

THE INFLUENCE OF A DIRECTIONAL COMPRESSION GARMENT
ON MUSCLE ACTIVITY AND PERFORMANCE
IN RECREATIONAL ALPINE SKIERS

by

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NOMENCLATURE

The following definitions were adopted for this study:

Completion Phase: Established by a shift in pressure from the middle to the tail of the ski. During this phase the knee and hip angles also increase as the skier adopts a more upright stance.

Compression Apparel (traditional): Tight fitting elastic clothing covering the upper or lower body designed to apply compressive force to the tissues.

Concentric Contraction: A contraction in which the force produced shortens the length of the sarcomere.

Directional Compression Apparel: Tight fitting elastic clothing covering the upper or lower body designed with layers of varying elasticity to apply compressive force to specific tissues or muscle groups.

Eccentric Contraction: A contraction in which the force produced increases the length of the sarcomere.

Fall Line: The path a ball would take rolling down the mountain.

Initiation Phase: This phase is marked by force change from the downhill ski to the uphill ski with an increase load on the uphill ski.

Isokinetic Contraction: Any muscular contraction that produces joint motion at a constant velocity.

Isometric Contraction: Any muscular contraction that does not produce a change in sarcomere length.

Isotonic Contraction: Any muscular contraction that occurs at a constant sarcomere tension.

Maximal Voluntary Isometric Contraction (MVIC): The maximal amount of force exerted by a muscle during an isometric contraction as measured by joint torque.

NOMENCLATURE CONTINUED

Median Frequency (MF): The median frequency of the power spectrum of a time-domain signal.

Motor Unit Action Potential (MUAP): Neural Impulse that stimulates a single motor unit of muscle fibers to contract, measured by sEMG in volts.

Muscular Fatigue: The physiological inability of muscle tissue to produce a sufficient amount of force required to sustain a given activity level.

Edge Angle: The angle between the snow and the base of the ski during alpine skiing to produce a given turn radius.

Rating of Perceived Exertion (RPE – BORG Scale): A numeric scale rating how difficult an exertion is for a subject, scaled from 6-20, 6 being no effort at all, and 20 being the absolute hardest you've ever worked.

Root Mean Square (RMS): The mean amplitude of the intensity spectrum of a EMG signal where $RMS = \sqrt{\frac{1}{T} \int_{t=1}^{t+T} EMG(t)^2 dt}$.

Ski Load = A function of mass, velocity and turning radius $F = \frac{mV^2}{r}$

Surface Electromyography (sEMG): Motor unit action potentials (MUAP) measured by electrode attached to the surface of the skin.

Turning Phase: The turning phase during which the skier enters and begins to exit the fall line. During this phase, the skier experiences the highest forces of the turn as they resist gravitational forces at the apex of the turn.

Ski Flexion: The amount of flex the ski must achieve to maintain contact to the snow at a given turning radius and edge angle.

Ski Radius: The radius of turn that the carving turn makes when on-edge angle and ski flexion are maximized.

NOMENCLATURE CONTINUED

Ski Waist Width: The maximum width under the binding at the center of the ski; measured in millimeters.

Turn Apex: The furthest point in the turn from the centerline (fall line) of the turning course.

Turn Radius: The distance from the apex of one turn to the apex of the next measured in meters

Up-unweighting: Occurs when there is slight extension of the ankles, knees, and to facilitate weight transfer from one ski to the other ski.

ABSTRACT

INTRODUCTION Recent studies reported reduced muscle activity in competitive alpine skiers using directional compression (DC). It is not known whether the effects of DC are limited to competitive skiers, or if similar changes would be observed in recreational skiers during a full day of skiing. The purpose of this study was to examine changes in hip and leg muscle EMG patterns in recreational alpine skiers when skiing with and without a lower body DC garment. **METHODS** 11 intermediate and expert skiers volunteered for this study. Subjects completed 2 randomized trials, one in a DC garment, and one in a non-compressive (NC) base layer. EMG of the *gluteus medius* (GMED), *gluteus maximus* (GMAX), *rectus femoris* (RF), *adductor longus* (ADL), and *vastus lateralis* (VL) were recorded using EMG during three measurement runs with standardized turns on each visit. Standardized turns were used to compare EMG response between conditions and measurement runs. Subjects also completed self-paced skiing bouts (SP) between measurement runs. Skiing performance (heart rate, velocity, and skiing load (vertical/runs) were measured during the SP bouts. 2x3 repeated measures ANOVA's was used to compare kinematic and EMG changes during measurement runs, as well as performance during self-paced skiing between ($p \leq 0.05$). **RESULTS** Subjects skied more runs (DC 18.60 ± 0.98 , NC 13.55 ± 1.06 , $p = 0.001$) and vertical (DC 4805.31 ± 304.31 m, NC 2373.56 ± 219.60 m, $p = 0.001$) during free skiing with DC than NC. Heart rate and ski velocity were not different between SP bouts. Peak edge angle was lower in the DC treatment (DC $55.06 \pm 10.70^\circ$, NC $57.90 \pm 9.10^\circ$, $p = 0.008$). Absolute muscle activity was lower in the DC condition for all muscles ($p \leq 0.05$), although no differences were observed in relative muscle activity. **CONCLUSIONS** No differences in relative muscle activity were detected, absolute muscle activity was lower in the DC condition. Subjects improved their self-paced skiing performance in the DC condition. There was also a trend towards lower RMS for all muscles in the DC treatment. Further research should investigate the influence of DC garments on repeated bouts of recreational alpine skiing on consecutive days.

CHAPTER ONE

INTRODUCTION

Development of Problem

The origins of skiing can be traced back 3,000-4,000 years to Scandinavia and other Northern European nations, where it was primarily used as a mode of transportation (Karlsson, 1984). Technological advances made in the early part of the 20th century allowed skiers to not only ski cross-country, but downhill as well. These advances made downhill, or alpine skiing, a popular pastime in nations such as Austria and Switzerland, which are considered the cradle of modern alpine skiing. Alongside competitive alpine skiing, recreational alpine skiing has become a popular winter sport (Karlsson, 1984).

