of motion patterns to minimise the risk of joint and ligament injury in freestyle skiers and snowboarders due to similarities between drop jumps and sport-specific movements. Unsurprisingly, low specificity warm-ups lead to minimal improvements in the performance task (Lindblom *et al.*, 2012). In summary, a warm-up should be of sufficient intensity to stimulate physiological and neural responses and include movements specific to the subsequent targeted performance task. In addition, the warm-up should allow sufficient time for energy supplies to be regenerated, fatigue to dissipate, and in turn potentiate the performance tasks. These principles can be applied across all sporting disciplines and should be used to guide warm-up practices for freestyle snow sport athletes.

Slopestyle and halfpipe skiing and snowboarding were first introduced to the Winter Olympics in 2014. Given that these sports are relatively new, and are commonly viewed as extreme niche sports, minimal research has been conducted on these athletes to date. One study has investigated the warm-up strategies in snowboard-cross athletes and concluded that the extent and content of warm-ups currently being implemented was sub-optimal and in need of improvement (Sporer *et al*., 2012). The main issues identified with the warm-up strategies were an insufficient general warm-up, long transition periods of inactivity between the warm-up and competing, and a lack of warm-up structure and consistency (Sporer *et al.*, 2012). However, limited research specific to freestyle snow sport athletes exists. The unique challenges faced by these athletes raises the question as to what is an appropriate pre-training, pre-competition, and within session warm-up? Another important question is how long do the positive effects of the various warm-up strategies last under extremely cold conditions? Therefore, to fully understand the specific warm-up requirements, it is essential to understand how varying external factors (i.e. extremely cold temperatures and periods of inactivity) affect the underlying mechanisms of subsequent performance of these athletes.

2.4 Environmental factors and performance

Freestyle snow sport athletes are required to train and compete in extremely cold climates (-30 to -10 ^{o}C) and often with varying periods of inactivity. It is likely that these two factors will have a detrimental effect on the benefits gained through warm-up and it is possible they will have an additive effect. To fully understand the impact of cold exposure on physical performance this literature review explores the concepts of thermoregulation, muscle temperature, cold exposure mediums (i.e. water and air), and transition periods of inactivity.

2.4.1 Thermoregulation during cold exposure

The thermoregulatory reflex centre is controlled by the hypothalamus, which attempts to control the body's temperature and maintain homeostasis. The human body consists of two thermophysiological compartments; i) the heat producing, homoeothermic core (i.e. deep body parts and tissues), and ii) the heat-loss regulating, poikilothermic shell (i.e. skin and subcutaneous tissue) (Vangaard, 2011). The size of the latter is largely dependent on environmental temperature. In warm environments, the shell is small, in cold environments the shell is large, acting as a buffer to protect the core from over-heating or over-cooling. The body's core temperature fluctuates throughout a day based on our circadian rhythm by ~1.5 ^{o}C (36 to 37.5 ^{o}C) with the coolest core temperatures occurring at night between 6pm and 6am. Core temperature may vary depending on sex, age, diet, fitness level, activity level, and the environmental temperature and humidity (Kräuchi, 2007).

The human body maintains its autonomic temperature control when exposed to environmental temperatures between 0 to 45 ^{o}C. Below and above this range, we adapt to the environment through actions and behaviours (e.g. adding or removing clothing, warm or cold showers, standing in the sun or shade). If core temperatures drop below 32 ^{o}C or rise above 44 ^{o}C, human bodily functions are compromised and begin to shut down (Vangaard, 2011). While the body has an effective thermoregulatory response for basic functioning in cold temperatures, it may not be sufficient to maintain body functions for optimal physical performance. In addition, there may be gender differences in tolerance of cold environments (Gagnon, Dorman, Jay, Hardcastle & Kenny, 2009; Iyoho, Ng, McFadden, 2017). It has been suggested that during cold exposure women may be at a physical disadvantage, having a greater surface area to volume ratio, less lean muscle mass, and a lower shivering capacity and therefore, may suffer greater hypothermia (Iyoho *et al.,* 2017). A significant body of research has examined the impact of cooling on neuromuscular function (Bergh & Ekblom 1979; Cross, Wilson, & Perrin,1996; Wakabayashi, Oksa, & Tipton, 2015; Westerlund, Oksa, Smolander, & Mikkelsson, 2009).

2.4.2 Cold exposure, body temperature and performance

Several reviews have assessed the effects of cold on performance and have come to a general consensus that decreases in muscle temperature in cold environments cause decrements in neuromuscular function, and increases in muscle temperature lead to improvement in neuromuscular performances such as jumping activities (Wakabayashi *et al.,* 2015; Nimmo, 2004; Racinais & Oksa, 2010). Dynamic exercise performance is affected to a greater extent by small changes in muscle temperature in comparison to isometric force production, as isometric contractions are not significantly reduced until muscle temperatures fall below 27 ^{o}C (Wakabayashi *et al*., 2015). Therefore, given that dynamic neuromuscular performance is more readily effected by cold and warm exposure, and that dynamic action is often critical for sporting success, these factors have been the subject of numerous studies (Bergh & Ekblom 1979; Cross *et al*., 1996; De Ruiter & De Haan, 2001; Oksa, Rintamaki, & Rissanen, 1997).

Neuromuscular performance is reduced or enhanced by 2 to 5 % for every 1 ^{o}C change in muscle/core temperature (Bergh & Ekblom 1979; Cross *et al*., 1996; De Ruiter & De Haan, 2001; Oksa *et al*., 1997; Racinais & Oksa, 2010; Schmid *et al*., 2010; Schmid, Moffat, & Gutierrez, 2012). This phenomenon has been demonstrated across several physical performance tasks, such as drop jumps, SJ, countermovement jumps (CMJ), sprints, and cycling. Oksa *et al*. (1997) reported linear reductions in drop jump performance with muscle temperature losses induced by environmental temperatures (i.e. air temperatures of 27 ^{o}C, 20

^{o}C, 15 ^{o}C, and 10 ^{o}C). For example there was a 48% decrease in average force production during the shortening phase of the jump when comparing jumps at 27 ^{o}C and 10 ^{o}C . In addition, there was an 18% decrease in take off velocity when comparing jumps at 27 ^{o}C and 10 ^{o}C . These changes represent a 2.8% and 1% decrease in performance, per degree of muscle temperature loss between 27 ^{o}C and 10 ^{o}C for average force production and take off velocity respectively. These findings are in agreement with Bergh and Ekblom (1979), who found 4 to 6 % decreases in jump height with each degree of muscle temperature loss below 36 ^{o}C. In further support of these findings, Sargeant (1987) observed 2 to 3 % reductions in sprint cycling power with each degree of muscle temperature loss below 36.6 ^{o}C. Therefore, it appears muscle-cooling leads to reductions in force, velocity and power output, as well as increased co-contraction of agonist and antagonist muscles during dynamic movements, resulting in reduced physical performance (Westerlund et al., 2009). A clear dose-response relationship exists between muscle temperatures loss and performance decay, as evidenced in Figure 2.2. On the other hand, neuromuscular function and performance appears to improve with increasing muscle temperature (Bergh & Ekblom, 1979; Sargeant, 1987).

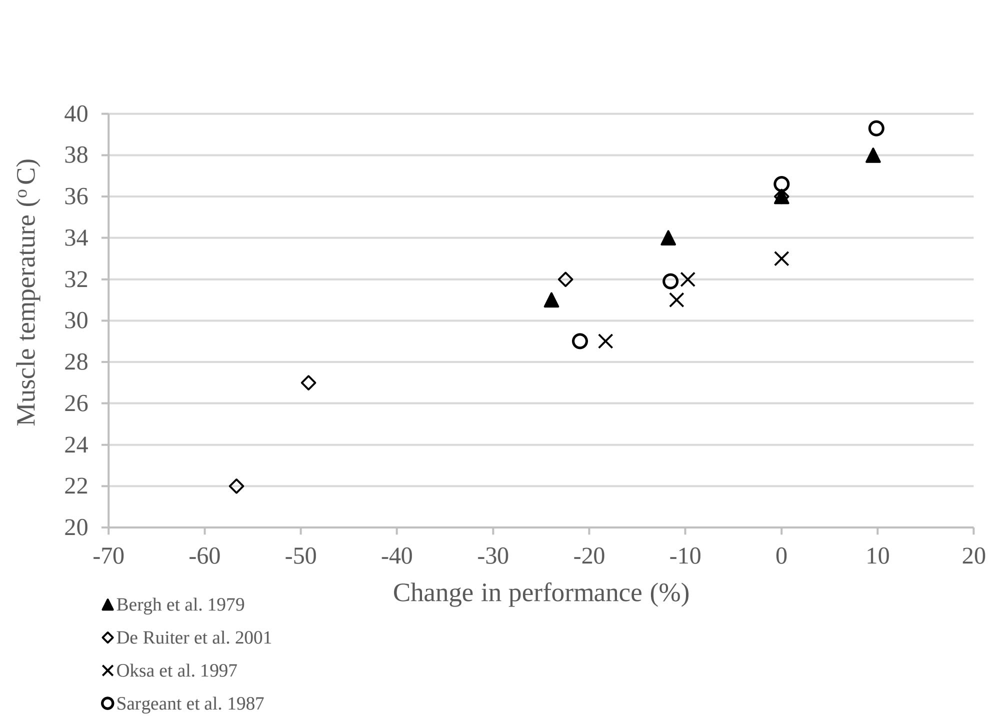

Figure 2.2. Effects of muscle temperature changes on explosive physical performance

It was originally thought that muscle temperature fluctuations were highly correlated with increases and decreases in skin and core temperature. However, Jutte, Merrick, Ingersoll, and Edwards (2001) observed that when exposed to cold (cryotherapy) and warm environments decreases and increases in muscle temperature were *moderately* to *very largely* correlated with changes in skin temperature (r = 0.46 and 0.71) and only *trivial* to *small* correlations (r = 0.21 and -0.05) were observed with core temperature (Jutte *et al.*, 2001). It appears that multiple factors contribute to changes in intramuscular temperature including, cooling time, skin temperature, adipose thickness (i.e. skin fold measurement), core temperature, and ambient environment temperature. Jutte *et al*. (2001) found that core temperature changes accounted for 4 % of the variance in intramuscular temperature and 21 % of the variance in skin temperature. They also showed the single strongest predictor of intramuscular temperature was cooling time (r^2 = 0.35) (Jutte *et al.*, 2001). Of particular note, intramuscular temperature continued to drop after the subjects were removed from the cool environment and did not return to baseline levels during the 120 min of passive re-warming (Jutte *et al.,* 2001).

It is evident from the previous research that cold exposure leads to decreased explosive neuromuscular performance, as environmental temperatures decrease performance declines at a greater rate (Bergh & Ekblom 1979; Cross *et al*., 1996; DeRuiter & De Haan, 2001; Oksa *et al.*, 1997). Although core and skin temperature have been used as predictors of intramuscular temperature, they appear to be poor predictors, and maybe misleading. The medium (i.e. air or water) and method of cooling (i.e. localised, whole body, or environmental) may also play an important part in the degree of intramuscular temperature lost. Several methods of cooling have been utilised to investigate the effects of cooling on neuromuscular function and include, localised cooling of muscles using ice bag application, cold water immersion, and more global cooling of the whole body using water immersion, temperature controlled environments, and natural ambient air. These cooling methods and mediums are subsequently discussed.

2.4.3 Localised cooling

Several studies have examined the impact of localised cryotherapy (i.e. ice packs and cold water immersion on specific areas of the body) on intramuscular temperature (Myrer, Measom, & Fellingham, 1998; Rupp, Herman, Hertel, & Saliba, 2012) and neuromuscular performance tasks, such as shuttle runs, unilateral and bilateral leg vertical jumps and drop jumps (Cross *et al.,* 1996; Kinzey, Cordova, Galen, Smith, & Moore, 2000; Richendollar et al., 2006; Schmid *et al.,* 2010; Schmid *et al*., 2012). Cooling occurs through either conduction (direct contact between cooling agent and tissue e.g. ice pack or still cold water) or convection (movement of cooling agent around the tissue e.g. moving cold water or cold air). The effects of the different types of cooling are subsequently explored.

2.4.3.1 Effects of ice pack cooling on body temperature and performance

While ice pack application is often used in sport to treat minor injuries, there is also an interest in how ice application affects subsequent sporting performance. Ice packs are known to have a positive effect on pain, but they are also known to cause decreases in intramuscular temperatures and nerve conduction velocity (Algafly & George, 2007; Enwemeka *et al*., 2002; Rupp *et al*., 2012). It is also thought that cold penetration into tissues increases with exposure duration (Myrer *et al*., 1998). Rupp *et al.* (2012) found it took between 39 to 42 min to cool the intramuscular temperature of the lower leg by 8 ^{o}C (baseline temperature = 38.6 ^{o}C) using cold water immersion (CWI) (12 ^{o}C) and ice bags, respectively. Following 90 min of passive re-warming, intramuscular temperature remained 8 ^{o}C and 5 ^{o}C lower than baseline for CWI and ice bag cooling, respectively. It was theorised that CWI has a greater cooling potential because it cools through mechanisms conduction and convection, whereas ice bags primarily cool via conduction. This finding supports earlier work by Myrer *et al*. (1998), who found that CWI and ice bags decreased muscle temperature at similar rates, but the tissue temperature remained cooler for longer following CWI (10 ^{o}C). A 3 ^{o}C difference was observed between cooling methods 30 min following the cooling interventions (Myrer *et al.*, 1998). These studies suggest that although the two methods of cooling result in similar rates of cooling, CWI results in prolonged tissue cooling.

Ice pack cooling has been shown to not only impact on tissue warmth, but also neural transmission rates. Algafly and George (2007) showed a 33 % reduction in nerve conduction velocity (0.4 m/s decrease) after ice pack application to the ankle leading to a 20 ^{o}C loss of skin temperature over a 20 to 30 min cooling period. Reductions in intramuscular temperature and nerve conduction velocity have the potential to negatively affect neuromuscular performance.

The impact of ice pack cooling on neuromuscular performance has been examined in several studies. For example, Schmid *et al*. (2010) found impaired motor performance in the leg following a 20 min ice bag application to the knee joint when performing a single leg drop jump from 30 cm, despite athletes feeling unaffected by the cooling. Similarly, Schmid *et al.* (2012) observed reductions in maximal force and increased drop jump contact time following 20 min of ice bag application to the anterior and medial aspect of the knee. Furthermore, Richendollar *et al*. (2006), found a 5 % reduction in jump height following cooling of the thigh (20 min of ice bag application) while a brief re-warming (i.e. 6 min of running, stretching and practice jumps) saw performance return to pre-cooling levels. Shorter periods of ice pack application have also been shown to have a negative effect on performance tasks. For example, Fischer, Van Lunen, Branch, and Pirone, (2009) found 10 min of ice bag application to hamstrings significantly reduced single leg vertical jump performance (i.e. 1 cm) in recreationally trained athletes. Duration of ice bag application appears to be a critical factor in how long the cooling effects last. Fischer *et al.* (2009) found that jump performance was unaffected 20 min following the removal of the ice bag (i.e. a 10 min treatment), whereas Myrer, Measom, and Fellingham (2000) found that a 20 min application of an ice bag to the triceps surae lead to a decrease in intramuscular temperature that did not return to baseline within 30 min of removal. Therefore, it appears that ice pack application between 10 to 20 min negatively impacts performance and longer application of the ice pack lengthens the period of performance decrement.

While, the above studies examined the effects of ice bag cooling on previously rested participants, little has been done to examine the effects of prior exercise on intramuscular cooling. Long, Cordova, Brucker, Demchak, and Stone (2005) demonstrated that 30 min of exercise (i.e. stationary cycle ergometer at 70 to 80 % of age predicted heart rate maximum) before application of an ice bag to the anterior thigh lead to a greater rate of cooling of the intramuscular tissue. They concluded that the body's thermoregulatory response to exercise added to the cooling rate (Long *et al*., 2005). Ice bag application has been shown to dramatically cool intramuscular temperature, reduce jump performance, and slow nerve conduction velocity. Although there is some conjecture in the literature, it appears that brief application of ice (10 min) has an immediate and residual effect on muscle temperature and performance following the removal of ice (Fischer et al., 2009). While these studies are of interest as they inform us of the impact on neuromuscular performance of cooling, CWI may provide greater insight into what occurs in a cold environment due to the convection and conduction cooling mechanisms of CWI.

2.4.3.2 Effects of cold-water immersion on body temperature and performance

CWI has also been widely used to reduce muscle temperature and blunt neuromuscular performance in a variety of performance tasks. Early work by Crowley *et al*. (1991) showed a 25 % decrease in mean power output and a 30 % decrease in peak power in trained cyclists performing the 30 s Wingate maximal cycling test following 30 min of CWI (11-12 ^{o}C). They calculated that the reduction in performance equated to approximately a 4 % per 1 ^{o}C reduction in muscle temperature. These findings align with work by Howard, Kraemer, Stanley, Armstrong, and Maresh (1994) who used the identical water temperature and observed 27 % decrease in peak torque of an isokinetic leg extension at 400 ^{o} / sec following 45 min CWI. In addition, a 25 % decrease in average power in higher speed extension (180, 300 and 400 ^{o} /s) was observed, while no effect of CWI on isometric strength was seen. They concluded that more dynamic tasks are effected due to slower de-activation rates of cross-bridges, slower nerve conduction velocity, and increased tissue viscosity due to the colder tissue temperatures (Howard *et al.*,1994). Dixon *et al*. (2010) examined changes in power production during a

CMJ following 45 min of CWI (11 to 12 ^{o}C) of the legs and found an 18 % decrement in performance. Similar decrements in performance were seen when Patterson, Udermann, Doberstein, and Reineke (2008) studied the impact of 20 min CWI (10 ^{o}C) on CMJ height and peak power. Immediately following immersion (i.e. 2 min post CWI) they observed a 17 % decrease in jump height and 16 % decrease in peak power (Patterson *et al.*, 2008). Furthermore, at 17 min (-11 %) and 32 min (-6 %) post treatment jump height remained less than baseline. A similar pattern was seen with peak power with 10 % and 6 % reductions still evident at 17 and 32 min respectively (Patterson *et al*., 2008). Finally, a study examining dynamic balance responses to limb cooling using CWI (12 ^{o}C) found 10 min immersion of the leg to the top of the thigh decreased the temperature of the vastus lateralis by 6 ^{o}C (33 to 27 ^{o}C) and performance in the Star Excursion Balance test decreased by 5 %, leading to the conclusion that the CWI of the thigh impairs balance particularly in squat dominant exercises (Montgomery, Hartley, Tyler, & Cheung, 2015). These studies suggest that CWI (11-12 ^{o}C) impairs performance tasks by 5 to 18 % and it is likely that longer immersion leads to greater performance decrement in dynamic tasks.