As ski racing has become more popular, the bulk of the research literature has focused on the biomechanical and physiological demands of ski racing, and techniques to maximize performance. Recently, as recreational skiing has become more popular, researchers have shifted their efforts to recreational alpine skiers. Over 9 million people in the United States participated in alpine skiing in 2014 / 2015, up 4.1% from 2013 / 2014 (Ski Industry America, 2015). An emerging area of research is changes in muscle activation and movement patterns associated with prolonged alpine skiing (Kröll, Müller, Seifert, & Wakeling, 2011). As skiing duration increases, alpine skiers tend to shift their skiing technique away from the carving technique towards the parallel ski steering technique (Kröll et al, 2011). While the kinematics of these two techniques are similar, there is a dramatic shift in relative EMG intensity from bilateral loading of both the

inside and outside leg towards unilateral loading of just the outside leg. These changes are especially prominent in the rectus femoris and vastus lateralis (Kröll et al, 2011). Due to the self-steering properties of the modern carving ski, shifting the load towards one ski increases the risk of “over-edging” a primary risk factor for knee injuries in alpine skiing (Hunter, 1999). Given the positive relationship between skiing duration and injury risk (Meyers et al., 2007), this shift towards the parallel ski steering technique could be the underlying mechanism for increased injury risk during prolonged alpine skiing in recreational alpine skiers.

Recently, the use of compression apparel in competitive and recreational sport has become increasingly popular. There is an abundance of literature documenting the effects of compression on muscle activity, however the exact mechanism(s) by which compression apparel improves performance is not clear (Fu, Liu, & Fang, 2013; Perrey, 2008). Compression apparel has been called a “second level of human skin” by researchers due to similarities such as compression of the underlying tissues and moisture wicking (Fu et al., 2013). The mechanisms by which compression garments might alter performance have yet to be elucidated however.

It has been proposed that compression apparel attenuates fatigue related changes in motor unit recruitment (RMS), (Wang, Xia, & Fu, 2016). Further, recent studies using directional compression tights in comparison to traditional compression in alpine skiers noted decreased RMS in competitive alpine skiers when directional compression garments were worn (Simons et al, 2016). A related study found that competitive alpine skiers used a more effective skiing style; bi-lateral loading, more anterior center of

pressure, decreased vGRF, while wearing a directional compression garment (Decker et al, 2016). This series of studies was conducted in competitive alpine skiers, it is not yet known how directional compression influences muscle activity or skiing performance in recreational alpine skiers.

Purpose

The purpose of this study is to evaluate the influence of a directional compression garment on muscle activity and performance in recreational alpine skiers.

Hypothesis

It is hypothesized that in the directional compression condition, subjects will complete a larger volume of skiing, maintain a more effective skiing style (carving turns vs. parallel ski steering turns) and experience smaller changes in muscle activity over the course of the day.

- $H_0: \Delta_{NC} = \Delta_{DC}$
- $H_{A1}: \Delta_{NC} < \Delta_{DC} - \text{Vertical, Runs}$
- $H_{A2}: \Delta_{NC} > \Delta_{DC} - \text{Edge Angle, Turn Time, RMS}$

Where Δ_{NC} is the average for dependent variables in the non-compression condition and Δ_{DC} is the average for dependent variables for the directional compression condition.

Limitations

The results of this study are only applicable to recreational alpine skiers. Given funding restrictions, we are not able to compare the effect of directional and traditional compression garments. Data was collected on separate days throughout the winter for each subject, and snow conditions varied between subjects and testing conditions despite the best efforts of researchers to control for weather variations. Since this study was conducted while the ski resort was open to the public, variation in the lift lines and non-skiing time could have varied between subjects and testing conditions. Finally, the results of this study depended on the subject's ability to follow instructions.

Delimitations

Researchers conducted measurement runs on the same slope with similar course sets for each participant in each condition. Subjects were limited to non-hiking terrain accessed by the Bridger, Pierre's Knob, and Alpine chairlifts at the Bridger Bowl Ski Area. Researchers recorded the run selection and order skied in the first visit, and subjects used that record to guide run order and selection during the second visit. Subjects were given at least seventy-two hours between testing conditions to allow for any delayed onset muscle soreness accumulated by the first session to be resolved before the second session. Subjects consumed similar diets on both days of testing, as well as 24 hours prior to testing, with lunch provided by the researchers on the day of testing. Subjects refrained from consuming alcoholic or caffeinated beverages prior to testing.

CHAPTER TWO

REVIEW OF REATED LITERATURE

Turning Technique in Alpine Skiing

Many researchers have investigated both slalom, characterized by a short turning radius (≤ 12 meters) and low horizontal offset (≤ 4 meters), and giant slalom, characterized by longer radius turns (20-26 meters) with greater horizontal offset (4-6 meters) style turns (Berg & Eiken, 1999; Hintermeister et al., 1995; Hintermeister, Oconnor, Lange, Dillman, & Steadman, 1997; Tesch, Larsson, Eriksson, & Karlsson, 1978). While there are many differences between the two techniques, they share common fundamentals. Early work defined the phases of each style turn, and the muscle activity associated with each (Hintermeister et al., 1995). This study described two distinct phases for slalom turns, and an additional third phase for giant slalom turns. Those authors described common initiation and turning phase for both styles. Muscle activity in both phases can reach above 100% MVIC in both slalom and giant slalom turns due to the high gravitational and resistive forces as the skiers move their center of mass into the fall line of the run. All turn phases were dominated by low-velocity, eccentric and isometric contractions as defined by joint angles, indicating a quasi-static component to alpine skiing (Hintermeister et al., 1995). During slalom and giant slalom skiing, knee joint range of motion is about 30° for the outside leg and 40° for the inside leg (Müller & Schwameder, 2003). In giant slalom, those authors described a third phase, completion,

where the subjects propelled themselves across the fall line into the initiation of the next turn.

Further investigations differentiated the parallel technique investigated by Hintermeister et al (1995), and the modern carving technique utilized by alpine skiers today (Müller & Schwameder, 2003). These researchers further divided the carving turn into four phases for both slalom and giant slalom: initiation, steering, completion, and up-unweighting (Müller & Schwameder, 2003). The initiation phase is marked by force change from the downhill ski to the uphill ski with an increase load on the uphill ski (Müller & Schwameder, 2003). During the steering phase of the turn, the radius of the ski carries the skier into the fall line. Gravitational forces increase during this phase until peaking at the apex of the turn (Müller & Schwameder, 2003). Using the parallel technique, this load is mostly distributed on the outside leg, however, using the carving technique, an increased co-loading of the inside leg during has been reported (Kröll et al., 2010). As the skier begins to exit the fall line, the completion phase is established by a shift in pressure from the middle to the tail of the ski. During this phase, the knee and hip angles also increase as the skier adopts a more upright stance. Lastly, the up-unweighting phase as the skier shifts their weight from the outside to the inside leg as the inside edge becomes the outside edge in the new turn. The carving turn can be further differentiated from the parallel turn by the length of the phases. During the carving turn, the turning phase is shorter, while the initiation and completion phases are longer than during the parallel turns (Müller & Schwameder, 2003).

Muscle Control in Alpine Skiing

Skiers utilize a large volume of muscle mass to execute each phase of the turn. Alpine skiing is dominated by eccentric and isometric contractions, defined by joint angles to resist the forces generated by vertical and horizontal displacement of the center of mass in relation to the fall line (Berg & Eiken, 1999; Berg, Eiken, Tesch, 1995). The force required to complete a turn is related to the mass of the skier, the velocity of the skier, and the radius of the turn they are completing. Skiing load can therefore be represented by the formula for centripetal force:

$$F = \frac{mV^2}{r}$$

Where F is the force generated by the turn, m is the mass of the skier, V is the velocity of the skier, and r is the turn radius. During skiing, the skier must produce enough force to resist this force during every turn.

Previous studies conducted using the parallel turning technique observed greater contributions of the knee extensor muscles of the outside leg during the turning phase (Hintermeister et al., 1995). Using the more modern carving technique, specifically the rectus femoris is active at a high intensity during multiple loading situations with the measurement leg active both as the inside and outside leg during alpine skiing (Kröll, Wakeling, Seifert, & Müller, 2010; Müller & Schwameder, 2003). The intensity of contraction is also dependent upon the slope or intensity of skiing. At greater slope angles, the EMG intensity was greater for both rectus femoris and vastus lateralis

muscles. In contrast, the biphasic contribution of the rectus femoris muscle during inside and outside turns is evident in both techniques (Kröll et al., 2010). Although the intensity of contraction in the rectus femoris muscle is similar in both the inside and outside leg, the median frequency appears to be higher during the outside turn (Kröll et al., 2010). Kröll et al. noted that the situational dependent loading of the rectus femoris of the inside leg could be a crucial point of fatigue during a full day of skiing (Kröll et al., 2010).

Fatigue in Alpine Skiing

During alpine skiing, the knee and hip flexor and extensor muscle groups are activated at a relatively high intensity. Over the course of an entire day of alpine skiing, it is probable that these muscle groups would be susceptible to fatigue (Kröll et al., 2011). Mechanical muscle damage could alter coordination patterns and force production capability due to the physical separation of myosin cross bridges and actin myofilaments during eccentric contractions. Previous studies have noted that alpine skiing is dominated by eccentric contractions (Berg et al 1995, 1999). Over the course of a day of skiing, and thousands of contractions, it is reasonable to believe that alpine skiers may experience some level of muscle damage. Previous studies found a 93% increase in creatine kinase after prolonged skiing (Berg & Eiken, 1999; Berg, Eiken, Tesch, 1995), indicating high levels of muscular damage. Creatine kinase is a muscular enzyme that leaks into the blood stream when muscles are damaged, such as after prolonged alpine skiing (Seifert, Kröll, & Müller, 2009; Seifert, Kipp, Amann, & Gazal, 2005).

Alpine skiers may also encounter mechanisms of physiologic fatigue such as

decreased substrate availability (glycogen), and altered ion concentration (hydrogen ions, lactate) (Andersen & Montgomery, 1988). Alpine skiing has been shown to significantly deplete muscle glycogen stores of both slow and fast twitch fibers (Tesch et al., 1978). Prolonged isometric and eccentric contractions may also occlude blood flow to the muscles, increasing the reliance on anaerobic metabolism, increasing the lactate concentration and decreasing the pH of skeletal muscle (Andersen & Montgomery, 1988). These factors contribute to skeletal muscle damage and may contribute to the pattern of increased injury rates towards the end of a skiing day (Hunter, 1999, Meyers et al. 2007).

Prolonged alpine skiing has also been shown to influence muscle activation. Multiple studies have shown found that after prolonged skiing sessions, the intensity relative EMG intensity shifts towards lower intensities during the turning phase, and higher intensities in the completion phase (Kröll et al., 2010, 2011). This shift is most apparent during the completion phase, where ground reaction forces reach their peak (Kröll et al., 2011; Kröll et al., 2005). Although significant for both the inside and outside leg, the greatest effects can be observed in the rectus femoris and vastus lateralis on the outside leg. This shift in intensity indicates that skiers are trending towards the parallel technique rather than the carving technique. While both techniques are effective, when utilizing the parallel technique with carving skis, alpine skiers are at an increased risk for injury (Kröll et al. 2011, Hunter et al., 1999).

Electromyography

Electromyography (EMG) measures muscle activity via motor unit action potentials (MUAP) (De Luca, 1997). Impulses travel down motor neurons, eventually depolarizing (activating) a motor unit. These electrical differentials at the muscle can be measured using surface EMG (sEMG). Raw EMG signals are sinusoidal waves representing the cumulative activity of all motor units within the measurement range of that electrode. By observing the amplitude and frequency characteristics of these waves, it is possible to make observations of the activation properties of the muscle.

The amplitude characteristics of a muscle are commonly analyzed using a root mean square calculation (RMS). Root Mean Square is a method of full wave rectification that takes all of the values within a certain window, squares them to remove the sign, averages the squared values, and takes the square-root of those values to retain the original amplitude. These windows are usually very short in length and have some overlap to smooth values (De Luca, 1997). Previous literature have suggested window lengths between 50 and 125 ms, with overlaps between 25 and 50 ms (De Luca, 1999). Root Mean Square provides a time sensitive measures of the volume of motor units active (De Luca, 1997). As muscles fatigue, more motor units will be recruited to meet the force production demands of the given task (De Luca, 1997).

Surface EMG is best utilized during static or quasi-static contractions, as changes in the force-velocity, or force-length relationship of muscle fibers can alter electromyographic signals independent of changes in recruitment patterns (Robertson et al. 2014).

To assess the frequency characteristics of an EMG signal, the signal must be converted from the time domain to the frequency domain. This is done using a Fourier transformation (FFT). The FFT calculates how much (power) of the signal is made up by each frequency contained within the signal. The relationship between frequency and power is called the power spectrum. Median frequency is a metric commonly utilized to represent the power spectrum. The median frequency is the frequency at which the power is evenly distributed about (Robertson et al., 2014).

The frequency content of a signal is positively related to conduction velocity along the fibers (Wakeling, 2009). While type II muscle fibers do exhibit higher conduction velocities, inherent limitations to EMG such as muscle-electrode distance, subcutaneous adipose tissue volume, and fiber type distribution, make it difficult to draw conclusions about fiber type recruitment from analysis of median frequency (Robertson et al., 2014). However, median frequency still provides basic information about the qualities of motor units being recruited, and changes in recruitment strategies that might accompany a change in task (Wakeling, 2004).