Overall it appears that localised cooling of muscles leads to decrements of performance in the range of 5 to 30 % (Figure 2.3) depending on the variable examined, the task performed duration, and modality of the cooling. CWI appears to have a greater impact on performance, and the effects appear to be prolonged when compared to ice bag application. The extended reduction in performance associated with CWI is likely due to heat transfer by conduction and convection. While this provides important insights into the effects of cooling on performance, sport rarely involves isolated cooling of limbs or muscle groups, but rather is more global in nature.

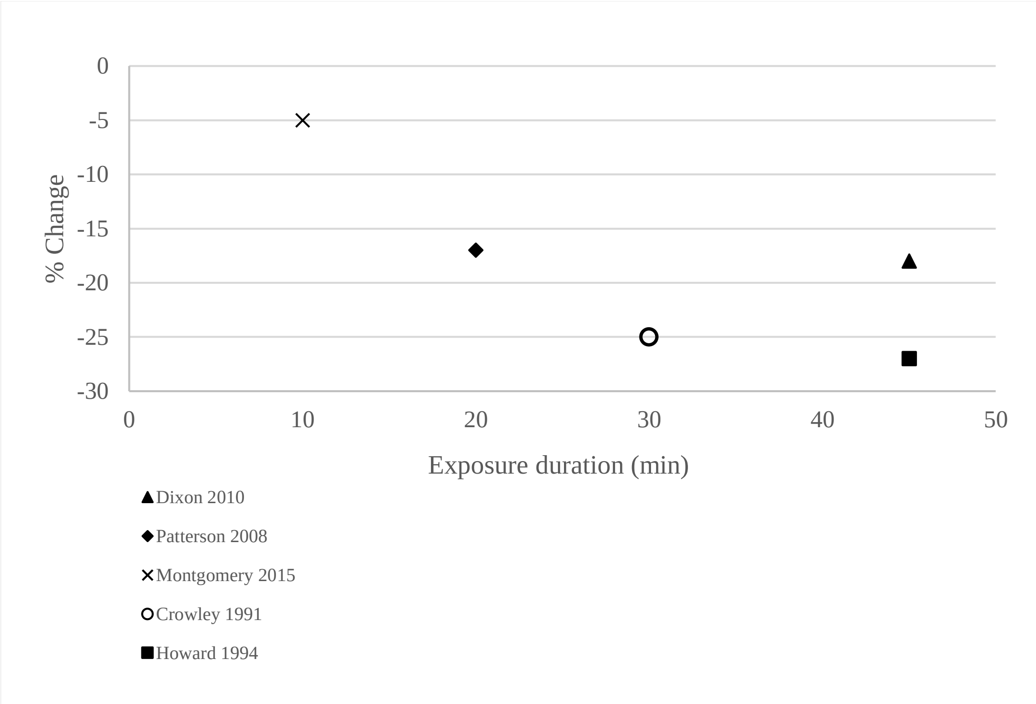

Figure 2.3. Reductions in physical performance following cold-water (10 to 12 ^{o}C) immersion for varying durations

2.4.4 Whole body cooling

It is evident that with increased cooling area of the body, greater reductions in muscle temperature and performance can be seen. It is therefore important to look at research that has examined whole body or ambient air cooling as this will have a greater application to athletes competing in cold environments.

There is substantially less research available on whole body cooling and its effects on neuromuscular function. While there is some research on whole body cryotherapy treatment for therapeutic purposes, the temperatures (-110 ^{o}C) and exposure durations used (2 to 4 min), make it difficult to draw conclusions relevant for sporting performance in cold environments, as exposure times are much greater (5 min plus) and temperatures experienced are less extreme (-30 to -10 ^{o}C). Of the whole-body cooling studies available, few have examined dynamic neuromuscular performance, therefore subsequent discussion will focus on the generalised effects of whole body cooling and the possible implications for sporting performance.

2.4.4.1 Temperature controlled environments

Several studies have been conducted in temperature-controlled environments investigating the effects of a range of temperatures on a number of performance tasks (Comeau *et al*., 2003; Oksa *et al*., 1997; Spitz *et al*., 2014). Comeau *et al*. (2003) investigated lower-limb force and torque production of physically active college age males exposed to a range of temperatures between 5 ^{o}C and 20 ^{o}C for a period of 40 min. They found 6 % and 7% decreases in peak torque and muscle temperature in the quadriceps and hamstrings, respectively when exposed to an air temperature of 5 ^{o}C compared to 20 ^{o}C (Comeau *et al*., 2003). It should also be noted that no difference in performance was noted between 15 ^{o}C and 20 ^{o}C. This supports earlier work by Oksa *et al*. (1997) who found much greater decreases in performance. They demonstrated that 60 min of exposure to 10 ^{o}C in an environmental chamber led to a 47 % decrease in drop jump performance in comparison to 60 min of exposure to 27 ^{o}C. It was concluded that reductions in force are greater as exposure duration to cold ambient air increases. Reductions (-4 %) were also observed in aerobic performance measures (2.4 km run and 2 km row times) following 30 min of exposure to 5 ^{o}C in an environmental chamber (Spitz *et al.*, 2014). They also concluded that the longer the elapsed time following warm-up in conjunction with cold air exposure led to significant reductions in performance. The above findings suggest that careful consideration should be given to the timing of warm-up, the transition period duration, the environmental conditions, and performance task of interest (Figure 2.4).

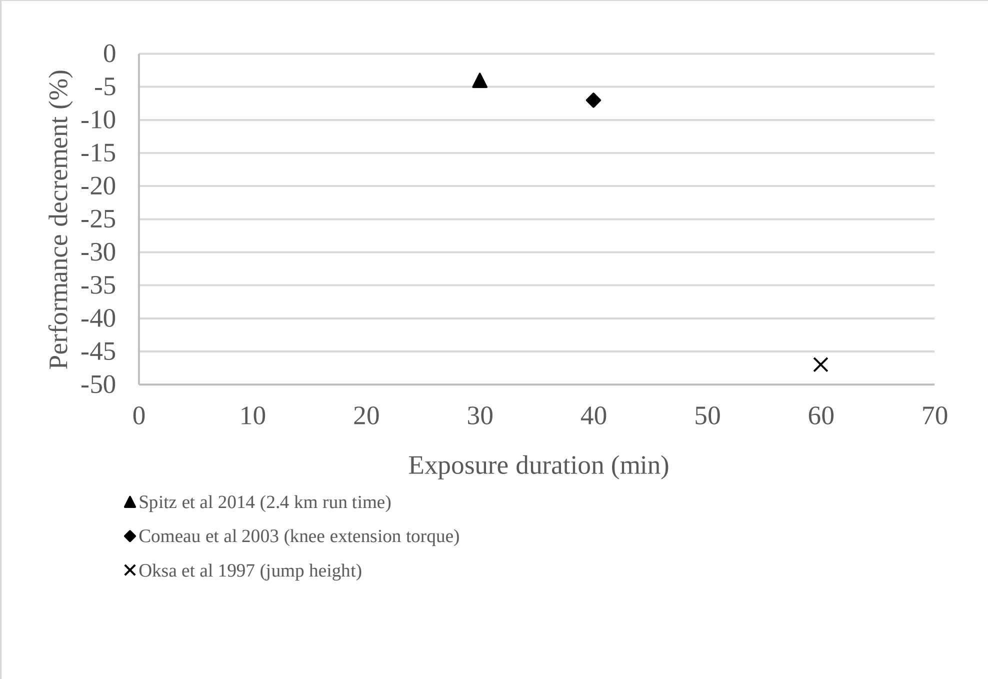

Figure 2.4. Reductions in physical performance following ambient air exposure (5 to 10 ^{o}C) for varying durations

In a study utilising a temperature relevant for snow sport athletes, Suzuki *et al.* (2014) examined the physiological responses in alpine ski racers during simulated on snow training in the cold. The skiers completed four 30 s high intensity sprints on a cycling ergometer interspersed with 10 min rest between bouts in 1 ^{o}C and 22 ^{o}C, respectively. The 10 min rest period was designed to replicate the time spent on a chair lift and/or waiting for the start of a race. They found oxygen consumption was significantly greater in the cold condition during the 3rd and 4th cycle sprint (50 % greater), skin temperature was significantly lower (30 ^{o}C versus 33 ^{o}C) despite the high intensity nature of the exercise, and there was a greater reliance on carbohydrate versus fat utilisation in the cold condition. Suzuki *et al*. (2014) concluded that together, these responses to the cold conditions lead to decreased work capacity of skiers in cold conditions.

A second study examining snow sport athletes explored the cognitive and proprioceptive responses of elite alpine skiers in cold versus warm temperatures (8 ^{o}C versus

24 ^{o}C) ambient conditions (Racinais, *et al.*, 2017). Like freestyle skiers, alpine ski racers are required to perform complicated movements involving reaction time, agility, aerial awareness, co-ordination, and proprioception after being exposed to very cold temperatures and periods of inactivity riding lifts and waiting at the top of courses. (Racinais, *et al.*, 2017). These conditions increase shivering and co-contraction of muscles, slow muscle contraction and nerve conduction velocity and could have an impact on motor control, postural control, balance, and proprioception. However, it was found that elite skier's proprioception (in a ski specific task) and cognitive ability was unchanged in the cold conditions. Racinais *et al.* (2017) proposed that there may be some habituation to cold conditions developed through the skiers usual training environment. It was also acknowledged that the cold condition temperature (8 ^{o}C) is at the warmer end of the spectrum experienced and that further study at colder temperatures was required (Racinais, *et al*., 2017).

In summary, performance decrements of 4 to 47 % have been observed in cold ambient environments (5 to 10 ^{o}C) depending on the performance task and duration of exposure (30 to 60 mins). In addition, it appears that energy utilisation changes during cold exposure which may impact on athletes' work capacity and therefore ability to train and compete for extended periods in cold conditions. To date, there is limited research on whole body cooling in appropriate temperature ranges commonly experienced by snow sport athletes. While some evidence suggests whole body cooling has a similar influence on neuromuscular functioning that has been observed in localised cooling, more research is required examining a variety of functional performance tasks in a range of relevant environmental conditions (Oksa *et al*., 1997; Spitz *et al*., 2014). The possibility of long-term adaptation to whole body cold exposure is also an important topic for snow sport athletes and is subsequently discussed.

2.4.5 Long term cold exposure adaptations

The human body can physiologically adapt to stressors imposed on it such as exercise, heat, cold, and altitude. It is therefore of interest to examine research exploring long-term adaptation to cold exposure. It has been observed that some individuals can adapt to long-term exposure to the cold by increasing their basal metabolic rate by up to 50 % of the norm (Vangaard, 2011). This metabolic adaptation has also been observed in Inuit populations that have had prolonged exposure to extremely cold environmental conditions (Vangaard, 2011). Similarly, a recent study provided evidence that repeated exposure to cryotherapy over a 3 month period can lead to neuromuscular adaptation in a drop-jump task (Westerlund *et al*., 2009). Following a single exposure to whole body cryotherapy (-110 ^{o}C) drop jump height (i.e. flight time) was significantly decreased (5 ms; $p< 0.05$); but after multiple exposures (3 times per week for 12 weeks) no reductions in drop jump performance were observed. This study also showed a decreased co-contraction of agonist and antagonist muscles in the drop jump task. Although, the temperatures and exposure duration used in this study have limited application to sport, these findings support earlier work by Young (1996) who found that winter swimmers reduced the negative performance responses to cold-water exposure over time. It can be concluded that during dynamic exercise, neuromuscular function may adapt to multiple exposures of extremely cold temperatures (Westerlund *et al*., 2009). Finally, Racinais *et al*. (2017) have suggested that the usual training undertaken by skiers may lead to habituation to cold temperatures which lead to improved performance of proprioception and cognitive tasks in these conditions. Freestyle snow sports athletes may spend between 170-230 days each year training on snow, with each training session lasting between 1 to 4 hours on snow. Therefore, given Westerlund *et al.'s* (2009) findings, it is feasible that these athletes may undergo some habituation and adaptation to cold environments as they experience much greater cold exposure time in comparison.

It is evident that cold exposure regardless of the medium has a negative impact on physical performance, where the magnitude of performance reduction is related to the temperature and exposure duration. Some adaptation to cold exposure may occur but more research involving sport-specific temperatures and movements is warranted. There is also a growing body of literature that indicates the length of the transition period following warm-up, prior to the start of training, or competition influences performance (Kilduff *et al*., 2013; Russell *et al*., 2015).

2.4.6 Transition periods

Following a warm-up, the transition period prior to training or competition, can positively influence performance if managed correctly. However, extended periods of inactivity during this time may also lead to null or negative effects on performance due to a variety of mechanisms**.**

Several studies have examined the performance effects of inactivity in team sport athletes (Kilduff *et al*., 2013; Rahnama, Reilly, & Lees, 2002; Russell *et al.*, 2015). Decreased jump performance was observed professional rugby players (-4 to -7 %) following a 15 min transition period (i.e. halftime) (Kilduff *et al*., 2013; Russell *et al*., 2015). Russell *et al*. (2015) and Kilduff *et al*. (2013) concluded that reductions in performance were significantly correlated to decreases in core temperature ($r = 0.62 – 0.70$, $p < 0.01$). The above studies were carried out in ambient air temperatures of 22 °C and 19 °C respectively. The impact of inactivity following warm-up could be further compounded with cold exposure and decreasing tissue temperature. According to Rahnama *et al*. (2002), reductions in performance following intra-competition breaks are often attributed to losses in muscle temperature and changes in neural function. Intra-competition periods of extended inactivity have also been associated with an increased incidence of injury once competition resumes due to the resulting decreases in muscle temperature and residual neuromuscular fatigue (Rahnama *et al*., 2002).

A recent study investigating the effects of elapsed time from the completion of a warm-up and cold exposure on subsequent exercise performance (2 km row or 2.4 km run) found that time elapsed (5 min vs 30 min) had minimal effect of aerobic performance (Spitz *et al.*, 2014). However, 30 min of inactivity coupled with cold exposure (5 °C) led to significant decrements in aerobic performance (4 %). These findings suggest that in events with unanticipated delays in training or competition, athletes should preserve body and muscle temperature through passive (i.e. additional clothing) and/or active strategies (i.e. dynamic warm-up) (Spitz *et al.*, 2014). Supporting this notion is a study involving competitive cyclists exposed to a 30 min period of inactivity at 16 °C following a 15 min warm-up which found a 9 % decrease in sprint cycling power output that was associated with a reduction in core temperature (-1 °C) (Faulkner *et al.,* 2013). The research indicates that the time elapsed following the completion of warm-up, prior to the performance task has a large impact on performance, which appears to be mediated by losses in muscle temperature and neural function. These losses in muscle temperature and neural function also seem to be amplified by cold exposure (Spitz *et al*., 2014).

2.5 Strategies for managing cold exposure and transition periods

Several studies have investigated strategies for managing cold exposure and transition time post warm-up to minimise the detrimental effects experienced. These strategies can be divided into active and passive methodologies

2.5.1 Active strategies

Active strategies involve physical activity to reverse the effects of inactivity, cold exposure and to enhance metabolic, physiological and neuromuscular function. Dixon *et al.* (2010) exposed college athletes to 45 min of CWI (12 ^{o}C) and then either remained inactive for 15 min or perform a 15 min re-warm-up (forward and backward locomotion, dynamic stretching, and core activation) before performing a CMJ. Following the CWI peak power was reduced by 22 % compared to the baseline but when the 15 min re-warm-up was completed the decrement in performance was reduced to 7 %. Although not examining performance, Myrer *et al*. (2000) looked at the effects of exercise on rewarming muscles following 20 min cold exposure (ice bag application) and found an 11 min warm-up (walking at 5 km/h) raised the muscle temperature significantly (6.75 ^{o}C). Conversely without exercise the muscle continued to cool following removal of the ice bag (1.9 ^{o}C after 11 min).

Shorter duration active strategies may also be effective. Lovell *et al*. (2013) found that a 5 min re-activation protocol (soccer specific intermittent agility exercises) between min 9 and 14 of a 15 min half time break reversed the initial losses in performance and improved CMJ by 1 %, corresponding with a 1 ^{o}C difference in muscle temperature compared to those who were inactive during that period. Similarly, Mohr *et al*. (2004) used a 7 min re-warm-up strategy in half time break in a simulated soccer game and found that the warm-up (running and soccer specific drills) was sufficient to maintain muscle temperature and sprint performance, while the control group (no warm-up) had reduced muscle temperature (2 ^{o}C) and sprint performance (2.5 %). Likewise, Richendollar *et al.* (2006) found a 6.5 min dynamic warm-up partially reversed the effects of a 20 min ice application on a single leg vertical jump. After 20 min of cooling and no re-warm-up JH was reduced by 4.7 % (p= 0.004), while the short warm-up (i.e. 3 min jogging, 3 min stretching, and 10 double leg CMJ's) produced a 4.9 % greater JH, likely due to rewarming of the muscle and increased neural priming.

These studies suggest that short to moderate length (5 to 15 min) active strategies are effective at rewarming muscle tissue and reducing the impact of cold and inactivity on neuromuscular performance. While active strategies are known to be effective, some success has been seen utilising passive strategies to maintain physiological and neuromuscular function during periods of inactivity and cold exposure.

2.5.2 Passive strategies

Passive heating strategies include external heating devices or heat maintenance garments. Studies have implemented these two heat preservation strategies under a variety of environmental conditions and durations. Faulkner *et al.* (2013) examined the effects of passive external heating using heated track pants (40 to 42 ^{o}C) during a 30 min transition period of inactivity following a 15 min warm-up. Following the 30 min of inactivity while wearing heated pants muscle temperature was 2.5 ^{o}C higher and sprint cycling performance was 9 % greater in comparison to non-heated track pants. Heat maintenance garments have also been successfully used to maintain tissue temperature during periods of inactivity. Professional rugby players wearing non-heated thermal jackets during a 15 min transition period maintained core temperature and CMJ performance in comparison to wearing non-thermal jackets (Kilduff *et al*., 2013; Russell *et al*., 2015). In summary, externally heated clothing and heat maintenance garments without external heating have successfully been used to maintain tissue temperatures and performance during transition periods (15 to 30 min) compared to those who did not use a passive heating strategy. Passive heating, therefore represents a plausible means of maintaining neuromuscular function during periods of inactivity.