Compression Garments

Early research on compression apparel investigated the effects of compression garments on patients with compromised venous function as a method of increasing venous valve function, venous velocity and venous return. It has been proposed that compression garments cause the shunting of blood flow from superficial veins towards deep veins (Perrey, 2008). Recently, researchers have expanded their interest from

clinical uses towards the use of compression apparel in sports and exercise. Research has focused on the influence of compression apparel on strength, changes in muscle function, and how compression can influence mechanisms associated with fatigue (Fu et al., 2013).

Some of the first researchers into compression apparel investigated the potential for compression garments to reduce soft tissue vibrations associated with dynamic movements (muscle oscillation) (Doan et al., 2003). That study found that those wearing compression apparel experienced significantly reduced muscle oscillation in both the longitudinal and anterior-posterior directions after a step-down jump compared to those not wearing compression apparel. Reduced muscle oscillation reduces muscle tuning, or the muscle activity that contributes to resisting or controlling these movements. It would be expected that decreased muscle oscillation would result in decreased EMG amplitude. Over time, this could have a significant positive effect on muscle activity during fatiguing contractions. These authors also discovered increased skin temperature in the compression condition. To a certain extent, increased muscle temperature is associated with optimal muscle function (Åstrand, 1977). The authors also proposed that the garment might have aided eccentric muscle contractions, via reduced oscillation, at the limits of range of motion in the knee and hip, which could help prevent injury (Doan et al., 2003).

Coza et al (2008) conducted a study to investigate the effects of compression apparel on muscle tissue oxygenation. This study investigated tissue oxygenation of the calf muscles (gastrocnemius medialis) during short-term (two minutes) dynamic exercise. In general, during the beginning of exercise, tissue oxygenation decreases rapidly

followed by a gradual recovery (increase) in tissue oxygenation. That study found the slope of curve of tissue oxygenation recovery was greater in the compression condition. In addition, the slope of the tissue de-oxygenation curve during the beginning of exercise was smaller in the compression condition. Subjects in the compression experienced faster tissue re-oxygenation, potentially indicating performance benefits. Although differences in oxygen consumption were not observed, increasing the supply of oxygen to muscle during the first two minutes of exercise, when the demand is far greater than supply, could improve muscle function (Coza et al, 2012).

Others have investigated the effect of different levels of compression on muscular fatigue. They found that although compression garments did not acutely influence torque production, they did attenuate decrements in torque production after the fatiguing sets of calf raises. While they did not observe any significant changes in EMG amplitude (RMS), there was a trend towards decreasing frequency with greater compression. They also observed a reduction in mean power frequency after the exercise. This effect was greater in the higher compression conditions. These results indicate that there may be a positive relationship between level of compression and the degree to which compression influences muscle activity. (Miyamoto, Hirata, Mitsukawa, Yanai, & Kawakami, 2011).

In a second study by Miyamoto et al (2014) the authors took a closer look at the effect of compression garments on fatigue. Using magnetic resonance imaging, they noted that after submaximal treadmill running, subjects displayed lower markers of fatigue in the compression condition. They proposed that this observation is most likely related to improved peripheral circulation and higher intervascular pressure gradients of

metabolites such as lactate, hydrogen ions, and free phosphates due to compression. These observations may explain the changes in muscle activation that the authors observed in their previous study (Miyamoto & Kawakami, 2014).

Fu et al (2012) investigated the effects of compression on strength and EMG in the lower extremity. Contrary to previous studies, this study employed 25 maximal isokinetic contractions at 60 and 300°/s rather than more natural movement patterns such as calf-raises or running. While no differences in force production (peak torque, peak power, average power, total work, regression of torque) were observed between compression conditions, there was a trend for higher peak torque and reduced regression of torque in higher compression conditions. Additionally, EMG amplitude (RMS) decreased significantly in the compression condition at both velocities. In conjunction with the similar torque values reported in each condition, this result indicates more efficient contraction in the compression condition. This may be beneficial for long duration exercises. Additionally, during the 60 °/sec trial, EMG mean frequency was significantly higher in the compression condition, indicative of increased conduction velocity in the compression condition (Fu, Liu, Zhang, Xiong, & Wei, 2012).

These results are supported by Zhang et al (2016). Using a similar study design, they found that while there were no differences in force production and work between control and compression garment, work fatigue was significantly lower in the compression condition at 60°/s. They also found EMG amplitude to be significantly lower for rectus femoris, vastus medialis, and vastus lateralis at both testing velocities. Although mean frequency did not change at 300°/s, it was significantly elevated during

the slower 60°/s trial. (Zhang, Fu, Xia, & Wang, 2016). These results indicate that compression apparel might be most effective in activities that occur at lower angular velocities, such as recreational alpine skiing.

Wang et al (2016) also investigated changes in muscle activation and force production in compression apparel at various angular velocities. They found that at both 60 and 300°/s, EMG amplitude was significantly lower in the compression condition as compared to the control condition despite no difference in strength force production. They also observed significantly higher mean frequency in both the rectus femoris and vastus lateralis in the compression condition at 60°/s (Wang et al., 2016). These results indicate that low velocity contractions, such as those found in recreational alpine skiing may benefit more from the use of compression apparel.

Coza and Nigg (2008) investigated the vibration dampening properties of compression apparel during treadmill running. They found that compression garments provided improved muscle oscillation dampening when compared to the control condition. In addition to the changes observed in dampening coefficient, they also noted a decrease in normalized EMG pre-activation and post-activation indicated improved contractile efficiency (Coza & Nigg, 2008).

Directional Compression Garments

Recently the use of directional compression garments has gained popularity, despite there being extremely limited data to support their use to improve sports performance (Fu et al., 2013). Laboratory studies found decreased muscle activity

(RMS) during run and cut maneuvers in hockey athletes when compared to traditional or no compression conditions (Chaudhari, Jamison, McNally, Pan, & Schmitt, 2014). These studies have also noted that directional compression garments may improve proprioception as kinematic variability is decreased. Recently, a novel directional compression garment has recently been investigated specifically for use in alpine skiing. A recent series of studies by Decker and Simons (Simons et al, 2016; Decker et al, 2016) conducted among competitive alpine skiers found significant changes in muscle activation and kinematics that indicate directional compression may be more beneficial than traditional compression garments (Simons et al, 2016; Decker et al, 2016). These studies observed decreased ground reaction force and improved dynamic balance among those wearing directional compression garments (Decker et al, 2016). These changes point towards a more effective skiing style. They also noted increased knee and hip flexion, and decreased muscle activation during turning among competitive alpine skiers. In conjunction with the improved ski technique noted above, these changes could point towards improved fatigue resistance in alpine skiers using directional compression garments (Simons et al, 2016).

Conclusion

Skiers tend to alter movement patterns before they are in a clinically fatigued state. Altered movement patterns could be a potential mechanism for injury. The use of directional compression garments may prevent changes in technique that result from

altered motor unit recruitment strategies. Directional compression apparel also appears to be most effective in movements that require high-force, low velocity contractions, such as those required by recreational alpine skiing. Additionally, recreational alpine skiers routinely encounter both cold environments and vibrations during skiing that could inhibit contractile effectiveness. The unique physiological and biomechanical demands of recreational alpine skiing put skiers at risk for injury as they change their movement patterns to adapt to external loads. Directional compression tights could prove useful in resisting the changes in muscle activation that lead to altered movement patterns.

CHAPTER THREE

THE INFLUENCE OF A DIRECTIONAL COMPRESSION GARMENT ON MUSCLE ACTIVITY AND PERFORMANCE IN RECREATIONAL ALPINE SKIERS

Contribution of Authors and Co-Authors

Manuscript in Chapter 3

Author: Cory James Snyder

Contributions: Primary investigator and developer of study methodology, directed data collection, processed and analyzed data, developed conclusions, and authored the manuscript.

Co-Authors: John G. Seifert

Contributions: Dr. Seifert assisted with development of study methodology, assisted in data collection, reviewed manuscript, aided in the development of conclusions.

Co-Authors: James Becker

Contributions: Dr. Becker reviewed the study design and recommended changes; assisted in data analysis and processing, reviewed and recommended changes to manuscript.

Co-Authors: Ed Adams

Contributions: Dr. Ed Adams reviewed the study design, reviewed and recommended changes to the manuscript.

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Taylor and Francis

Introduction

The use of compression garments as an ergogenic aid in sports has becoming increasingly popular (Fu et al., 2013). A bulk of that research has investigated the influence of compression garments on muscle activity and performance. Recently, studies have shown that compression garments may reduce muscle activity during both static and dynamic tasks (Chaudhari et al., 2014, Coza and Nigg., 2008, Fu et al., 2011, Kerherve et al., 2017, Li et al., 2011, Miyamoto et al., 2010, Wang et al., 2016, Zhang et al., 2016). Although the mechanism by which compression garment influence muscle activity or performance has yet to be elucidated.

As textile and clothing design has improved, directional compression (DC) garments have become increasingly popular. Where traditional compression garments apply compression uniformly to the underlying tissues, DC garments are constructed of separate panels of material with different elastic properties (Fu et al., 2013). These garments apply greater compression to specific underlying tissues, while minimizing compression in areas where it might not be as importance. Recently a DC garment was designed specifically for use in alpine skiing (Opedix Knee-Tec 2.0, Opedix, Denver, CO, USA). Recently, this garment has been studied in competitive alpine skiers during a simulated training session (repeated runs). This study found that when compared to traditional compression garments, skiers experienced reduced muscle activity in muscles of the thigh and hip during competitive ski training (Simons et al., 2016). The same group demonstrated that skiers utilize a more effective turning technique, shifting their center of pressure more anteriorly and medially (Decker et al. 2016). By shifting their

center of pressure closer to the edge of the ski, these skiers improved the coupling of the ski and snow, likely improving the effectiveness of any force applied to the ski. The results indicate that the use of DC garments could potentially improve the quality of skiing in competitive alpine skiers. However, it is not known if these results will also be applicable to recreational alpine skiers.

During a normal day of recreational alpine skiers, a skier could expect to complete thousands of contractions, and exercise for up to three hours at a relatively high intensity, and as such are susceptible to some level of fatigue (Tesch et al., 1978, Turnbull et al., 2009). Alpine skiers are likely to experience muscular fatigues as modern alpine skiing is dominated by eccentric contractions (Müller and Schwameder, 2003, Seifert et al., 2005). Recent studies have shown that muscle activity changes before major changes in technique occurs, which could be a mechanism for injury (Kröll et al., 2011). This study found that after prolonged skiing sessions, the intensity relative EMG intensity in the muscles of the quadriceps shifts towards lower intensities during the turning phase, and higher intensities in the completion phase (Kröll et al., 2010, 2011). This shift is most apparent during the completion phase, where ground reaction forces reach their peak (Kröll et al., 2011; Kröll et al., 2005).

Although significant for both the inside and outside leg, the greatest effects of prolonged alpine skiing can be observed in the rectus femoris and vastus lateralis on the outside leg. The shift towards lower intensities of the rectus femoris on the inside leg indicates that skiers are not loading the skis bi-laterally, while the shift towards higher intensities during the completion phase of the turn in the vastus lateralis of the outside leg

indicates a greater reliance on unilateral loading of the outside ski. These shifts in intensity are indicative of a shift towards the parallel ski steering technique and away from the carving technique. While both techniques are effective, when utilizing the parallel technique with modern carving skis, alpine skiers are at an increased risk for injury (Kröll et al. 2011, Hunter et al., 1999). Preventing or prolonging shifts towards parallel ski steering technique and maintaining bi-lateral loading of both the inside and outside ski could be beneficial in lowering injury risk and increasing value perception in recreational alpine skiers.

Therefore, the purpose of this study was to investigate the influence of a directional compression garment on muscle activity and performance variables in recreational alpine skiers. It was hypothesized that in the directional compression condition, subjects would complete a larger volume of skiing, maintain a more effective skiing style, and experience smaller changes in muscle activity during a day of simulated recreational alpine skiing.

Methodology

Informed Consent

Prior to testing all subjects were asked to read and sign an Informed Consent approved by the Montana State University Institutional Review Board. Study procedures were verbally explained to each subject, and subjects had an opportunity to ask questions about the study procedures or informed consent before entering the study. If subjects

wished to withdraw from this study, they were free to do so at any time. All subject data was coded, and both data and codebook were stored on a password-protected computer.