The research presented suggests inactivity and cold exposure leads to decreased intramuscular temperature. This decline has been shown to continue after the exposure to cold is removed and the decreased intramuscular temperature leads to reduced performance. Engaging in warm-up activities can lead to a reversal of the reduction in performance through several possible mechanisms including increased blood flow, raising intramuscular temperature, increased nerve conduction, and enhanced metabolic processes. Given the abundance of literature that suggests cold exposure leads to decrements in performance and that active strategies can reverse these negative effects; it is intuitive that strategies be put in place to combat the effects of cold exposure and inactivity on performance. Furthermore, it is evident that passive and active methods can be effective strategies for maintaining or improving performance through tissue rewarming and a range of other mechanisms (i.e. maintaining metabolic processes, nerve conduction velocity, inter-, and intra-muscular co-ordination). Therefore, both active and passive strategies should be considered when managing athletes that are exposed to cold temperature and/or are faced with planned and unplanned periods of inactivity.

2.6 Warm-up strategies in snow sports

During on snow training freestyle athletes spend extended periods of time in extremely cold temperatures (-30 to -10 ^{o}C). Training in such conditions can lead to decreased body temperature. Although these athletes engage in high intensity activity lasting between 30 to

60 s they may spend extended periods inactive (5 to 15 min) riding on ski lifts, reviewing video or waiting for their next turn to drop. This most likely leads to reduced muscle temperature, which has been shown to result in decreases in performance and an increased risk of injury. Although, wearing warmer clothing is a practical solution, the athletes wear less thermal clothing to minimise the restriction of their movements. Therefore, the air temperature, wearing performance based clothing, and long rest to work ratios create a situation which may reduce neuromuscular performance and increase the risk of injury.

There is a limited research on athletes engaged in intermittent high intensity training in cold environments, (e.g. ski and snowboard freestyle athletes), and the impact that warm-ups and re-activations could have in the prevention of injury and enhancement of performance. Suzuki *et al*. (2014) examined this issue in elite alpine skiers by assessing work capacity at moderately cold temperatures (1.5 ^{o}C versus 22 ^{o}C) and found intermittent high intensity training in cold environments leads to decreased body temperature (i.e. skin temperature 5 ^{o}C colder when training in 1.5 ^{o}C versus 22 ^{o}C) and decreasing work capacity (i.e. VO_2 higher both at rest and during exercise in cold condition) throughout a training session. They concluded that maintaining a normal body temperature is critical to minimising the impact of cold on intermittent, high intensity exercise performance. It was suggested that if dynamic exercises were performed prior to each ski run losses in body temperature and work capacity across a training session may be minimised (Suzuki *et al*., 2014).

Similarly, a study examining warm-up for bobsleigh and skeleton athletes found that a 20 min high intensity warm-up (shorter rest periods between drills) including jogging, skipping, leg swings, sub-maximal, and maximal sprinting over 20 m, 30 s of push ups, dead bugs and planks performed 15 min before the start of the run significantly improved task performance (20 m sprint pulling a weighted sled) (Cook *et al*., 2013). In addition, wearing a heat retention garment during the 15 min transition period lead to significantly faster times than simply performing the active warm-up (P = 0.004, ES = 0.30). The following critical warm-up factors were identified for events occurring in extreme cold climates: duration, adequate intensity of warm-up, and maintenance of body temperature (Cook *et al*., 2013). Critically, the authors also concluded that an important component is the athlete's belief in, and acceptance of the warm-up routine.

Finding an optimal warm-up and potentiation protocol to assist with injury prevention while enhancing the physiological capabilities required for on snow performance may prove to be of great benefit to snow sport athletes. Snow sport warm-up strategies must account for the possible impacts of cold temperatures and varying transition periods that have been shown to have a detrimental effect on performance. If the performance enhancement and injury prevention benefits can be demonstrated to athletes and coaches, athlete buy-in and adherence to a given warm-up strategy can be vastly improved. Including conditioning exercises that have face validity (i.e. plyometrics) may also help prevent injury and enhance performance through proprioceptive and potentiation mechanisms, as well as increase athlete adherence due to the sports specific nature of the exercises.

2.7 Conclusion

Current warm-up practices of freestyle snow sports athletes appear to be sub-optimal from an injury prevention and performance enhancement perspective. These sports are high-risk, and there is a susceptibility to lower limb injuries, (e.g. ACL ruptures). It would therefore seem advantageous to improve warm-up practices using a sport-specific dynamic exercises prior to training and competition, and potentially within training and competition where long periods of inactivity may occur. Furthermore, it may be possible to enhance performance through PAP mechanisms particularly at the beginning of a competition run, which may lead to better overall performance.

To enhance performance, it is necessary to perform a sport-specific warm-up of sufficient length and intensity, while allowing time for fatigue dissipation and the re-synthesis of energy sources. In addition, it appears that the inclusion of a high intensity, sport relevant conditioning activity, such as plyometrics, can elicit a PAP response. In contrast, exposure to cold temperatures (i.e. localised, global, ice, CWI, or air) is detrimental to performance. The extent of performance reduction is dependent on the duration, cooling method, and temperature athletes are exposed to. In addition to cold exposure, extended transition periods of inactivity compromise performance due to reductions in tissue temperature and neural function. However, active and passive strategies have previously been effectively implemented to maintain tissue temperature and neuromuscular performance.

Winter sport coaches, support staff and athletes must carefully consider the environmental conditions and constraints when designing and implementing a beneficial and practical warm-up prior to on-snow training and competition. It may be possible to undergo a thorough NWU prior to training, however an extended transition period following warm-up (> 18 min) prior to training or competition may eliminate any positive physiological and neuromuscular benefits elicited by the NWU. Therefore, implementing effective strategies to maintain, rewarm and reactivate tissue, and the neuromuscular function, may in turn enhance performance, and minimise injury risk in freestyle ski and snowboard athletes.

Chapter 3: Methodology

The following chapter outlines the experimental approach, participant characteristics, data collection procedures, data processing, and statistical analysis of the collected and processed data.

3.1 Experimental approach to the problem

In freestyle ski and snowboard, athletes are frequently exposed to extremely cold temperatures (-30 to -10 ^{o}C). Although the athletes dress in clothing and outerwear designed to keep the athletes warm in these environmental conditions, the effectiveness of this for maintaining tissue warmth and functioning while inactive is relatively unknown. In addition, there are often extended transition periods between the off-snow warm-up and the start of training or competition. The aims of this study were therefore, to examine the effects of cold exposure following a standardised NWU, along with the effects of passive re-warming (PRW) and reactivation (RA) protocols on SJ performance in freestyle snow sport athletes. The impact on performance was assessed via a SJ protocol consisting of a submaximal isometric contraction in the bottom of the squat followed by an explosive concentric phase and subsequent flight phase in an attempt to simulate on snow performance demands. A novel approach of exposing athletes to extremely cold conditions in the form of an industrial temperature controlled freezer was used. The athletes wore their normal on-snow training clothing during testing.

The experimental design was a randomised controlled crossover design. All participants took part in the following conditions:

I. 10 min dynamic NWU with 5 min a PRW at 30 min following initiation of the warm-up.
II. 10 min NWU with 5 min RA performed at 30 min following initiation of the warm-up.

3.2 Participants

Nine freestyle ski (n = 8) and snowboard (n = 1) athletes (age = 21.1 ± 5.0) comprised of 6 males (body mass = 68.2 ± 15.3 kg; height = 172 ± 11 cm) and 3 females (body mass = 65.8 ± 1.9 kg; height = 168 ± 6 cm) were recruited to participate in the study. Participants had all competed at national or international events in their respective disciplines.

Inclusion criteria required that the participants:

I. Were ranked top 16 in the world in their discipline (elite athletes), or
II. Had competed at national and / or international age group competitions (development athletes), and
III. Were uninjured and able to train with no restrictions. This included any medical illnesses

Approval of ethics to conduct research was granted by the Auckland University of Technology Ethics Committee (approval number 16/ 215, Appendix 1). Prior to participation, the nine participants were provided an information sheet (Appendix 2) outlining the purpose and procedures of the study. All participants provided written informed, voluntary consent or had parents sign an assent form for those under 16 at the time of the study (Appendix 3 & 4).

3.3 Procedures

3.3.1 Familiarisation procedures

Participants visited the High Performance Centre in Wanaka on three occasions. The initial visit was a familiarisation session consisting of the NWU, RA protocol, strength testing and familiarisation with the SJ protocol to be used during the experimental procedure. All participants designated as elite athletes had completed the NWU used in the study on previous occasions, as part of their normal preparation for physical training, whereas the developmental athletes were unfamiliar with the NWU (Table 3.1). All participants completed the NWU prior to strength testing.

Table. 3.1 Dynamic neuromuscular warm-up and reactivation protocols

DYNAMIC NEUROMUSCULAR WARM-UP	
EXERCISE	**PURPOSE**
Forward & backward jogging	General locomotion and generating tissue warmth, raising heart rate
Side shuffle left & side shuffle right	Continuing to raise tissue temperature, introducing lateral movement pattern
Carioca left & carioca right	Dissociation between lower and upper body, thoracic mobility
Short bursts of high knees forward & jog backwards	Increased intensity of movement, working on hip flexor speed and power
Short bursts of butt kickers forward & jog backwards	Increased intensity of movement, focus on hamstring quickness
Walking Lunge to high knee drive & backwards lunge with rotation over front leg	Increasing range of movement, dynamic hip flexor stretch, gluteal activation, thoracic mobility and low level balance
Alternating sumo squats left & Alternating sumo squats right	Increasing range of movement in squat pattern, dynamic adductor stretch
High skip forward & skip backwards	Increasing intensity, low level plyometric, focus on hip extension and vertical force production
Long skip forward & skip backward	Increasing intensity, low level plyometric, focus on hip extension and horizontal force production
3 x 3 double leg bounds of increasing intensity 50% 75% 100% effort	Increasing intensity of force production, force absorption and re-utilisation of stored elastic energy. Sport relevant movement with maximum intensity, & potentiation of hip extensors
EACH EXERCISE IS REPEATED TWICE OVER 15 METRES BEFORE MOVING ONTO THE NEXT EXERCISE	

REACTIVATION PROTOCOL	
EXERCISE	**PURPOSE**
5 x squat of increasing depth with rotational reach	Increasing range of movement hips and thoracic spine
3 x each side reverse lunge to high knee drive	Gluteal, hamstring and core activation
5 x drop squat and stick & hold	Priming of co-contraction of core, quadriceps, hamstrings, glutes to create stability
5 x push up	Core bracing and upper body activation
3 x band chop each side	Priming of rotational movement
2 x each way 180 - 360 jump and spin	Connection of upper and lower body in rotational movement, landing & bracing following rotation
3 x drop squat to vertical jump	Co-contraction, stabilisation, rate of force development, priming of stretch shorten cycle (SSC)
REPEAT TWICE- 15 SECS RECOVERY BETWEEN EACH EXERCISE	

Following completion of the NWU, maximum strength was assessed using an isometric mid-thigh pull (IMTP). A high correlation (*r*= 0.97) has been shown between peak force produced in the IMTP and one-repetition maximum back squat strength (McGuigan, Newton, & Winchester, 2010). High correlations (*r* = 0.87) have also been observed between isometric strength and SJ performance (Kawamori *et al.*, 2006). Each participant used an overhand grip and self-selected their preferred stance and posture, which placed the bar at the mid-thigh position, as this has been shown to be as effective as using a predetermined hip and knee angles (Comfort, Jones, McMahon & Newton, 2015). Once the bar was positioned correctly, each participant had two warm-up pulls of 5 s in duration at approximately 50 % and 75 % of their maximal effort. Following the warm-up pulls, the participants' hands were strapped to the bar using standard weightlifting straps. Each participant was given the instruction "to pull as hard and fast as they could for 5 s". Participants completed three attempts to produce their maximal force, and each trial was separated by three minutes. The participants completed the IMTP inside a power cage (Fitness Works, Auckland, New Zealand) bolted to the concrete floor. Force was measured at a sampling frequency of 1000 Hz using two dual-axis force plates (PS

2142, Pasco, Roseville, USA) and analysed using the Weight Room software interface (Weight Room Version 1.0.278.0, High Performance Sport New Zealand, Rosedale). The data from the IMTP and baseline data from the SJ protocol were used to calculate the Dynamic Strength Index (DSI) to assist in understanding the unique force producing qualities of this athlete group. The DSI was calculated in the following manner: PF-SJ/ PF-IMTP. This provides a ratio to help guide assessment of how well an athlete can dynamically utilise their force producing capability (Thomas, Jones, & Comfort, 2015). This method has been shown to have excellent reliability (ICC= 0.95; % CV= 2.94) for assessing strength qualities in athletes with a minimum of two years strength and conditioning training (Sheppard, Chapman, & Taylor, 2011). It has been suggested that if an athlete has a DSI of < 0.60 a greater emphasis should be placed on ballistic resistance training, while a DSI of >0.80 indicates a need for development of maximal strength training (Thomas *et al*., 2015.). However, previous research also cautions that the DSI ratio ranges may be sport-specific and therefore should be used to generate norms within sports as opposed to being used as a general guideline across all athletes (Sheppard *et al.*, 2011; Thomas *et al*., 2015).

The RA protocol (Table 3.1) and repeated SJ protocol were demonstrated to the participants following the strength testing. The RA protocol was performed as a circuit and repeated twice to ensure increased muscle temperature and priming of appropriate energy systems and movement patterns that are relevant to freestyle snow sport athletes. During the SJ protocol, participants were asked to squat to a self-selected depth with their hands on their hips and isometrically hold the position for 5 s; at the end of the isometric hold, participants were instructed to jump as high and fast as possible; and then land and stabilise as quickly as possible in the bottom position of the jump. A protocol using a SJ with a 5 s isometric hold between each jump was chosen as in the respective snow sport disciplines the athletes are often required to engage in an explosive triple extension movement after having held a fixed position for between 3-5 s. The 5 s time frame allowed time for the participants to jump and stabilise and remain static for several seconds before jumping again. A self-selected depth was used, as this has been shown to maximise individual jump performance (Mitchell, Argus, Taylor, Sheppard, & Chapman, 2017). Five consecutive (i.e. repeated) SJ were completed in this manner. The athletes were also permitted to perform additional familiarisation trials until they were competent and comfortable with the above protocols. A minimum of 48 hours rest was provided between the familiarisation session and the first experimental session.

3.3.2 Experimental testing procedures

Participants reported to the High Performance Centre in Wanaka to undertake the experimental conditions described below on two separate occasions. All participants completed both conditions, one condition per day in a randomised order to eliminate the learning effect. Each testing session took approximately 60 min to complete. Participants completed the different experimental conditions at the same time of day and had a minimum of 48 hours of recovery between testing sessions. The participants completed the testing during a transition week when there was no on-snow or off-snow training. Participants were encouraged to maintain consistency in the timing and contents of their nutritional intake and activity levels prior to coming in for testing.

On testing days, participants reported to the High Performance Centre and were asked to wear clothing that they would normally wear for training and competition under extremely cold environmental conditions (-20 to -18 ^{o}C), including thermal underwear, beanies, gloves, jackets, pants and socks. Participants were instructed to wear the same clothing for both testing occasions. Participants were given the discretion to choose what they wore as they have demonstrated a personal preference as to how warm or cool they like to feel during training.

Normal gym training shoes were worn throughout the warm up, time in the cold environment and for jump testing.

The NWU was designed to progressively increase in exercise intensity and progress from general to sport-specific warm-up exercises. It has been suggested that warm-ups are most effective when performed around 70 % of heart rate max and the NWU herein was designed to be within this range with adequate time between exercises to allow for some recovery. The intensity at which each participant was working was assessed using the Borg CR10 (Borg, Hassmen, & Langerstrom, 1987) modified rating of perceived exertion (RPE). Upon completion of the NWU, the participants walked approximately 50 m to the controlled cold environment (Figure 3.1).

Figure 3.1 Participant sitting in extremely cold environment (i.e. walk-in freezer) at a temperatures between -20 to -18 ^{o} Celsius

Once in the cold environment, participants were seated in a chair in a position similar to that of a ski lift and were permitted to put on other outerwear items (jackets, beanies, gloves, etc.). Participants remained seated inactive in the freezer, until they were asked by the researcher to leave the freezer at pre-determined time-points (Table 3.2) to complete the SJ protocol. Five consecutive SJ were completed as described in the familiarisation section and immediately following the 5^{th} jump, the participants returned to the freezer. SJ performance was measured using two dual-axis force plates (PS 2142, Pasco, Roseville, USA) synchronised with a linear position transducer (LPT) (GM 184, Gold Mine, Auckland, New Zealand) attached to a belt at the front of the participants' waist (Figure 3.2) using a sampling frequency of 1000 Hz. The force plates and LPT were placed immediately outside the freezer to decrease the amount of time the participants would spend in the warmer ambient temperature and thus minimise any re-warming effects that may occur during the 60 s (i.e. time required to complete the SJ protocol).

Figure. 3.2 Jump testing protocol set up

In Condition 1, 20 min following the completion of the NWU, the participants were brought out of the freezer and sat at ambient room temperature (18 to 20 ^{o} Celsius) for 5 min to passively re-warm (PRW) before being placed back in the cold environment. The SJ protocol was then repeated at the pre-designated time-points (Table 3.2). In Condition 2, 20 min following the initial NWU, participants came out of the freezer and completed the 5 min RA protocol (Table

3.1). Immediately following RA, participants returned to the freezer. The SJ protocol was then repeated at the pre-designated time points (Table 3.2).