Subjects

The population for this study was recreational alpine skiers. Using a purposive sampling method, subjects were selected from the sampling frame of recreational level alpine skiers living in or near Bozeman, Montana (N=11, Table 3.1). Potential subjects were recruited to participate in this study by the primary investigator. To qualify for this study, subjects were able to meet the standards of expert or high intermediate skiers as defined by the Professional Ski Instructors of America (PSIA) and without recent major musculoskeletal injury or illness. These skiers were able to execute long and short radius carved turns on easy and moderate terrain, and long and short radius parallel steering turns on more difficult terrain.

Table 3.1 – Subject Data

	Age (years)	Height (m)	Weight (kg)	Ski Experience (years)
Mean ± SD	33.18 ± 16.58	1.73 ± 0.08	71.26 ± 12.5	15.45 ± 18.16

Design

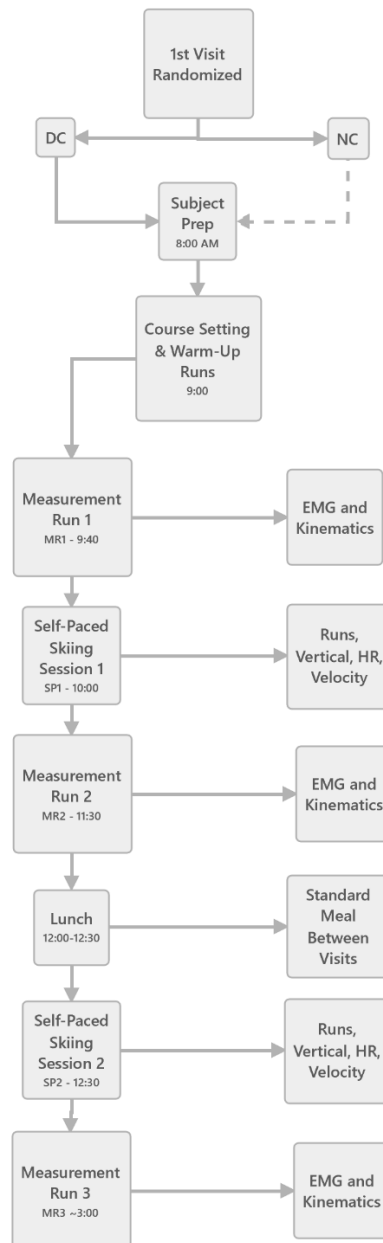
Subjects that consented to participation reported to the Bridger Bowl Ski Area (Bozeman, MT) for two days of testing. Subjects completed two randomized trials, one in directional compression garment (DC) (Knee-Tec 2.0, Opedix, Denver, CO, USA), and one in non-compression control garment (NC) of the subject's preference. Each visit consisted of three measurement runs, and two self-paced skiing sessions. Measurement

run 1 (MR1) and measurement run 2 (MR2) took place at approximately 9:45 and 11:30, while measurement run 3 (MR3) took place when the subject reported that they felt like they could complete 1 or 2 more runs. Measurement runs were immediately repeated if the subject fell or failed to complete the measurement run in a satisfactory manner. Prior to MR1, subjects completed 1-2 warm-up runs on a trail adjacent to the measurement run trail with similar vertical drop and slope profile. The first self-paced skiing session (SP1) occurred between MR1 and MR2. The second self-paced skiing session (SP2) occurred between lunch (after MR2) and MR3. During the SP1 and SP2 sessions, subjects skied at a self-selected intensity on lift accessed terrain at Bridger Bowl excluding the Schlassman's lift. Subjects were prohibited from selecting any terrain that required hiking or excessive poling or skating to return to the lift. Run selection and order was recorded to guide run selection on the subsequent visit. If the subject was unable to replicate SP1 or SP2 before a time limit was reached, or the subject felt they had 1-2 runs left, the skiing session was terminated and the subsequent measurement run was recorded. If the subject replicated SP1 or SP2 and had not yet reached the time limit or felt they had more than 1-2 runs left, subjects repeated laps on the warm-up slope until either of those criteria had been met. Subjects were provided a standardized meal between MR2 and the SP2. This design was intended to replicate a normal day of recreational alpine skiing (Figure 3.1).

Prior to each visit, subjects were asked to consume a normal lunch and dinner before testing, as well as refrain from caffeine and alcohol consumption 24 hours prior to testing. Subjects were also asked to refrain from physical activity for 24 hours prior to

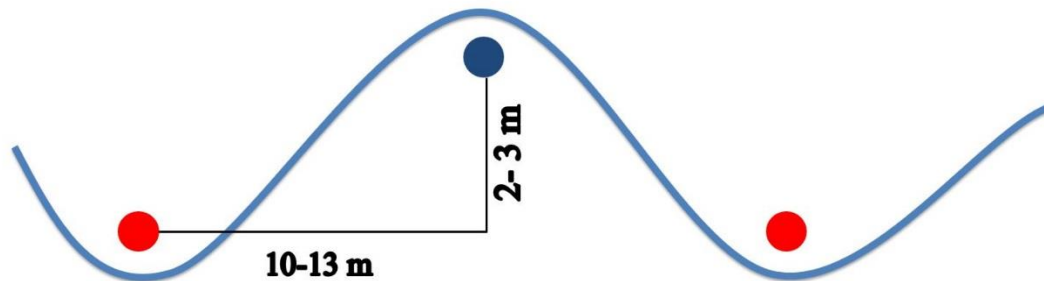
each visit. Subjects reported to the Saddle Peak Lodge at Bridger Bowl by 8:00AM for each visit having eaten breakfast but refrained from caffeine consumption.

Figure 3.1 – Study design and workflow



The primary investigator prepared the subject, while a second investigator prepared the measurement slope. Measurement runs took place on the “Hanton’s Hollow” trail, which has a grade of 20-28°. One subject completed all measurement runs on a separate slope with a similar slope profile. Brush gates were set with 12-13 meters of vertical distance with 2-3 meters of horizontal offset to define standardized measurement turns (Figure 3.1). Measurement run courses were set at variable offsets due to limitations on hill space, and to minimized double fall line sets. All courses were measured and set by two course setters. When possible, course setters worked together to minimize inter-setter variation.

Figure 3.2 Course setting diagram.



Measurements

Heart Rate and GPS Wireless heart rate & GPS monitors (Polar Electro, Kempele, Finland) were worn during the entire visit to record heart rate in beats per minute (BPM) and ski route. Monitors were worn around the chest at the base of the sternum, underneath clothing and directly against the skin. Watches were worn on the subjects’ wrists and recorded distance skied (m), and average

velocity $m \cdot s^{-1}$ during SP1 and SP2. Measurement runs were not included in SP1 or SP2. Heart Rate and GPS measurements were recorded at 1 Hz.