Table 3.2 Testing procedure timing

Activity/Exercise	Condition 1	Condition 2
Neuromuscular warm-up	0-10 min	0-10 min
Sitting in freezer	10-14 min	10 – 14 min
5 Squat jumps (out of freezer)	14-15 min	14-15 min
Sitting in freezer	15-18 min	15-18 min
5 Squat jumps (out of freezer)	18-19 min	18-19 min
Sitting in freezer	19-26 min	19-26 min
5 Squat jumps (out of freezer)	26-27 min	26-27 min
Sitting in freezer	27-30 min	27-30 min
Passive re-warming (out of freezer)	30-35 min	NA
Reactivation protocol	NA	30-35 min
Sitting in freezer	35-39 min	35-39 min
5 Squat jumps (out of freezer)	39-40 min	39-40 min
Sitting in freezer	40-43 min	40-43 min
5 Squat jumps (out of freezer)	43-44 min	43-44 min
Sitting in freezer	44-51 min	44-51 min
5 Squat jumps (out of freezer)	51-52 min	51-52 min

NA = not applicable

3.4 Dependent variables

The Borg CR10 (Borg *et al*., 1987) modified RPE scale was used during the dynamic NWU and the RA protocol to assess the intensity of effort. It has been suggested that a certain level of intensity of warm-up (equating to ~ 70 % heart rate max) (Bishop, 2003a) is required to induce physiological and neuromuscular changes. The RPE was chosen as it represents a non-invasive and easily repeatable method for assessing internal physical load for an individual. The Borg CR10 is also sensitive to intermittent exercise protocols, such as the NWU and RA protocol used in this study (Eston, 2012; Wong *et al.,* 2011).

Concentric rate of force development, concentric impulse, peak concentric force, peak concentric velocity, peak concentric power, jump height, landing force, and landing time-to-stabilisation were measured during the SJ protocol, as they are considered important kinematic and kinetic jump performance variables (Bridgeman *et al*., 2017; Hori *et al*., 2009; Sheppard *et al.,* 2008; Taylor *et al.,* 2010).

3.5 Data processing

The force-time and displacement-time data from the force plates and LPT (Figure 3.3), respectively were processed and analysed using the Weight Room software interface (Weight Room Version 1.0.278.0, High Performance Sport New Zealand, Rosedale). This methodology involved the combination of displacement data and vertical ground reaction forces for the various calculations. The velocity of the system was determined using a first-order derivative of the displacement data.

1. Initiation of the concentric phase of the SJ was defined as the point where the velocity-time curve increased above 0.01 m/s.

2. The start of the flight phase was determined as the point where the vertical ground reaction force dropped to zero.
3. The subsequent landing phase was determined as the point of contact, when the vertical ground reaction force was above 10 N.

The area under the concentric force-time curve represented concentric impulse (N.s). Peak rate of force development (N/s) was determined by calculating the slope of the force-time curve from the initiation of concentric phase to the time-point at which peak force occurred. Jump height was determine by the length of the flight phase based on ground reaction force. Time-to-stabilisation was calculated from the time of initial landing contact until the athlete stabilised at the bottom of the squat within 5 % of body weight.

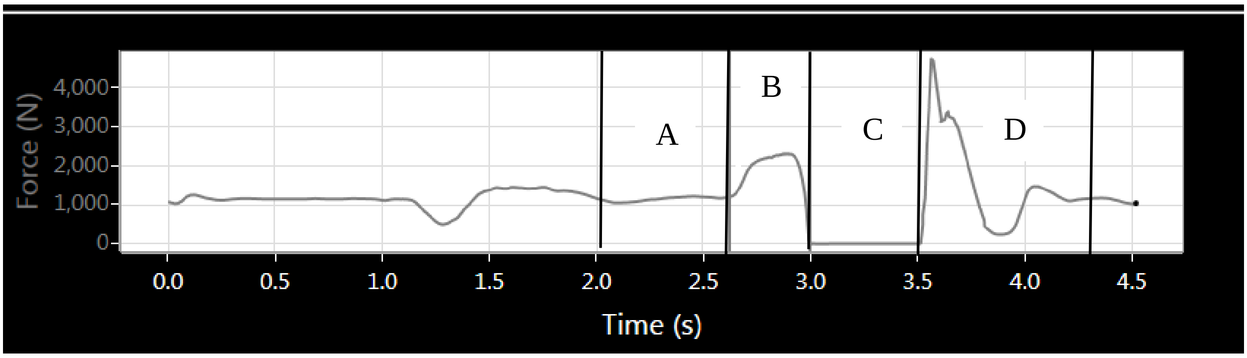

Figure 3.3 Squat jump force-time trace and the identified phases: A) isometric hold in the bottom of the SJ, B) concentric phase, C) flight phase, D) landing phase

3.6 Statistical analysis

Means and standard deviations were used to represent the centrality and spread of the data. All data were visually inspected and outliers > 3 standard deviations from the individual mean scores were removed from the analysis.

3.6.1 Reliability

The within session and inter-day (between session) reliability of the SJ protocol was assessed using the experimental data. The within session reliability was calculated for the dependent variables using three jumps (the best and worst jumps were removed from the data set) from each of the athletes from the baseline data. The inter-day reliability was calculated using the mean of three jumps from Condition 1 and mean of three jumps from Condition 2 collected at 4 min post warm-up. This information is presented in the results section.

The within session and inter-day reliability of the dependent variables measured during the SJ testing were expressed as the intra-class correlation coefficients (ICC) and standard error of measurement expressed as a coefficient of variation (CV%) based on within-subject means and standard deviations using 90% confidence intervals. The level of acceptance for reliability was set at ICC > 0.70 (Hopkins, Schabort, & Hawley., 2001). An ICC> 0.90 indicates a "perfect" agreement with minimal variation (Atkinson & Nevil, 1998), an ICC > 0.80 represents "excellent agreement", whereas ICC ranges within 0.70 - 0.80 are considered "average" (Hopkins & Manly, 1989). The CV% reliability threshold was set at 10%. A typical error > 10% is considered a "large" variation whereas a typical error < 10% is considered a small variation (Cormack, Newton, McGuigan & Doyle, 2008). Reliability was considered to be "good" when the ICC was > 0.70 and the CV was < 10 % (Bradshaw, Hume, Calton & Aisbett, 2010). Reliability was considered to be "excellent" when the ICC was > 0.80 and the CV was < 5 %.

3.6.2 Within condition effects

All jump performance variables that showed "good" within session reliability (ICC > 0.70; CV < 10 %) were used to assess the effects of cold exposure, PRW (Condition 1) and RA

Condition 2) on jump performance by comparing jump performance at the 14 min time point to all other time points (i.e. 18, 26, 39,43, 51 min) within each condition. The effects of cold exposure on jump performance during each condition was assessed via multiple paired-sample t-tests ($P < 0.05$), effect size (ES) and mean percentage differences (MDiff%) calculations.

3.6.3 Between condition comparisons

All jump performance variables that showed "good" between day reliability (ICC > 0.70; CV < 10 %) were compared between Condition 1 and Condition 2 at three key time points: 4 min, 8 min and 16 min post PRW (Condition 1) and RA (Condition 2) protocols. Repeated measures post-only cross-over analyses were conducted using a customised spreadsheet to compare the effects of conditions across the subjects (Hopkins, 2006). Multiple paired-sample t-tests, effect size (ES) and mean percentage difference (MDiff%) calculations were also used to determine statistical significance ($P < 0.05$) and the magnitude of differences between conditions for a given dependent variable. ES thresholds for differences in means were described as <0.2 (trivial), 0.2-0.6 (small), 0.6-1.2 (moderate), 1.2-2.0 (large), 2.0-4.0 (very large) and >4.0 (extremely large) (Hopkins *et al*., 2001).

Differences between Condition 1 and Condition 2 were considered meaningful when ES were greater than 0.20, and percentage differences were greater than 5 %. Magnitude based inferences based on degrees of freedom (n-1), *P*-values and effect sizes were used in conjunction to determine whether Condition 2 was likely to have a beneficial, negligible, or harmful effect of SJ performance.

Chapter 4 Results

The following chapter reports the outcomes obtained from the reliability and experimental studies. The results are reported as means, standard deviations, change in means, ICC, CV, *P*-values, and effect sizes. The descriptive statistics of the nine participants are displayed below in Table 4.1.

Table 4.1 Descriptive statistics. Data are reported as Mean ± SD.

N	All 9	Elite 4	Development 5	Male 6	Female 3
Age (Years)	21.1 ± 5.0	18.5 ± 4.2	22.8 ± 4.1	18.5 ± 4.1	24.6 ± 2.1
Mass (kg)	67.4 ± 12.2	60.3 ± 11.1	73.1 ± 10.6	68.2 ± 15.3	65.8 ± 1.9
Peak Force IMTP (N)	2140 ± 504	2164 ± 495	2121 ± 568	2333 ± 508	1753 ± 581
Relative IMTP Force (BW)	3.3 ± 0.6	3.7 ± 0.5	2.9 ± 0.6	3.5 ± 0.6	2.7 ± 0.3
Peak Force SJ (N)	1413 ± 291	1268 ± 175	1528 ± 330	1457 ± 358	1324 ± 25
Relative SJ Force (BW)	2.1 ± 0.1	2.2 ± 0.1	2.1 ± 0.1	2.2 ± 0.1	2.1 ± 0.1
DSI (PF SJ/ PF IMTP)	0.68 ± 0.12	0.60 ± 0.08	0.74 ± 0.12	0.63 ± 0.12	0.76 ± 0.26
Jump Height (cm)	28.7 ± 4.3	26.5 ± 3.3	30.4 ± 2.9	30.5 ± 3.5	25.0 ± 3.6

Isometric mid-thigh pull (IMTP) relative peak force per body weight; squat jump (SJ) peak force.; Relative SJ Force per body weight; Dynamic strength index (DSI)

4.1 Reliability study

Both within session and inter-day reliability of the SJ protocol was assessed. Variables with ICC and CV % above 0.70 and below 10 % were in an acceptable range (Bradshaw, Hume, Calton & Aisbett, 2010).

4.1.1 Within session reliability

Within session reliability for all SJ performance variables is displayed in Table 4.2. PF, PV, PP and IMP were considered to have excellent within session reliability (ICC > 0.90; CV < 5.5 %); and JH had a good level of reliability (ICC > 0.70; CV < 10 %). All other variables were deemed unreliable (ICC < 0.70 and/or CV > 10 %).

Table 4.2 Within-session reliability of kinematic and kinetic variables for the squat jump in freestyle snow sport athletes

	Trial 1 Mean± SD	**Trial 2 Mean ± SD**	**TE (90%CI)**	**CV% (90%CI)**	**ICC (90%CI)**
Peak Force (N)	1365 ± 271	1367 ± 271	35(24–68)	3.2(2.2-6.3)	0.98(0.92-0.99)
Peak RFD (N/s)	4997 ± 1758	4678 ± 2355	949(641-1819)	20.0(14.546.7)	0.70(0.27-0.95)
Peak velocity (m/s)	2.61 ± 0.15	2.65 ± 0.16	0.05(0.030.09)	1.9(1.3-3.7)	0.90(0.59-0.98)
Peak power (W)	3151 ± 641	3177 ± 637	99(67-190)	3.2(2.2- 6.3)	0.98(0.89 0.99)
Jump height (cm)	26.0 ± 4.9	27.1 ± 3.0	2.0(1.38-3.92)	8.6(6.0 - 17.9)	0.75(0.17-0.94)
Impulse (N*s)	468 ± 96	460 ± 80	20(13-38)	5.4(3.7- 11.0)	0.95(0.77 0.99)
Landing Force (N)	2093 ± 707	2218 ± 545	273(184-524	16.3(11.736.8)	0.81(0.32-0.96)
TTS (s)	0.69 ± 0.09	0.73 ± 0.12	0.06(0.040.12)	8.7(6.0 - 18.1)	0.68(0.03 0.93)

Mean and standard deviation (SD), typical error of measurement (TE) expressed in raw values and as a coefficient of variation (CV%) and intra-class correlation (ICC) for each variable, Confidence intervals (CI), Rate of force development (RFD), Time-to-stabilisation (TTS)

4.1.2 Inter-day reliability

The inter-day reliability for all SJ performance variables is displayed in Table 4.3 below. PF, JH and IMP had excellent inter-day reliability (ICC > 0.80; CV < 5.3 %). All other variables were considered unreliable.

Table 4.3 Inter-day reliability of kinematic and kinetic variables for the squat jump in freestyle snow sport athletes

	Day 1 Mean± SD	Day 2 Mean ± SD	TE (90%CI)	CV% (90%CI)	ICC (90%CI)
Peak Force (N)	1446 ± 285	1443 ± 303	30(20 – 59)	2.1(1.4 -4.1)	0.99(0.95 0.99)
Peak RFD(N/s)	4526 ± 157	4283 ± 1579	642(434-1231)	19.3(13.9-44.8)	0.83(0.38-0.96)
Peak velocity (m/s)	2.54 ±0.16	2.54 ± 0.36	0.25(0.17-0.47)	9.9(6.9-21.0)	0.22(0.52-0.77)
Peak power (W)	2998 ±711	3028 ± 1122	448(302 -858)	13.2(9.4-28.9)	0.77(0.22-0.95)
Jump height (cm)	27.3 ± 5.1	28.7 ± 5.8	1.4(0.9-2.7)	5.2(3.6-10.5)	0.93(0.71-0.99)
Impulse (N*s)	471 ± 99	467 ± 78	22(15- 42)	4.6(3.1-9.2)	0.94(0.73-0.99)
Landing Force (N)	2246 ± 277	2355 ± 576	320(216-613)	14.1(10.0-31.1)	0.50(0.25-0.88)
TTS(s)	0.71 ± 0.13	0.67 ± 0.08	0.08(0.06-0.16)	11.7(8.2-25.2)	0.42(0.34-0.85)

Mean and standard deviation (SD), typical error of measurement (TE) expressed in raw values and as a coefficient of variation (CV%) and intra-class correlation (ICC) for each variable, Confidence intervals (CI), Rate of force development (RFD), Time-to-stabilisation (TTS)

4.2 Condition comparisons

4.2.1 Condition comparisons across all time points

PF, JH and IMP were considered to be highly reliable jump performance variables and therefore, these variables were chosen to be compared in the two experimental conditions across all time points. In both conditions, JH (Figure 4.1) and PF (Figure 4.2) decreased significantly as the duration of cold exposure and transition period increased. Across both conditions, increasing *negative* effects were observed on jump performance (i.e. progressing from *small* to *moderate*) as the duration of cold exposure increased. Following the initial NWU, jump height performance decreased (MDiff% = -4 to -8 %) with increased cold exposure across both conditions. Following the PRW in Condition 1, JH decreased by a further 4 %, representing a total decrease of 8% in comparison to baseline. The negative effects of cold exposure on JH were reversed slightly following the RA protocol of Condition 2, with a 1.9 % increase in JH between 26 min (i.e.16 min post-NWU) and 39 min (4 min post-RA), resulting in a total decrease of 9 % in comparison to baseline. The positive reversal effect of the RA was not observed in PF which continued to decrease with increased cold exposure and transition period duration.

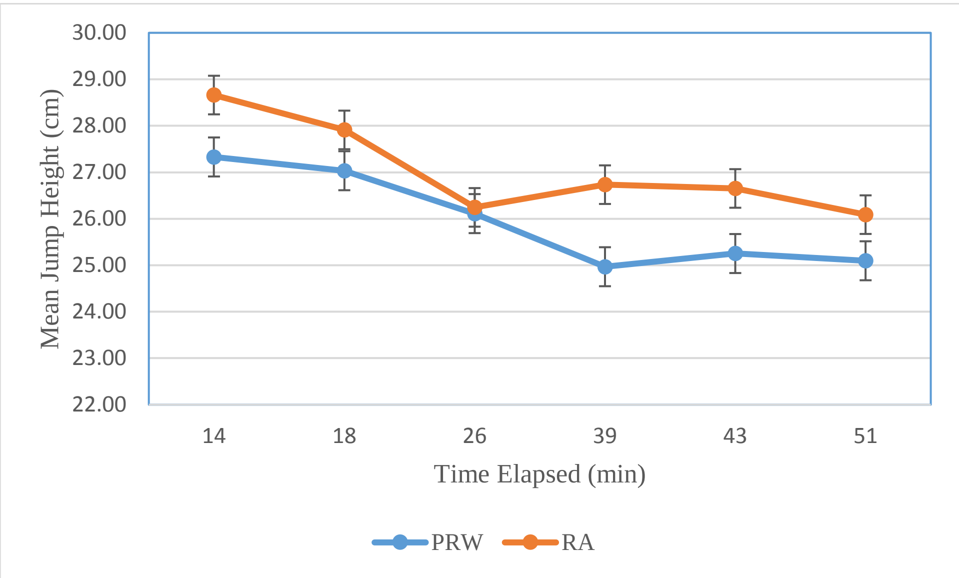

Figure 4.1 Jump height means across all time points from initiation of the NWU

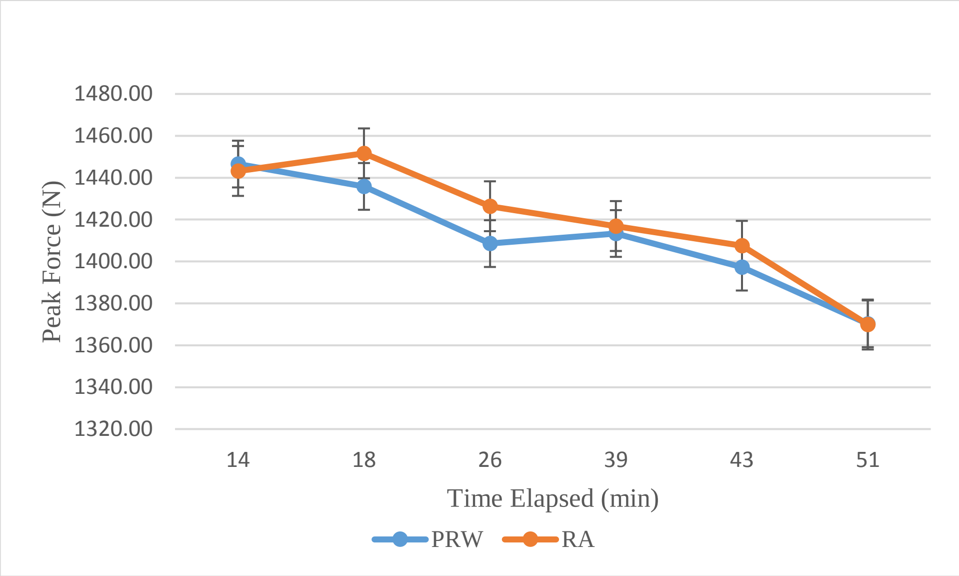

Figure 4.2 Squat jump peak force means across all time points from the initiation of the NWU

In Condition 1, *small* to *moderate* significant reductions in JH were observed between the following post-NWU time points 14 and 26 min (ES = 0.24; *P = 0.01)*, 14 and 39 min (ES = 0.46; *P = 0.01)*, 14 and 43 min (ES = 0.41; *P = 0.002)* and at 14 and 51 min (ES = 0.44; *P = 0.003)* (Figure 4.1). *Small* significant reductions were seen in PF between the post-NWU time points 14 min and 51 min (ES=0.27; *P= 0.0001*); which represents a 5 % reduction in PF (Figure 4.2).

In Condition 2, *small* to *moderate* significant reductions in JH were observed between the following post-NWU time points 14 and 26 min (ES = 0.42; *P = 0.03)*, 14 and 39 min (ES = 0.33; *P = 0.01)*, 14 and 43 min (ES = 0.35; *P = 0.001)* and at 14 and 51 min (ES = 0.44; *P = 0.0009)* (Figure 4.1). *Small* significant reductions were seen in PF between the post-NWU time points 14 min and 51 min (ES=0.24; P= 0.02) (Figure 4.2). This represents a 5 % reduction in PF between these time points.

Trivial non-significant differences (ES < 0.2; *P* > *0.10*) were seen in IMP across all time points. Cold exposure and transition period duration appear to have minimal effect on IMP (Figure 4.3) .

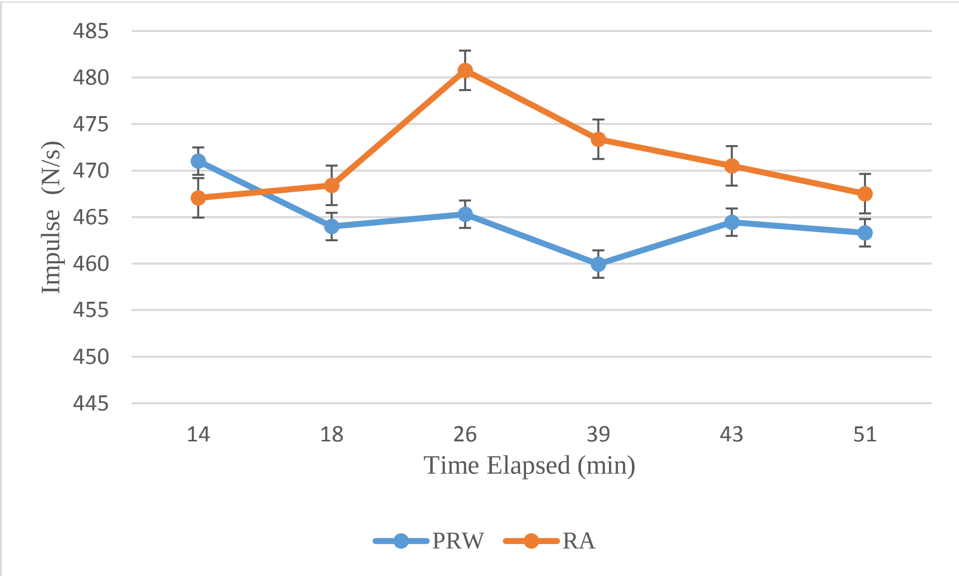

Figure 4.3 Jump impulse means across all time points from initiation of the NWU

4.2.2 Condition comparisons post reactivation and passive rewarming

PF, JH and IMP were compared between conditions at the three identified time points of 4 min (Table 4.4), 8 min (Table 4.6) and 16 min (Table 4.8) post PRW (Condition 1) and RA (Condition 2).

4.2.2.1 Thirty-nine minutes: four minutes post reactivation and passive rewarming

A *small* significant difference (ES=0.30; *P* =0.02) was observed between PRW (Condition 1) and RA (Condition 2) protocols for JH at 4 min post PRW and RA, respectively. The RA protocol had a *likely beneficial* effect on JH at 4 min post RA (Table 4.5). *Trivial* non-significant differences were observed between Conditions 1 and 2 for PF and IMP.

Table 4.4 Squat jump performance in freestyle snow sport athletes four minutes post passive rewarming and reactivation in an extremely cold environment

	Passive Rewarming Mean ± SD	**Reactivation Warm-up Mean ± SD**	***P*-Value**	***ES* (95% CI)**	**MDiff%**
Peak Force (N)	1413 ± 307	1417 ± 287	0.836	0.01 ± 0.11	0.3 ± 3.5%
Jump height (cm)	25.0 ± 5.8	26.7 ± 5.4	0.020	0.30 ± 0.25	6.8 ± 7.7%
Impulse (N*s)	459 ± 86	473 ± 93	0.104	0.16 ± 0.20	2.9 ± 4.8%

The 39 min time point (4 min post reactivation and rewarming) was used for statistical comparisons between conditions. Means and standard deviation (SD), typical error of measurement (TE) expressed in raw values and as a coefficient of variation (CV%) and intra-class correlation (ICC) for each variable, Confidence intervals (CI)

Table 4.5 Likelihood of a reactivation protocol having a beneficial, negligible or harmful effect on squat jump performance in freestyle snow sport athletes in extremely cold environment 4 min post re-activation

	Beneficial	**Negligible**	**Harmful**
Peak Force (N)	0.2% Most unlikely	99.7% Most likely	0.1% Most unlikely
Jump height (cm)	81.3% Likely	18.6% Unlikely	0.1% Most unlikely
Impulse (N*s)	30.8% Possibly	69.1% Possibly	0.2% Most unlikely

Comparison of Condition 1 (passive rewarming) and Condition 2 (reactivation protocol) @ 39 min time point

4.2.2.2 Forty-three minutes: eight minutes post reactivation and passive rewarming

A *small* significant difference (ES = 0.24; *P* = 0.02) was observed between PRW and RA protocols for JH at 8 min post rewarming and RA respectively. The RA protocol had a *likely beneficial* effect on JH at 8 min post RA (Table 4.7). *Trivial* non-significant differences were observed between Conditions 1 and 2 for PF and IMP.

Table 4.6 Squat jump performance in freestyle snow sport athletes eight minutes post passive rewarming and reactivation in an extremely cold environment

	Passive Rewarming Mean ± SD	**Reactivation Warm-up Mean ± SD**	***P*-Value**	***ES* (95% CI)**	**MDiff%**
Peak Force (N)	1397 ± 293	1407 ± 284	0.553	0.03 ± 0.11	0.4%
Jump height (cm)	25.3 ± 5.9	26.7 ± 5.2	0.02	0.24 ± 0.19	5.4 ± 5.7%
Impulse (N*s)	464 ± 90	470 ± 87	0.438	0.067 ± .19	1.3 ± 5.1%

The 43 min time point (8 min post reactivation and rewarming) was used for statistical comparisons between conditions. Means and standard deviation (SD), typical error of measurement (TE) expressed in raw values and as a coefficient of variation (CV%) and intra-class correlation (ICC) for each variable, Confidence intervals (CI)

Table 4.7 Likelihood of a reactivation protocol having a beneficial, negligible or harmful effect on squat jump performance in freestyle snow sport athletes in extremely cold environment 8 min post reactivation

	Beneficial	**Negligible**	**Harmful**
Peak Force (N)	0.4% Most unlikely	99.5% Most likely	0.1% Most unlikely
Jump height (cm)	67.1% Likely	32.9% Possibly	0.0% Most unlikely
Impulse (N*s)	7% Unlikely	92.4% Likely	0.6% Most unlikely

Comparison of Condition 1 (passive rewarming) and Condition 2 (reactivation protocol) @ 43 min time point

4.2.2.3 Fifty-one minutes: sixteen minutes post reactivation and passive rewarming

A *trivial* non-significant difference (ES = 0.24; $P = 0.08$) was observed between PRW and RA protocols for jump height at 16 min post PRW and RA, respectively. The RA protocol *possibly* had a beneficial effect on JH and PF at 16 min post RA (Table 4.9).

Table 4.8 Squat jump performance in freestyle snow sport athletes sixteen minutes post passive rewarming and reactivation in an extremely cold environment

	Passive Rewarming Mean ± SD	Reactivation Warm-up Mean ± SD	*P*-Value	*ES* (95% CI)	MDiff%
Peak Force (N)	1370 ± 281	1369 ± 271	0.99	0.01 ± 2.0	0 ± 6.6%
Jump height (cm)	25.1 ± 5.8	26.1 ± 5.5	0.08	0.17 ± 0.2	3.9 ± 5.6%
Impulse (N*s)	463 ± 91	467 ± 88	0.336	0.046 ± 1	0.9 ± 2.7%

The 51 min time point (16 min post reactivation and rewarming) was used for statistical comparisons between conditions. Means and standard deviation (SD), typical error of measurement (TE) expressed in raw values and as a coefficient of variation (CV%) and intra-class correlation (ICC) for each variable, Confidence intervals (CI)

Table 4.9 Likelihood of a reactivation protocol having a beneficial, negligible or harmful effect on squat jump performance in freestyle snow sport athletes in extremely cold environment 16 min post reactivation

	Beneficial	Negligible	Harmful
Peak Force (N)	41.5% Possibly	17.8% Unlikely	40.7% Possibly
Jump height (cm)	38% Possibly	61.8% Possibly	0.1% Most unlikely
Impulse (N*s)	0.5% Most unlikely	99.5% Most likely	0.0% Most unlikely

Comparison of Condition 1 (passive rewarming) and Condition 2 (reactivation protocol) @ 51 min time point

4.3 Case studies: responders versus non-responders

4.3.1 Responders

Participants were termed responders if they showed an improvement in JH following the RA protocol when comparing individual JH performance at the 26 min time point (16 min post NWU) to the 39 min (4 min post RA), 43 min (8 min post RA) and 51 min (16 min post RA) time-points.

Responder 1 (Figure 4.4) showed an initial 6.5% improvement in JH from pre to post-RA. This enhancement in JH was greatest 8 min post-RA and remained elevated 16 min post-

RA. In Responder 1, JH also improved slightly following PRW and was enhanced at 8 and 16 min post PRW (2.9 %).

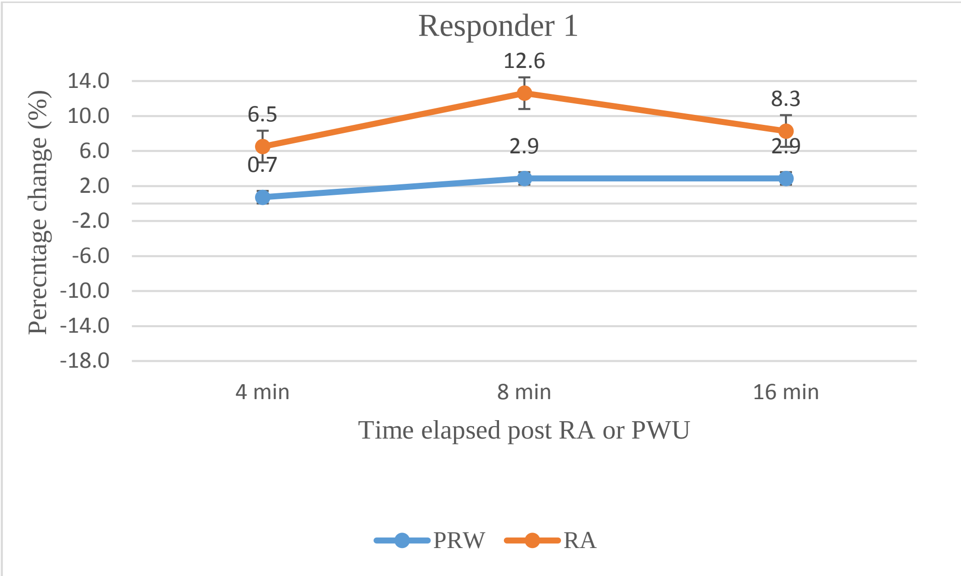

Figure 4.4 Responder 1 percentage differences in jump height pre- versus post-passive rewarming (PRW) and reactivation (RA)

Responder 2 (Figure 4.5) JH was enhanced 4 min post-RA (i.e. 14 % increase) and remained elevated 16 min-post (i.e. 8 % increase). Following the PRW, responder 2 had a negative response 8 min post-PRW (i.e. 7 % decrease). However, by the 16 min post-PRW only a 2 % reduction in JH was observed.

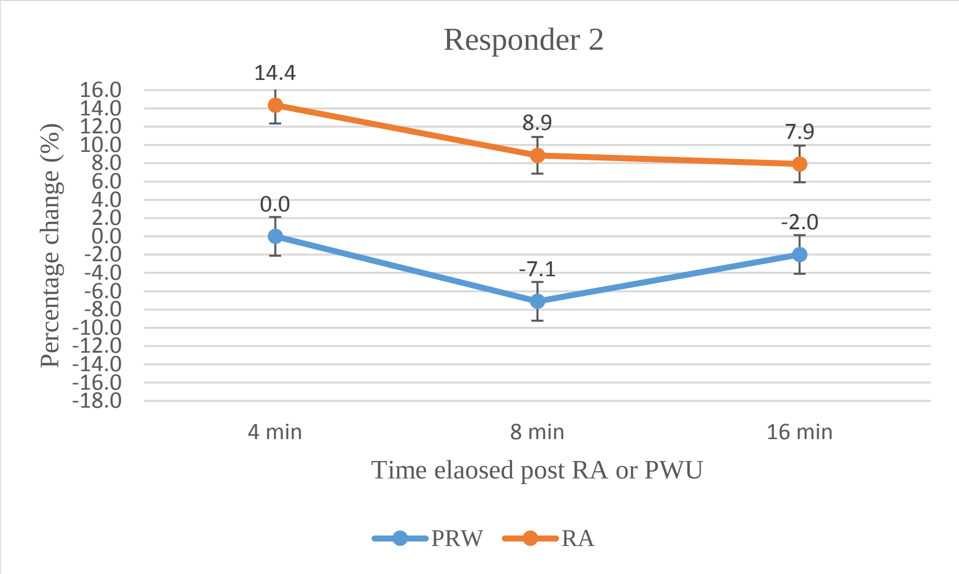

Figure 4.5 Responder 2 percentage differences in jump height pre- versus post- passive rewarming (PRW) and reactivation (RA)

In responder 3, JH was enhanced at 4 min post-RA and remained elevated 8 min post-RA. However, JH returned to pre-RA levels 16 min post-RA. Following the PRW, responder 3 had large reductions in JH performance across the post-PRW time-points. Responder 3 also had a 2-fold reduction in JH at 16 min post-PRW vs. 4 min post-PRW (Figure 4.6).

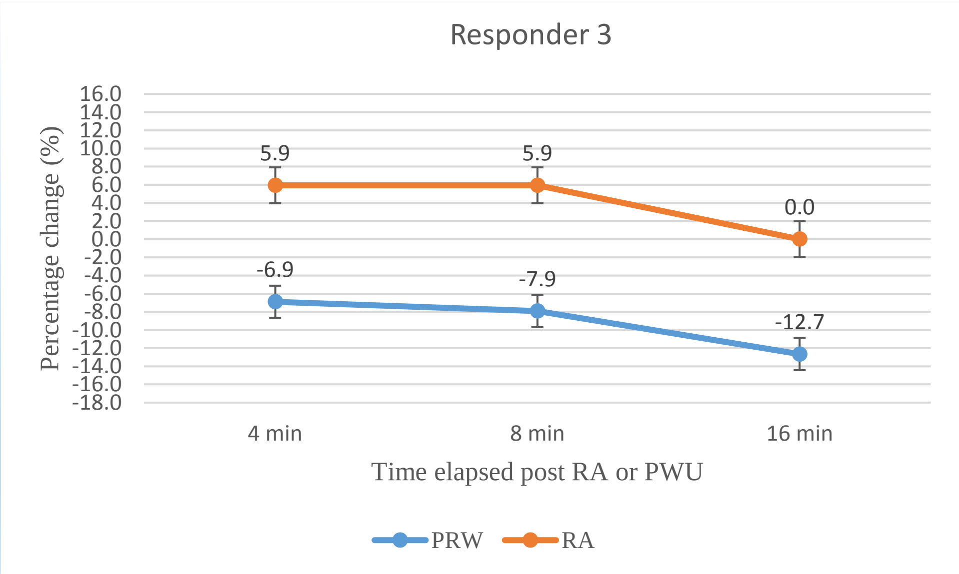

Figure 4.6 Responder 3 percentage differences in jump height pre- versus post- passive rewarming (PRW) and reactivation (RA)

4.3.2 Non-responders

Participants were termed non-responders if they had no improvements or reductions in JH, when comparing individual JH performance at the 26 min time point (16 min post NWU) to the 39 min (4 min post RA), 43 min (8 min post RA) and 51 min (16 min post RA) time-points, respectively.

Non-responder 1 showed minimal change in JH at all post-RA time points. Following the PRW, non-responder 1 had a decline in JH with the largest reduction in JH observed 16 min post-PRW (Figure 4.7).

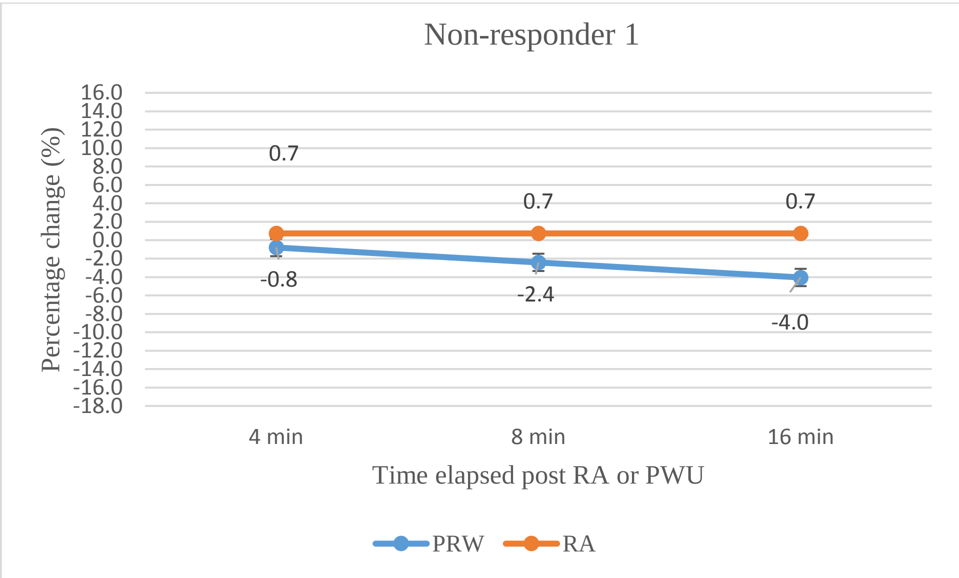

Figure 4.7 Non-responder 1 percentage differences in jump height pre- versus post-passive rewarming (PRW) and reactivation (RA)

Non-responder 2 showed a linear decline in JH following RA (i.e. from -3 to -7 %). Non-responder 2 had a very large reduction in JH 4 min post-PRW and large reductions 8 and 16 min post PRW (Figure 4.8).