Kinematics Inertial Measurement Units (IMU) (Electronic Realization, Bozeman, MT, USA) were mounted to the posterior of the right boot. The IMU's recorded 3-dimensional accelerations and angular velocities at 100 Hz during each measurement trial.

Electromyography Data acquisition took place unilaterally on the right leg. Myoelectric activity of the *gluteus medius* (GMED), *gluteus maximus* (GMAX) *rectus femoris* (RF), *adductor longus* (ADL), and *vastus lateralis* (VL) muscles was measured using 4 -bar bipolar Ag/AgCl electrodes (5x1mm electrodes, 5mm interelectrode spacing, CMMR >80dB at 60Hz, 16 bit A/D conversion, Gain=300, 2 mΩ input impedance, Trigno IM, Delsys INC, Natick, MA, USA). Electrodes were placed over the belly of the muscle in line with the pennation angle of the fibers at the midpoint of the muscle origin and myotendinous junction according to SENIAM recommendations (Hermens et al, 2000). Analog EMG signals were amplified at the source and recorded at 1926 Hz (Tringo Personal Activity Monitor, Delsys INC, MA, USA,).

Data Processing

Heart Rate and GPS Self-paced skiing session runs were identified using hybrid plots of elevation and velocity. The start of each run was identified as the time point where elevation began to decrease, and velocity began to increase. The end of each run was identified as the time point where elevation began to reach a

minimum plateau, and velocity approached zero. Relative peak heart rate (HR_{peak}) was measured during each skiing session as a percent of maximum heart rate ($HR_{max}=220-Age$). Relative average heart rate (HR_{mean}) was measured across all runs during each skiing session as a percent of maximum heart rate ($HR_{max}=220-Age$).

Peak velocity (V_{peak}) was measured each skiing session in meters per second ($m \cdot s^{-1}$). Average velocity (V_{mean}) was measured across all runs during each skiing session in meters per second ($m \cdot s^{-1}$).

Kinematics Instantaneous edge angle was calculated as the cumulative integral of z-axis (anterior/posterior) angular velocities. Peak edge angle (EA_{peak}) was visually identified as the peak edge angle during each turn in degrees. Angular drift was corrected using a linear detrend function ($R^2=0.8759$), and zero-crossings between EA_{peak} were used to identify turn switches, or the time point where the right ski was approximately flat between turns. The first and last turns were dropped from the analysis such that ten consecutive turns were included in all kinematic and EMG analysis beginning with the second right foot turn and ending with the second-to-last left foot turn. The first and last turns were dropped to only include turns when subjects were completing normal skiing movements, not accelerating into the course, or taking a lax line selection at the end of the course. Turn time (TT) was calculated as the time between midpoints.

Electromyography EMG signals were filtered using a zero-phase 4th order bandpass digital Butterworth filter with a low-end cutoff of 20 Hz and a high-end cutoff of 400 Hz. Cutoff frequencies were determined using a residual analysis such that 95%

of signal power was retained. Each measurement run was divided into single turns using the midpoints identified using edge angles and normalized to 100% of turn duration using a spline interpolation. Each turn was then divided into windows of 10% normalized turn duration. Right and left turns were combined to create 20 windows defining each double-turn cycle, however these windows were not included in the statistical analysis. Filtered and cropped signals were full wave rectified and smoothed using a root mean square function with a 50 ms window length and 25 ms window overlap (RMS, mV). Median frequency (MF, Hz) was calculated using an FFT to resolve the signal into the frequency domain. Median frequency was then calculated as the frequency about which the signal power was equally distributed. Relative EMG response was calculated for RMS and MF as percent of MR1.

$$MR2 = \frac{MR2}{MR1} \cdot 100$$

$$MR3 = \frac{MR3}{MR1} \cdot 100$$

Root mean square, median frequency, and relative EMG response were calculated for each turn. Each subject in each condition in each treatment was therefore represent by 10 individual turns. All kinematic and EMG calculations were done using custom scripts in MATLAB (Mathworks, Natick, MA, USA).

Statistics

A 2x3 repeated measures ANOVA was used to determine interactions in SP1, SP2 and SP_{total} performance, and between the DC and NC conditions. If significant interactions were detected, Bonferroni post-hoc tests were employed to

determine significance. A separate 2x3 repeated measures ANOVA was used to determine interactions measurement run performance (MR1, MR2, MR3) between conditions (DC, NC). If significant interactions were detected, Bonferroni post-hoc tests were employed to determine significance. To control for differences in vertical skied between conditions, a 2 by 3 repeated measures ANCOVA was used to determine interactions in measurement run performance while accounting for vertical skied. If significant interactions were detected, Bonferroni post-hoc test were employed to determine significance. Significance was set a $p \leq 0.05$ for all tests.

Results

One subject was excluded from analysis due to non-physiologic EMG response, which led to a sample size reduction from 11 to 10 subjects