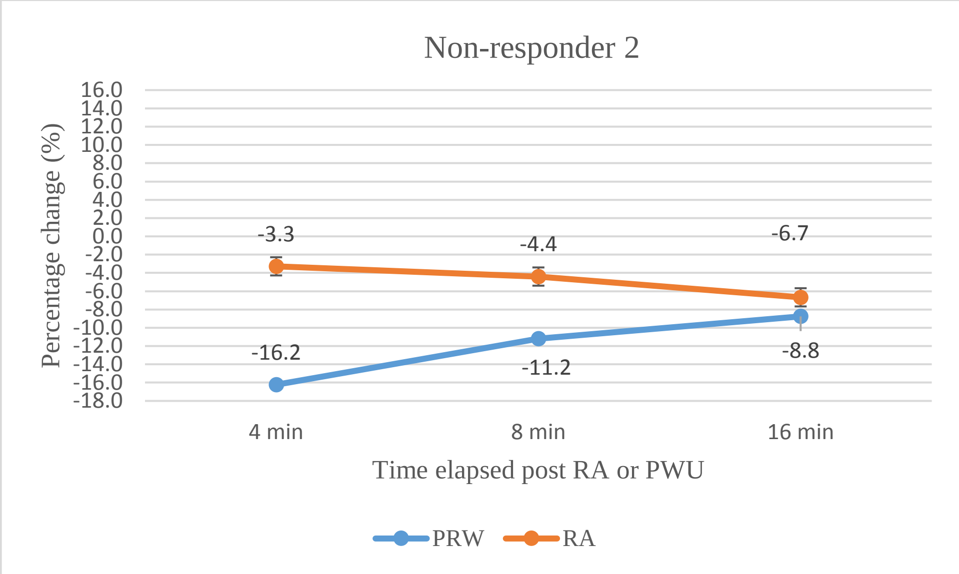

Figure 4.8 Non-responder 2 percentage differences in jump height pre- versus post-passive rewarming (PRW) and reactivation (RA)

Non-responder 3 had a decline in JH following RA (i.e. from -1.8 to -5.8 %) as assessed at 4, 8 and 16 min post-RA (Figure 4.9). Non-responder 3 also had a very large reduction in JH 4 min post-PRW (i.e. decrease of 14 %); lesser reductions in JH 8 min (-2.5 %) and 16 min (-6 %) post-PRW were observed.

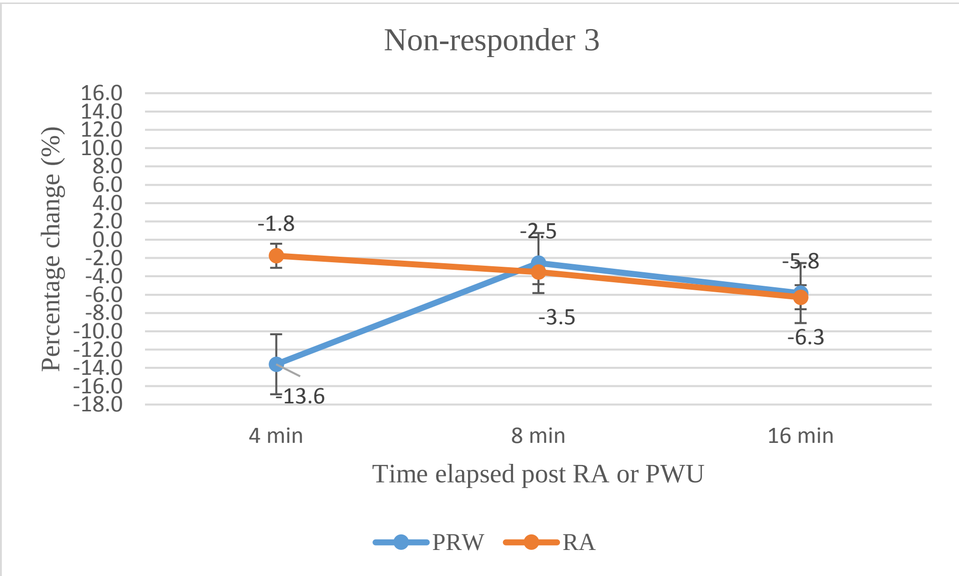

Figure 4.9 Non-responder 3 percentage differences in jump height pre- versus post-passive rewarming (PRW) and reactivation (RA)

Chapter 5: Discussion

The aim of this thesis was three-fold. Firstly, to assess the within session and between session reliability of a SJ protocol as a measure of jump performance in freestyle ski and snowboard athletes. Secondly, to examine the effectiveness of a RA protocol to combat the impact of extended cold exposure in comparison to PRW at room temperature. Lastly, to examine the effectiveness of a dynamic NWU for athletes that are exposed to extremely cold conditions (-20 to -18 ^{o}C), and the resulting performance potentiation and decay due to the NWU and cold exposure.

JH, PF, and IMP proved to be reliable dependent variables to monitor SJ performance. Of note, the RA protocol described herein reversed the *harmful* effects of cold exposure and potentiated JH at 4 and 8 min following its completion. The dynamic NWU was ineffective at maintaining SJ performance as performance decreased as cold exposure and inactivity duration increased.

5.1 Reliability

This thesis assessed both the within session and inter-day reliability of a freestyle ski and snowboard specific SJ protocol using two portable force plates synchronised with a LPT. Previously, the concentric-only SJ has been shown to have excellent test-retest reliability across a range of athletic populations (Alemany *et al*., 2005; Artega, Dorado, Chavarren, & Calbert, 2000; Markovic, Dizdar, Jukic, & Cardinale, 2004; Viitasalo & Aura, 1984). In addition, it has been shown that minimal familiarisation is required by participants to perform the SJ proficiently (Alemany *et al*., 2005).

The results of this study show that PF, PV, PP and IMP have excellent within session reliability (ICC > 0.90; CV < 5.5 %). JH was also shown to have good within session reliability (ICC > 0.70; CV < 10 %). This supports previous findings that SJ is a reliable performance test when assessed utilising a number of testing devices, such as force plates (Argus, *et al*., 2014; Cronin *et al*., 2004; Hori *et al*., 2009; Moir, Sanders, Button, & Glaister, 2005), LPT (Cronin *et al*., 2004; Taylor *et al*., 2010), contact mats (Markovic *et al*., 2004) and synchronised force plate-LPT systems (Alemany *et al*., 2005). The findings herein, also suggest that there is minimal learning involved with the SJ protocol and that using a system that integrates force-time data from force plates and displacement-time data from an LPT is reliable for measuring SJ performance in freestyle ski and snowboard athletes.

Excellent inter-day reliability outcomes were also reported for JH, IMP and PF. This finding is in agreement with previous inter-day reliability research on athletic populations (Alemany *et al*., 2005; Argus *et al*., 2014; Hori *et al*., 2009; Markovic *et al*., 2004; Moir *et al*, 2005). Argus *et al.* (2014) found excellent reliability for PF and IMP (ICC= 0.86-0.97) in recreationally trained men performing SJ with varying squat depths (i.e. knee angles in the bottom position of the SJ). However, they reported poor reliability (ICC= 0.63) for IMP utilising a self-selected knee angle. Similarly, Moir *et al*. (2005) and Cronin *et al*. (2004) reported excellent reliability for PF in recreationally trained males (ICC = 0.91-0.96). In addition, Markovic *et al*. (2004) reported excellent reliability for JH in recreationally active males performing a SJ (ICC = 0.97). The findings in the current study along with previous SJ performance research, indicate that JH, PF and IMP have good reliability. Practitioners can use these variables to accurately measure, assess and monitor SJ performance. In contrast, TTS, RFD, PP, and PV had poor reliability and were therefore excluded from the intervention portion of the study.

The poor reliability of TTS supports some of the previous findings using similar landing tasks (Flannagan, Ebben, & Jensen, 2008; Wickstrom, Tilman, Smith, & Borsa, 2005). Flannagan *et al*. (2008) found that TTS between trials using a single leg drop-jump task had poor reliability (ICC < 0.70) in collegiate track and field athletes. These findings are partially supported by Wickstrom *et al.* (2005), who reported fair reliability for TTS during single leg landings (ICC = 0.78). In this study, Wickstrom *et al*. (2005) classified reliability co-efficient 0.70 to 0.79 as fair. Conversely, Tran *et al*. (2015) using a similar cohort of athletes to those in the current study, reported excellent TTS reliability during a double leg drop landing task in developmental (ICC = 0.88) and elite surfers (ICC = 0.90). The simplicity of a drop landing as opposed to a SJ landing may help explain the differences in reliability between these two tasks. It is also plausible that insufficient familiarisation with the SJ landing task leads to higher TTS variability in the freestyle ski and snowboard athletes. It has been suggested that as few as two to three familiarisation sessions of four to eight trials may be required to achieve a high level of stability or reliability within a given measure (James, Herman, Dufek, & Bates 2007). However, it was also reported that some landing variables in their study failed to show reliability irrespective of the number of trials undertaken (James *et al.,* 2007). James *et al*. (2007) also noted that the performance task used in their study (a step off or drop jump) is not representative of most functional tasks. Functional performance tasks are normally preceded by a jumping task that adds movement complexity and therefore, caution is advised when comparing these findings to more complex movement patterns. Although, TTS was an unreliable variable in the current cohort of athletes, an increased number of familiarisation sessions may have improved the consistency of SJ landing technique, however, this notion warrants further investigation.

In agreement with the current findings, poor SJ RFD reliability has also been reported in the literature. Taylor *et al.* (2010) found RFD to have poor reliability during loaded CMJ (40 kg) in professional rugby players, expressed as within-subject variability (CV = 13 to 17 %). Similarly, Hori *et al*. (2009) found RFD during a CMJ to have poor reliability (ICC = 0.66; at sampling frequencies between 200 and 500 Hz) in recreationally active males. Hori *et al*. (2009) suggest that using force plates with the highest possible sampling rate is best practice, however, these findings reveal minimal difference in measurement outputs using sampling rates between 200 and 500 Hz. Furthermore, Moir *et al*. (2005) also observed poor inter-day peak RFD reliability (ICC= 0.53, CV= 13 %) during the SJ in recreationally active students. However, they found that average RFD had excellent reliability (ICC = 0.84, CV= 6.5 %) and concluded this variable could be used as part of an assessment protocol (Moir *et al*., 2005). The poor peak RFD SJ reliability findings of the current study are aligned with previous research, which has used a variety of jumping tasks, such as loaded and unloaded CMJ and SJ. Hansen, Cronin and Newton (2011) revealed that the method of analysis chosen significantly changes the resultant SJ RFD output. Therefore, practitioners should carefully consider the portion of the SJ force-time curve analysed when selecting the appropriate RFD calculation method. It is apparent that inconsistencies exist in the method used to calculate RFD within the current body of literature. Exploring the reliability of average RFD and concentric phase time-bound RFD outputs (i.e. 0 to 50 ms, 0 to100 ms, 0 to 250 ms), similar to the highly reliable IMTP research of Haff, Ruben, Lider, Twine, and Cormie (2015) may be worthwhile for future SJ research.

Variables such as PP and PV have previously been shown to be reliable (ICC > 0.80) within testing sessions when performing CMJ using force plates (Hori *et al*., 2009). This finding was further supported by Argus *et al*. (2014), who found excellent reliability for PP (ICC= 0.84 to 0.98) in recreationally trained males across a variety of JS depths (i.e. varying knee angles). Additionally, they observed excellent reliability for PV (ICC = 0.89 to 0.94) across a variety of knee angles. However, poor PV reliability was observed when participants used a self-selected SJ depth (ICC=0.59) (Argus et al., 2014). Adding to this, Moir *et al.* (2005), found excellent inter-day reliability for PP (ICC = 0.97) and PV (ICC = 0.93) in recreationally trained males performing a SJ and suggested that little familiarisation is required when athletes use a performance task related to their normal sporting activities. In contrast, in the current study PV and PP exhibited poor reliability in freestyle snow sport athletes. This may have been due to the heterogeneous nature of the group with vastly differing ages, resistance training experience, strength levels, DSI and inclusion of male and female athletes of varying capability within their sport. It may also be that with greater familiarisation to the task, and specifying a starting knee angle for the SJ, that the reliability of these variables (i.e. PP, PV, RFD and TTS) would be improved. Lastly, the findings in the current study may differ from previous studies, due to the novel SJ protocol implemented. Previous studies have used 3 to 4 s isometric holds (Cronin *et al*., 2004; Moir *et al.*, 2005) prior to jumping, while the present study used a 5 s isometric hold. In addition, previous studies had longer periods of recovery (20 to 60 s) between individual jumps, while in the current study only 5 s separated each jump.

To summarise the reliability outcomes, JH, PF, and IMP measured by force plates (using 1000 Hz sampling rate) synchronised with a LPT can be used to accurately assess and monitor SJ performance (using self-selected squat depth) following an intervention with a heterogeneous group of snow sport athletes. In contrast, PP, PV, TTS, and RFD were deemed unreliable and should not be used to measure or monitor SJ performance without sufficient familiarisation.

5.2 Effects of cold exposure and potentiation strategies on performance

JH, PF, and IMP were used to assess; i) the effects of cold exposure and, ii) the potentiation effects of PRW and RA on SJ performance in freestyle ski and snowboard athletes.

5.2.1 Effects of cold exposure on squat jump performance

The impact of cold exposure and time-elapsed following the initial NWU were assessed by examining SJ performance across all testing time points (i.e. 4, 8, 16, 29, 33, and 41 min post-NWU). The cold exposure duration and elapsed time between the initial and final testing time-points consisted of 36 min of cold exposure and a total elapsed time of 41 min, respectively. JH was significantly reduced due to cold exposure duration and elapsed time following the NWU (Figure 4.1). There was an 8 to 9 % decrease in JH between the 14 min time point (4 min post NWU) and the 51 min time point (41 min post NWU). PF also decreased in a similar fashion with increased cold exposure and time-elapsed (Figure 4.2). A *small* significant negative effect on PF was observed between the 14 min and 51 min time points, representing a 5% decrease overall.

These findings align with previous research examining the harmful effects of cold exposure on physical performance. Richendollar *et al*. (2006) found a 5 % decrease in vertical jump performance in college age men following 20 min ice application to the anterior thigh. They also found a 14 % decrease in 10 m agility shuttle and a 3 % decrease in a 40 yd sprint performance (Richendollar *et al*., 2006). Similar outcomes were observed by Kahn, Nuhmani, and Kapoor (2012), who found a 5 % reduction in JH in collegiate hockey players following ice application to the anterior thigh for 10 min. Fischer *et al*. (2009) also found a significant decrease in JH (3 %) in male and female college athletes following a 10 min application of ice to the posterior thigh area (i.e. hamstring muscle group). This information suggests that 10 to 20 min of ice applied directly to the leg may reduce JH by 3 to 5 %.

Similar reductions in performance have been observed with exposure to i) cold water immersion and ii) cold ambient air temperatures. Patterson *et al*. (2008) found a 17% decrease in CMJ height following a 20 min cold-water exposure (10 ^{o}C) in recreationally active male and female college students. Likewise, Dixon *et al.* (2010) reported reductions in CMJ power in Division 1 male athletes, following 45 min of cold water immersion (12 ^{o}C). This also supports earlier work by Crowley *et al.* (1991), who found that the cooling of the lower limbs in water between 11 to 12 ^{o}C for 30 min, resulted in a 25 % reduction in sprint cycling peak power (i.e. Wingate cycle test) in collegiate males. They estimated a 4 % loss in peak power per 1 ^{o}C of change in muscle temperature (Crowley *et al*., 1991). While cold water immersion (10 ^{o}C to 12 ^{o}C) has been shown to decrease performance in dynamic tasks, it is important to consider the impact of exposure to cold ambient air as it is more specific to what is experienced by snow sport athletes competing in cold environments.

Fewer studies have examined dynamic performance in cold ambient air temperature, however, the limited research available aligns with the outcomes from other cooling methodologies. Comeau *et al*. (2003) found a significant reduction in hamstring and quadriceps force in physically active college males following a 40 min exposure to ambient air temperatures of 5 and 10 ^{o}C. The resulting loss of force production was accompanied by a steady reduction in skin temperature. The authors concluded that the loss of force production could contribute to a decrease in athletic performance. Finally, a ski specific study by Suzuki *et al.* (2014) used a climatic chamber to expose athletes to cold temperatures (i.e. 1 ^{o}C) commonly experienced by alpine skiers and where the athletes performed simulated high intensity training in the chamber. They found significant reductions in skin temperature (4 ^{o}C) with 50 min of cold exposure despite performing 30 s of high intensity cycling every 10 min. They concluded that cold exposure is likely to have a negative impact on performance during on-snow training and competition (Suzuki *et al*., 2014). As was seen in the current study, there is clear evidence that cold exposure either through cold-water immersion or cool ambient air temperature has a significant impact on explosive neuromuscular performance and specifically jump performance from a static position.

Although the underlying mechanism for decreased jump performance with cold exposure was not examined in the current study, it can be inferred that the reductions in performance most likely occurred as a result of decreased muscle temperature. A review on the effect of temperature on neuromuscular function concluded that an athletes' jump performance can decrease by 2 to 5 % for every 1 ^{o}C of muscle temperature loss (Racinais & Oksa, 2010). Decreased muscle temperature is thought to slow contractile rates of muscle fibres leading to less forceful and powerful contractions (De Ruiter & De Hann, 2000). Muscle cooling is also thought to cause greater antagonist activation and decreased agonist activation leading to impaired efficiency and co-ordination (Oksa, Rintamaki, Makinen, Hassi, & Rusko 1995; Oksa, *et al*., 1997). Furthermore, body temperature is known to decrease at a high rate from the onset of cold exposure, with a drop of 2 ^{o}C with exposure to 5 ^{o}C for 30 min (Spitz *et al*., 2014). Given the duration of exposure to extremely cold temperatures in the current study (36 min at -20 to -18 ^{o}C), which were significantly colder than previous studies, and that the physiological mechanisms of homeothermy struggle to maintain peripheral muscle temperatures in optimal ranges even in moderately cold temperatures, it is very likely that muscle temperatures were significantly reduced in these athletes.

An examination of thermoregulatory responses during cold exposure following exercise suggests that the cold exposure can lead to a greater temperature loss due to thermoregulatory lag and active heat distribution to the limbs (Castellani, Young, Kain, Rouse,

& Sawka, 1999). Following exercise, the body's response is to facilitate heat dissipation and with immediate exposure to cold, there may be a lag in switching from heat dissipation to the heat conservation required in cold temperatures (Castellani, *et al*., 1999). When exercising, there is a greater muscle perfusion in the active muscles for the purposes of heat dissipation. This perfusion can remain elevated for an extended period post-exercise and may lead to greater temperature losses (Castellani, *et al*., 1999; Raccuglia *et al.*, 2016). These findings are supported by Long *et al*. (2005) who found that in recreationally active males, 30 min exercise followed by exposure to cold lead to the intramuscular temperature of the quadriceps cooling almost 8 times faster than those not exposed to prior exercise. In the current study, participants were immediately transitioned from exercising (i.e. the 10 min NWU) into an extremely cold climate and there is a likelihood that thermoregulatory lag contributed to the speculated loss of muscle temperature from the active muscles, and contributed to reduced JH and PF. It is unlikely that thermoregulatory lag would have been a factor following the RA protocol given the brevity of the exercise intervention (i.e. 5 min).

Therefore, considering the previous research findings, it is probable that SJ performance in the current study was affected by decreased muscle temperature in conjunction with time elapsed following the NWU, and the impact may have been compounded by thermoregulatory lag. It could be estimated from findings in previous research that the athletes involved in the current study sustained muscle temperature losses in the range of 0.5 to 3.0 ^{o}C that resulted in JH and PF decreases of 2 to 15 % and 2 to 9 %, respectively. The subsequent muscle temperature losses may have been higher in the present study as the temperatures experienced were much colder than comparative studies, however, the extremely cold temperatures may have been offset by wearing of appropriate clothing. It could be argued that the decline in JH and PF was a direct result of fatigue induced by the SJ testing protocol, which consisted of 6 sets of 5 jumps with 5 s isometric holds between each jump, interspersed across the testing conditions. In previous SJ studies, it is common for each jump to be separated by 20 to 60 s; however, in the current study 5 SJ were executed with 5 s between each jump and during that period athletes remained in the bottom of the squat position with the muscles isometrically contracted. Another potential factor is psychological, that is, the motivation to perform maximal effort SJ may have diminished across the 6 sets of SJ over the 40 min period. However, the downward trend in JH was reversed at 39 min (4 min post-RA) and 43 min (8 min post-RA), which would suggest fatigue and motivation may not have been the key limiting factors impairing SJ performance.

Two strategies (i.e. PRW and RA) were employed to reduce the potential impact of cold exposure, and inactivity, and to enhance jump performance, and these are subsequently discussed.

5.2.2 Potentiation effects of passive re-warming and active re-activation on squat jump performance

To assess the effectiveness of the RA versus PRW, JH, PF and IMP were compared at the following time points 4 min post RA or PRW (39 min), 8 min post RA or PRW (43 min) and 16 min post RA or PRW (51 min). *Small* significant differences (6.8 % and 5.4 %) in JH were observed between the two conditions (PRW vs. RA) at 4 min (Table 4.4) and 8 min (Table 4.6) post-RA vs. post-PRW. However, only *trivial* non-significant differences (3.9 %) in JH were observed between conditions 16 min post post-RA vs. post-PRW (Table 4.8). These findings indicate that the RA protocol was more effective than the PRW at minimising the effects of cold exposure on SJ performance for a minimum of 8 min following completion.

It also appears that the moderate to high intensity 5 min RA stimulus had a potentiation effect on SJ performance. This supports the assertion by Saez saez de Villarreal, Gonzalez-

Badillo, and Izquierdo (2007) who suggested that warm-up protocols that include high intensity dynamic exercises can have a positive impact on jump performance. Although many PAP protocols utilise external loads, it has also been suggested that jumping (i.e. plyometric exercises) specific warm-ups with no external loading may provide a sufficient stimulus to enhance and potentiate jump and sprint performance by 2 to 7 % (Seitz & Haff, 2016). That is, plyometric conditioning activities, such as the exercises used in the current RA protocol, have proven to be an effective means of eliciting a PAP response. For example, Turner, Bellhouse, Kilduff, & Russell (2015) found a 2 to 3 % improvement in 10m sprint performance in collegiate males, 4 to 8 min following plyometric exercise (alternating bounds). Tobin and Delahunt (2014) also found that plyometrics (ankle hops, hurdle hops and drop jumps from 50 cm) increased jump height by 4 % in professional rugby players within 1 min of completion. Furthermore, plyometrics have been shown to enhance sprint and jump performance soon after they are performed (30 s to 4 min following a given PAP stimulus) (Seitz & Haff, 2016). These findings support the outcomes of the current study, which suggest that largest PAP response should occur 4 min following reactivation in freestyle ski and snowboard athletes. Other researchers have found that 8 to 12 min rest following an externally loaded PAP stimulus is required to elicit the optimal SJ performance response (Gouvêa *et al*., 2013; Kilduff *et al*., 2008). *Small* jump performance improvements (ES = 0.24) following externally loaded PAP stimulus have been observed across a range of athletic populations (Gouvêa et al., 2013), while rest periods of shorter (1 to 6 min) and longer durations (16 to 24 min) did not appear to elicit a stronger PAP response (Gouvêa *et al*., 2013). Since the PAP stimuli in studies by Gouvêa *et al.* (2013) and Kilduff *et al*. (2008) used external loads, there is an increased fatigue response immediately following the PAP activity in comparison to an unloaded PAP stimulus (i.e. plyometrics) and we must be cognisant that PAP is a balance between fatigue produced by the conditioning task and the resultant improvements in the performance tasks. The plyometric activities utilized in the current study (drop squats, jumps with 180 to 360 ° spins and drop squat to vertical jump) are most likely to produce less fatigue than activities using additional external loads, and therefore allow for faster dissipation of fatigue and realisation of the potentiation effects.

As previously discussed, intramuscular temperature maintenance appears to be important for maintaining physical performance capabilities during dynamic actions, such as jumping. The RA protocol in the current study provided an adequate PAP stimulus, which may have also offered a sufficient physical stimulus to reverse some of the temperature losses that occurred due to cold exposure (24 min) and time-elapsed following the initial NWU (29 min). Conversely, based on the findings, it is likely that the 5 min of PRW at room temperature was insufficient to reverse the losses in muscle temperature. This aligns with previous research, demonstrating that intramuscular temperature continues to decline even after cold exposure is terminated and the amount of activity (duration and intensity) a body is engaged in, has a direct effect on the body parts involved (Myrer *et al*., 2000).

It appears a hot external temperature is required to minimise intramuscular temperature loss during inactive transition phases. Raccuglia *et al*. (2016) observed that wearing heated over-trousers (43 ^{o}C) in an ambient air temperature of 18 ^{o}C was able to offset the loss of intramuscular temperature during a 30 min transition phase. They also observed that a minimal decrease in the heat of the over trousers (3 ^{o}C) meant intramuscular temperature was not maintained. Intramuscular temperature loss during the 30 min transition phase without the heated over-trousers was 1.3 ^{o}C, which aligns with previous findings (Raccuglia *et al.*, 2016). Similarly, Faulkner *et al.*, (2013) found that athletes using over trousers with internal heating elements maintained intramuscular temperature 1 ^{o}C higher than those not wearing the over trouser. This maintenance of temperature lead to a 9 % difference in sprint cycling peak power output following 30 min of inactivity (Faulkner et al., 2013). Interestingly, passive heat maintenance garments without additional heating have also been shown to be effective in minimising temperature loss. Russell *et al*. (2015) demonstrated that using a survival jacket to trap warm, still air around athletes reduces core temperature loss. This helped maintain CMJ performance following a 15 min transition phase, leading to a 3 % difference in jump performance between those that wore the jacket versus those that did not (Russell *et al*., 2015). The PRW protocol in the current study did not use any additional heating sources, and given the findings of previous studies, it is feasible that intramuscular temperature continued to decline during this period and could account for some of the differences observed in JH between the two experimental conditions.

The findings in the current study, along with the current literature, suggest that cold exposure leads to decreased neuromuscular performance and short duration active re-warming strategies are effective in potentiating physical performance and minimising losses in body temperature due to inactivity in cold to extremely cold environments. While passive re-warming strategies without utilising heat maintenance garments appears to be insufficient to prevent performance decrement and continued intramuscular cooling.

5.3 Case studies: responders versus non-responders

As a group, there were *small* significant improvements in JH following the RA protocol. However, at an individual level, some individuals had a beneficial response (responders) and some had a harmful response (non-responders) to the RA protocol. This aligns with previous studies examining PAP, which have reported differing outcomes of potentiating activities between individuals (Hilfiker *et al.*, 2007; Kilduff *et al*., 2008; Seitz & Haff, 2016). For example, Hilfiker *et al*. (2007) observed eight responders (62 %) and five non-responders (38 %) to a drop jump PAP protocol in a similar cohort of athletes to those in the current study (ski jump, alpine ski, freestyle ski and snowboard and gymnastics). Explanations offered for varying responses include individual differences in strength, muscle architecture, genetic make-up and resistance training experience (Hilfiker *et al.*, 2007). In the current study, it is also possible that the responders were less effected by exposure to the cold and in turn were better able to maintain their core and intramuscular temperature in comparison to the non-responders. As previously mentioned, motivation may have also played a role, in that the responders may have coped mentally with the experimental testing process better than the non-responders and were able to give maximal effort throughout.

5.3.1 Responders

Responders were classified as individuals displaying a 5 % improvement in jump performance following the PRW or RA protocol (i.e. 5 % improvement on JH from time point 26 min). Responders were only observed in Condition 2, following the RA protocol. Although upward trends in JH were observed following the PRW, these values did not increase above the 5 % threshold described above.

The three responders in this study were a mix of developmental and elite male (n=1) and female (n=2) freestyle skiers with varying strength levels (i.e. IMTP peak forces between 2.7 to 3.7 x body weight) and DSI ratios (0.65-0.73). The RA stimulus elicited potentiation effects of greater than 5 % at 4 min and 8 min post RA, which is supported by previous research, suggesting that plyometric activities can elicit a PAP response with a small recovery window (Bridgeman *et al*., 2017; Chen *et al*., 2013; Seitz & Haff, 2016; Tobin & Delahunt, 2014). Bridgeman *et al.* (2017) found a greater CMJ PAP response at 2 min (ES = 0.64) and 6 min (ES = 0.17) in comparison to 12 min following sets of 5 loaded drop jumps with 10 and 20 % of body mass. Chen *et al*. (2013) found a 2 % improvement in CMJ only 2 min following 5 drop jumps. Similarly, Tobin and Delahunt (2014) found the largest significant improvements in CMJ height (5 %) 1 min following alternate leg bounding. The responders discussed below had varying individual responses to the RA protocol, which are most likely due to their unique strength qualities and experience within their sport.

Responder 1, a 15 year-old male skier with 2 years of training experience, relative IMTP strength of 3.7 times body weight, and DSI of 0.65, had his largest PAP response 8 min post-RA (Figure 4.4). This aligns with previous reports stating that the optimal PAP response can occur 8 to 12 min following a given PAP stimulus (Gouvêa *et al*., 2013; Kilduff *et al.*, 2008). Kilduff *et al*. (2008) observed that 70 % of their athletes had the greatest PAP response at 8 min following three sets of three repetitions at 87 % one-repetition maximum squat. Utilising a relatively heavy external load lead to increased fatigue and therefore greater recovery time was required to see the potentiation effect. Kilduff *et al*. (2008) also saw other players enhance their PAP responses at 4 min (15 % of the athletes) and 12 min (15 % of the athletes). This reinforces previous assertions that PAP is an individualised response as previously it has been reported that unloaded stimuli allow PAP to occur soon after completion (Chen *et al*., 2013; Hilfiker *et al*., 2007; Seitz & Haff, 2016; Tobin & Delahunt, 2014). It is possible that responder 1 experienced greater fatigue from the body weight plyometrics in the RA and therefore could not realise the benefits until the fatigue had fully dissipated at 8 min post-RA.

In stronger athletes, it is likely that the RA protocol elicited a faster and larger PAP response, as stronger athletes are believed to recover more quickly from a given plyometric PAP stimulus. This was observed in Responder 2, who had an optimal PAP response 4 min following the RA protocol (Figure 4.5). Responder 2 was a 22 year-old female skier with only 1 year of resistance training experience, a moderate amount of relative strength of 2.7 times body weight and DSI of 0.73. It has been reported that although both stronger and weaker athletes can benefit from traditional PAP inducing exercises (i.e. those involving external loading), it remains unclear if the exercise used to elicit a PAP response is affected by strength levels (Seitz & Haff, 2016). It is feasible given the age of Responder 2, she had developed greater jump specific strength through sport participation than was displayed in the IMTP. In addition, given her DSI ratio, this athlete appeared to be more able to harness her strength capability in a dynamic manner. As the performance task in the current study (i.e. SJ) primarily involves dynamic movement of the lower body, it is possible this athlete was better able to use their sport-derived strength and athleticism in a familiar movement pattern. A fundamental reason for specificity of a warm-up is to prime co-ordination of the targeted movement (i.e. agonist-antagonist co-ordination and timing), and it is possible that for Responder 2, the RA achieved exactly that, allowing an enhanced SJ performance.

Responder 3, a 24 year-old elite level female skier with 3 years resistance training experience, a relative strength of 3 times body weight and a DSI of 0.69, also responded optimally at 4 min post RA. Although the response was not as large as Responder 2 (6 % vs 14 %), this may be due to her performing closer to her physical potential throughout the testing protocol (Figure 4.6). Hilfiker *et al*. (2007) suggested that highly trained athletes may have reduced room for improvement in physical performance, and that small improvements should be viewed as beneficial. It may also be that this athlete is not able to harness her strength as effectively in a dynamic task given her DSI.

Although examination of the mechanisms of PAP is beyond the scope of the current study, it is possible to speculate that the RA protocol may have produced a PAP response by enabling more effective recruitment of type II muscle fibres, the priming of SJ specific muscles and coordinating optimal SJ mechanics (i.e. the selection of optimal squat depth to maximise JH) (Saez saez de Villarreal *et al*., 2007). In addition, the RA had several exercises that targeted vertical force production and therefore, was specific to the performance task in the current study. Finally, the three responders had DSI ratios between 0.65 and 0.73, and this may indicate they are more likely to respond to a potentiation of a dynamic task such as SJ. It is suggested that athletes with DSI ratio below 0.6 require increased amounts of ballistic training, and those above 0.8 require greater strength training. The responders in this study appear to sit firmly in the centre of these ranges indicating good ballistic capability given the appropriate conditions.

5.3.2 Non-responders

Non-responders were classified as an individual displaying minimal, no change or decrements in jump performance following the PRW or RA protocol. Although there were reversals in the decrement of JH following the PRW (Figure 4.8 and Figure 4.9) from time point 39 min to 51 min (Non-responder 2 = 7 %; Non-responder 3 = 10 %) these JH remained below the JH achieved immediately prior to PRW (i.e. 26 min post NWU).

The three identified non-responders in this study were also a mix of developmental and elite male (n=2) and female (n=1) athletes with similar resistance training experience, varying strength levels (i.e. IMTP peak forces between 2.4 to 4.1 times body weight) and DSI ratios (0.51 to 0.86). As previously mentioned, Hilfiker et al. (2007) suggested that non-responders are often exposed to much greater stimuli in their sport and therefore the protocols used to produce the PAP stimulus are often insufficient to elicit a PAP response. It has also been previously suggested that stronger athletes respond better to PAP protocols (Seitz & Haff, 2016). However, two of the non-responders were also the two strongest athletes participating in the study. It is plausible that the stronger non-responders were negatively affected by the cold exposure resulting large losses in body temperature; and/or the RA stimulus was insufficient, and therefore unable to effectively reverse the harmful effects of cold exposure. In addition, both stronger athletes had lower DSI ratios indicating they are not as effective at utilising their force production in a ballistic manner and this may have been further exacerbated by the cold exposure and potential fatigue from the RA protocol.

Non-responder 1 was a 17 year-old elite male skier with 2 years resistance training experience, a relative strength of 4.1 times body weight and a DSI of 0.51 (Figure 4.7). Although JH was not improved following the RA protocol, SJ performance appeared to be unaffected by fatigue from the RA protocol. The RA stimulus appeared to have had a greater beneficial effect than the PRW in this athlete, with JH continuing to decline post-PRW compared to post RA. It is possible that due to the strength level and the intensity of the stimulus experienced in his sport, that the RA protocol was insufficient to induce a PAP response. Although, the RA protocol was unable to reverse the effects of cold exposure, it proved more beneficial than PRW. Lastly, given the DSI of this athlete, it is possible that his ability to perform a dynamic task is further compromised by the cold exposure and the RA may have a greater fatiguing effect on his dynamic athletic ability.

Non-responder 2 was a 17 year-old elite male skier with 2 years resistance training experience, a relative strength of 3.9 times body weight and a DSI of 0.55. His response to the RA was unusual given his strength levels and resistance training experience (Figure 4.8). He was an athlete who would have been predicted to have a faster and greater PAP response to the RA stimulus. Accumulated fatigue from the SJ protocol, the detrimental effects of cold exposure and an insufficient PAP stimulus are the most likely explanations for the decline in JH. Additionally, non-responder 2 was known to give maximal effort during all training and testing sessions, therefore it is plausible that the NWU, the six sets of SJ and the RA stimulus caused increased levels of physical and mental fatigue throughout the intervention leading to reduced jump performance. Although JH did not improve following the RA, it appears that the RA was of greater benefit in comparison to PRW protocol. Finally, as with non-responder 1, this athlete has a low DSI and his ability to perform ballistic actions due to fatigue from the RA protocol may have further compromised his jump performance.

Non-responder 3, a 26 year-old developmental female skier with 2 years resistance training experience, a relative strength of 2.4 times body weight and a DSI of 0.86, had large reductions in performance following the RA and PRW protocols (Figure 4.9) most likely due to a combination of factors including strength level, fatigue, cold exposure, and motivation. The RA protocol used in this study may not have been of sufficient length or intensity to effectively increase blood flow, re-warm the body, reactivate, and potentiate SJ performance. PRW was a less harmful intervention for this athlete at 4 min post PRW compared with RA. However, between 8 and 16 min post PRW and RA, the differences in JH were minimal suggesting neither intervention was beneficial for this athlete. Finally, given the DSI of this athlete, suggesting she was more explosive than strong, fatigue from the 30 SJ performed, along with fatigue from the RA protocol, may have resulted in her non-responsiveness.

Based on these findings, when the non-responders are training and competing in extremely cold temperatures, they may require more frequent and effective re-warming strategies and re-activation activities during extended periods (> 8 min) of inactivity (i.e. post-NWU and/or between on-snow training and competition runs). For the stronger non-responders, it could be that a RA protocol of greater intensity is required to elicit and PAP response. For example, Bridgeman *et al.* (2017) demonstrated additional loading of 20 % of body mass during the PAP stimulus leads to greater improvements in CMJ height in comparison to a body mass only PAP stimulus. In addition, it may be that stronger athletes need to be exposed to more strength-based tasks as opposed to dynamic tasks. Conversely, those with higher DSI ratios may require a low volume dynamic RA that does not cause fatigue and allows these athletes to potentiate their ballistic capabilities.

It is evident from the responders and non-responders in the current study, along with previous research, that physical performance responses to a given NWU, PRW and RA stimulus are highly individual and a one-size fits all approach should not be adopted. Therefore, it is recommended that specific NWU, PRW and RA strategies be developed for each athlete, based on their unique strength qualities (i.e. dynamic force versus maximal force production capabilities) to enhance and maximise performance in extremely cold temperatures.

Chapter 6: Summary and Practical Applications

6.1 Summary

The purpose of this study was to examine the reliability of a snow sport-specific SJ protocol as an assessment tool and use it to investigate the effectiveness of a NWU, RA, and PRW in extremely cold temperatures.

The freestyle ski and snowboard specific SJ protocol showed good within session and inter-day reliability for assessing JH, PF and IMP. Therefore, the protocol can be used to accurately measure and monitor SJ performance changes in developmental and elite snow sport athletes, and in turn, assess the effectiveness of acute and chronic (i.e. NWU, PAP and training) interventions. Other jump variables including PP, PV, RFD, and TTS showed poor reliability, therefore caution is advised when using these variables to assess and monitor SJ performance. Lack of familiarisation and complexity of the SJ protocol could explain the poor reliability of TTS, while self-selected squat depth may have contributed to lack of PP and PV reliability (Argus *et al*., 2014; James *et al*., 2007).

The NWU was ineffective at maintaining jump performance in extremely cold temperatures. *Small* significant decreases in JH (9 %) and PF (5 %) were observed following

36 min of cold exposure. The reductions in JH and PF were likely related to decreased muscle temperature. Cold exposure, inactivity, and thermoregulatory lag are all possible contributors to this loss of muscle temperature.

The RA had a *small* significant influence on JH and a *likely beneficial* effect at 4 min and 8 min following reactivation, resulting in JH improvements of 7 % and 5 % respectively. The plyometric based activities of the RA elicited a PAP response on JH and likely reversed or minimised further loss of muscle temperature. Whereas, the PRW protocol appeared to a have a minimal effect on JH (i.e. no PAP response), it is also likely that the PRW stimulus was insufficient at reducing/negating the muscle temperature losses caused by cold exposure.

Varying individual responses (i.e. responders vs non-responders) to the RA were also observed. The responders experienced a PAP response following the RA, most likely due to PAP mechanisms (i.e. preferential recruitment of type II fibres, increased motor unit synchronisation, decreased reciprocal inhibition of antagonists), tissue rewarming, and priming of the SJ movement (Chen *et al*., 2013; Seitz & Haff, 2016; Tobin & Delahunt, 2014). The non-responders experienced a null or detrimental response to the RA stimulus; which may have been a result of fatigue, reductions in muscle temperature, motivation, and/or an insufficient RA stimulus.

The outcomes from this study may contribute to the design and implementation of warm-up and reactivation strategies for snow sport athletes exposed to extremely cold temperatures and periods of inactivity (> 8 min).

6.2 Study limitations

There were several limitations in this study that are outlined below:

6.2.1 Sample size and heterogeneity

The low number of participants in the study may have limited the power for estimation of the magnitude of inferences in snow sport athletes. There are difficulties in recruiting elite level athletes and in this cohort injury rates and general fatigue are high at the time of year the study was conducted. In the current study illness and injury played a role in limiting the number of participants recruited.

Compounded by the sample size is the diversity of experience and training age within the participant group. This heterogeneous group of males and females varied in chronological age, athletic training age, strength levels, experience, and sport-specific performance capabilities. Drawing definitive conclusions from this heterogeneous group of athletes is difficult and would be misleading, hence the inclusion of individual case studies. Individualisation is a key aspect of an effective warm-up, and should be given due consideration when designing warm-ups and reactivation protocols for a specific sport and athlete. One size does not fit all and does not need to in individual sports, such as freestyle skiing and snowboarding.

6.2.2 Assessment protocols

Although showing good reliability within and between testing sessions, the validity of using a SJ to assess neuromuscular function in this group of athletes could be questioned. The snow sport athletes in the study are involved in a sport that requires significant eccentric force absorption, isometric, and concentric force production using specialised equipment (i.e. skis, snowboards and specialised boots). The SJ protocol attempted to recreate some similarities of the sport through insertion of an extended isometric hold prior to the jump, however, this alone may not be a true representation of the sports' demands.

In relation to the SJ protocol, the testing of the SJ at ambient air temperature removed "real world" validity, as the participants are not be removed from the cold to perform their sport. Although jumping did not occur in the cold environment due to logistical reasons, this may have influenced the SJ performance. It should also be acknowledged that in the real world, snow sports athletes do not go immediately from being seated on a lift to engaging in explosive movements and may ski or ride 30 s to 2 min to the top of the training or competition course. However, future research should consider testing in the cold environment.

Muscle temperature has also been cited as a factor in reducing performance following cold exposure. Although not intended to be addressed in the current study, the inclusion of a core, skin or muscle temperature measure, would have provided greater insight into the mechanisms causing the changes in SJ performance. The RA protocol most likely led to a reversal in the decline of jump performance through tissue warming, and, or priming of the SJ movement pattern and mechanics. However, without measuring core, skin or muscle temperature fluctuations, these claims remain purely speculative.

The use of a subjective perceptual scale addressing thermal comfort may have added greater context and have identified other factors which lead to an impact on performance of the SJ.

Further related to the measurement of muscle temperature is the clothing worn by participants which would have influenced this variable. Although participants were given the discretion to wear what they felt comfortable in at the temperatures experienced in this study, the individual clothing choices may have impacted on muscle temperature, and therefore may have also been a factor in the their jump performance.

6.2.3 Environmental conditions

The study assessed neuromuscular functioning following exposure to extremely cold temperatures (-20 to -18 ^{o}C). These snow sport athletes are also exposed to warmer temperatures (-5 to 8 ^{o}C) during training and competition depending on the time of year and geographical location. Examining the effects of varying temperature ranges and altitudes on physical performance along with different warm-up intensities and durations would assist in better understanding the effects of the environment and warm-up on snow sport athletes.

6.3 Practical applications

General and specific dynamic warm-ups have been shown to be highly effective in preparing and enhancing training and competition performance in snow sport athletes. Transition phases between warm-up and training or competition make it difficult to retain the performance benefits provided by a dynamic warm-up. This issue is compounded by the duration of cold exposure experienced by these athletes. In addition, at the starting gate of events there is often only a small area for athletes and coaches to congregate, providing little space for athletes to perform a suitable dynamic warm-up.

This study suggests that engaging in jump specific movements and maintaining tissue warmth is beneficial to performing tasks that require effective jumping and landing mechanics. Furthermore, the NWU used in this study at the intensity undertaken by the athletes was ineffective in preventing SJ performance decay when athletes are inactive and exposed to extremely cold temperatures. It is therefore recommended that snow sport athletes subjected to periods of inactivity between runs during training and competition perform sport specific RA protocols to minimise performance decay and possibly potentiate performance.

Coaches and support staff working with snow sports athletes exposed to extremely cold temperatures, and variable transition phases between warm-up and training and competition, should consider implementing the following warm-up strategies. In doing so, it may be possible to minimise the harmful effects of cold exposure and inactivity on performance and maximise the potentiation effects on performance:

(i) Implement a higher intensity warm-up to help maintain neuromuscular function for longer in cold temperatures but taking 5 to 10 min before being exposed to the cold to minimise the impact of thermoregulatory lag.

(ii) Limit periods of athlete inactivity in extremely cold temperatures.

(iii) Re-activate the neuromuscular system in cold environments after inactive periods of more than 4 min (i.e. between runs and chair lift rides). Re-activation should be short and high intensity (i.e. 2 to 5 min) and include exercises which can be performed in a small area and involve the priming of snow sport-specific movement patterns (i.e. jumping & landing mechanics).

(iv) Take additional measures to maintain athlete body temperature between training and competition runs, such as wearing more thermal base layers, heated socks, thermal outerwear, heated jackets, heated over pants and/or unheated jackets designed for temperature retention.

(v) Identify responders and non-responders (i.e. athletes that respond well to NWU and RA protocols, and athletes that do not); and individualise the warm-up and reactivation strategies accordingly.

(vi) Identify optimal recovery times for individual athletes when using reactivation protocols as athletes will respond more positively at differing recovery points e.g. 4, 8 or 12 min following the reactivation.

(vii) Ensure there is a sufficient quantity of movement specific exercises included in the warm-up and reactivation protocols.

6.4 Future Research

It has been established that following NWU, extremely cold temperatures have a detrimental effect on SJ performance. Given the sporting demands, future research examining the effects of warm-up and exposure to extremely cold temperatures on isometric and eccentric strength and force absorption, would be beneficial for freestyle ski and snowboard athletes. Furthermore, the inclusion of specific NWU and RA protocols designed to potentiate isometric strength, eccentric strength and force absorption capabilities would be advantageous. Assessing the effects of RA protocols under on-snow conditions (i.e. performing RA on-hill in sport-specific clothing and equipment) would also add more sport-specific context to future research.

Investigating the effects of passive heat maintenance and retention clothing, (i.e. heated clothing and thermal jackets) on muscle & core temperature, SJ performance, and on-snow performance in snow sport athletes would also add to the current body of literature. Examining temperature maintenance and performance in a variety of environmental temperature ranges, such as those experienced at previous (i.e. -5 to 8 ^{o}C) and future Winter Olympic (Pyeong Chang, South Korea -12 to 5 ^{o}C) and world championship venues would be of benefit to optimising athlete performance.

Finally, although research outcomes may suggest that a specific warm-up protocol, or specific clothing may lead to enhanced performance in snow sports, what likely determines whether there will be athlete uptake of these strategies is the athletes belief and perception of how these things make them feel and will ultimately override research findings.

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Appendices

Appendix 1: Ethical Approval

AUTEC Secretariat

AUT

Auckland University of Technology
D-88, WU406 Level 4 WU Building City Campus
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

28 June 2016

Travis McMaster
Faculty of Health and Environmental Sciences

Dear Travis

Re Ethics Application: **16/215 The impact of post-activation potentiation, recovery time, and re-activation protocols on neuromuscular performance in freestyle snow sport athletes.**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 28 June 2019.

As part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through http://www.aut.ac.nz/researchethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 28 June 2019;
- A brief report on the status of the project using form EA3, which is available online through http://www.aut.ac.nz/researchethics. This report is to be submitted either when the approval expires on 28 June 2019 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this. If your research is undertaken within a jurisdiction outside New Zealand, you will need to make the arrangements necessary to meet the legal and ethical requirements that apply there.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

Appendix 2: Participant Information Sheet

Participant Information Sheet

Date Information Sheet Produced: 1 July 2016

Project Title: Warm-up, Re-activation and Neuromuscular Performance

Introduction

My name is Shane Crowhen, I am completing my Masters Degree in Sport and Exercise at AUT University, Auckland. On behalf of my supervisors Dr Travis McMaster and Professor Michael McGuigan, I would like to formally invite you to assist in our study which aims to establish what effects a warm-up and re-activation have on snowsport athletes.

I propose to do this by; 1) testing athletes repeated squat jump before and after a warm-up and reactivation.

Invitation to participate

You are invited to take part in the above mentioned research project. Your participation in this research is voluntary. Together, you and your whanau should decide whether or not you would like to be involved. You don't have to be involved, it won't affect your standing in Snow Sports NZ and you can stop being involved in the study at any time.

Your consent to participate in this research will be indicated by your signing and dating of a consent form. Signing the consent form indicates that you have freely given your consent to participate, and that there has been no coercion or inducement to participate by the researchers from AUT.

What is the purpose of the study?

The purpose of this study is to establish what effects a warm-up and re-activation gave on snowsport athletes. This study is to be conducted as part of a Master's Degree thesis. The results of this study will be submitted to peer-reviewed journals.

How was I identified to participate in the study?

- You have been identified and invited to participate in the study because you are an elite level freestyle ski and snowboard athlete who is currently competing domestically and internationally and are ranked among the top 16 in the world; or you are a developmental freestyle ski and snowboard athletes who is competing in junior national and, or international competitions.

What happens in the study?

We will ask you to come to the High Performance Sport New Zealand, Wanaka training facility to complete 3 testing session lasting 30 to 60 minutes.

- During the first testing session you will be asked to:
    1. Have your weight recorded.
    2. Complete an isometric mid thigh pull to measure strength.
    3. Complete a test involving 5 maximum squat jumps which will be video recorded
- During the second and third session you will be asked to:
    1. Have your weight recorded.
    2. Complete a warm-up in your outerwear pants
    3. Complete a re- activation in your outer wear
    4. Sit in a cold environment between -18 to -20 °C in your outwear clothing following warm-up and re-activation
    5. Complete a test involving 5 maximum squat jumps which will be video recorded

What are the discomforts and risks?

- You will experience discomforts and risks which are similar to that of your regular on snow training.

What compensation is available for injury or negligence?

- In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

What are the benefits?

- Findings of this study will be used to assess how warm-up effects athletes jumping and landing ability and could therefore enhance performance. You will be provided your individual results as well as the mean and median results of the study so that you can identify your personal weaknesses which can be altered to improve performance.

How is my privacy protected?

- The data from the project will be coded and held anonymously in secure storage under the responsibility of the principal investigator of the study in accordance with the requirements of the New Zealand Privacy Act (1993).
- All reference to participants will be by code number only in terms of the research thesis and publications. Identification information will be stored on a separate file and computer from that containing the actual data.
- Only the investigators will have access to computerised data.

What are the costs of Participating?

- There is no monetary cost to you to be involved in this research, the only cost is time. The testing will be conducted at the High Performance New Zealand, Wanaka, training facility

Opportunity to consider invitation

- Please take the necessary time you need to consider the invitation to participate in this research.
- It is reiterated that your participation in this research is completely voluntary.
- If you require further information about the research topic please feel free to contact Shane Crowhen or Travis McMaster (details are at the bottom of this information sheet).
- You may withdraw from the study at any time without there being any adverse consequences of any kind.

How do I join the study?

- If you are interested in participating in this research feel free to contact either Shane Crowhen or Travis McMaster (details are at the bottom of this information sheet).

Participant concerns

- If you have any questions please feel free to contact Shane Crowhen or Travis McMaster. Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor – Travis McMaster.
- Concerns regarding the conduct of the research should be notified to the Executive Manager, AUTEC, Kate O'Connor, ethics@aut.ac.nz or phone +64 9 921 9999 x6038.

Researcher Contact Details:

Shane Crowhen, School of Sport and Recreation, AUT University. Email: shane.crowhen@hpsnz.org.nz or phone +64 21 477 303

Project Supervisor Contact Details

Primary Supervisor: Dr Travis McMaster, Sports Performance Research Institute New Zealand, School of Sport and Recreation, AUT University. Email: travis.mcmaster@aut.ac.nz

Secondary Supervisor: Dr Mike McGuigan, Sports Performance Research Institute New Zealand, School of Sport and Recreation, AUT University. Email: mmcguiga@aut.ac.nz or phone +64 9 921 9999

Thank you for considering participating in this research.

Approved by the Auckland University of Technology Ethics Committee 28 June 2016, . AUTEC Reference number 16/215.

Appendix 3: Participant Consent Form

Participant Consent Form

AUCKLAND UNIVERSITY OF TECHNOLOGY
TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

Project Title: Warm-up, Re-activation and Neuromuscular Performance

Project Supervisor: *Dr Travis McMaster*

Researcher: ***Shane Crowhen***

○ I have read and understood the information provided about this research project in the Information Sheet dated 1 July, 2016.

○ I have had an opportunity to ask questions and to have them answered.

○ I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.

○ I am not suffering from any current injury or illness that may impair my ability to perform the required tasks nor am I below the age of 16 years.

○ I agree to answer questions and provide physical effort to the best of my ability throughout testing.

○ I agree to take part in this research.

○ I wish to receive a copy of the report from the research (please tick one): Yes○ No○

Participant's signature:

....

Participant's name:

....

Participant's Contact Details (if appropriate):

....
....

Date:

***Approved by the Auckland University of Technology Ethics Committee on 28 June 2016 AUTEC Reference number* 16/215.**

Note: The Participant should retain a copy of this form.

Appendix 4: Participant Assent Form

Participant Assent Form

Project Title: Warm-up, Re-activation and Neuromuscular Performance

Project Supervisor: ***Travis McMaster***

Researcher: ***Shane Crowhen***

- ○ I have read and understood the sheet telling me what will happen in this study and why it is important.
- ○ I have been able to ask questions and to have them answered.
- ○ I understand that while the information is being collected, I can stop being part of this study whenever I want and that it is perfectly ok for me to do this.
- ○ If I stop being part of the study, I understand that all information about me, including the recordings or any part of them that include me, will be destroyed.
- ○ I agree to take part in this research.

Participant's signature:

....

Participant's name:

....

Participant Contact Details (if appropriate):

……………………………………………………………………………………………

Date:

Approved by the Auckland University of Technology Ethics Committee on 28 June 2016 AUTEC Reference number 16/215

Note: The Participant should retain a copy of this form.