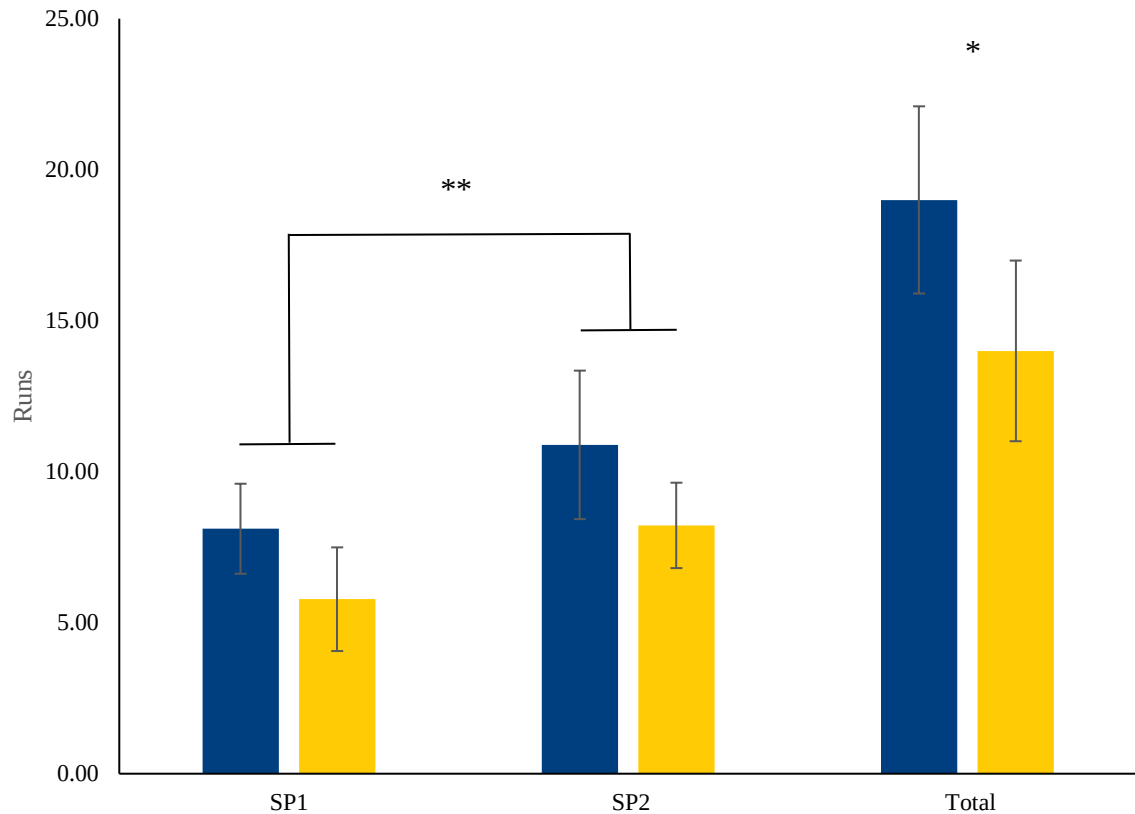
Self-Paced Skiing

Runs No significant condition by time interaction was observed for number of runs during the self-paced skiing sessions ($p=0.820$). However, significant main effects of condition ($p=0.001$) and time ($p=0.001$) were observed. Subjects completed more runs in the DC condition (19 ± 3) than the NC condition (14 ± 3) (Figure 3.2). Subjects skied more runs in the SP2 session (9 ± 2) than the SP1 Session (7 ± 1) (Figure 3.3).

Figure 3.3 – Mean and standard deviation of runs skied in the DC (blue) and NC (gold) conditions during SP1, SP2 and Total self-paced skiing sessions.

* indicates significant main effect of condition at $p < 0.05$.

** indicates significant main effect of time at $p < 0.05$

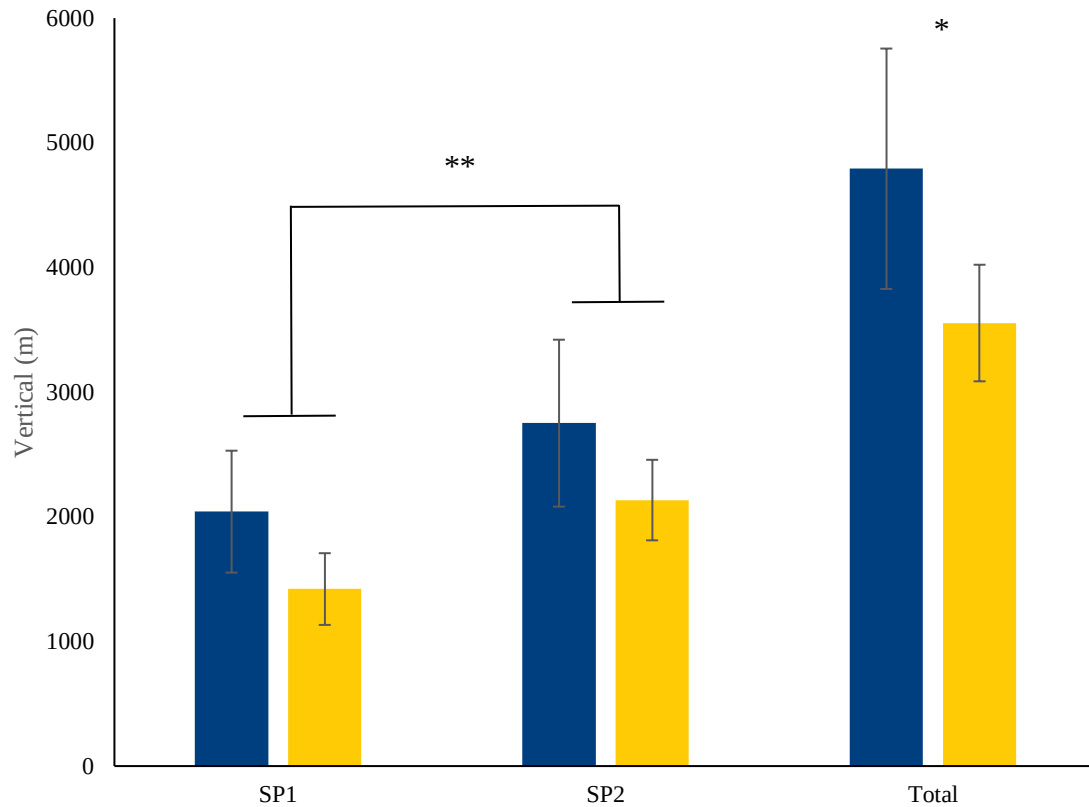


Vertical No significant condition by time interaction was observed for vertical skied during the self-paced skiing sessions ($p=0.859$). Significant main effects of condition ($p=0.002$) and time ($p=0.001$) were observed. Subjects skied more vertical in the DC condition (4791.7 ± 965.1 m) than the NC condition (3554.0 ± 3.0 m) (Figure 3.4). Subjects skied more vertical in the SP2 session (2426.43 ± 413.4 m) than the SP1 Session (1672.32 ± 367.1 m) (Figure 3.4).

Figure 3.4 – Mean and standard deviation of vertical skied in the DC (blue) and NC (gold) conditions during SP1, SP2 and Total self-paced skiing sessions.

* indicates significant main effect of condition at $p < 0.05$.

** indicates significant main effect of time at $p < 0.05$



Heart Rate and Ski Velocity No condition by time interaction, or main effects of condition were observed for HR_{peak} (interaction $p=0.149$, condition $p=0.109$), HR_{mean} (interaction $p=0.090$, condition $p=0.481$), V_{peak} (interaction $p=0.382$, condition $p=0.517$), or V_{mean} (interaction $p=0.152$, condition $p=0.517$). Main effects of time were observed for HR_{peak} ($p=0.002$), and HR_{mean} ($p=0.000$), but not V_{peak} ($p=0.479$), or V_{mean} ($p=0.431$). Both HR_{peak} and HR_{mean} were greater in the SP2 sessions than the SP1 sessions (Table 3.2).

Table3.2 – Relative Heart Rate and Velocity during SP1/SP2 sessions.

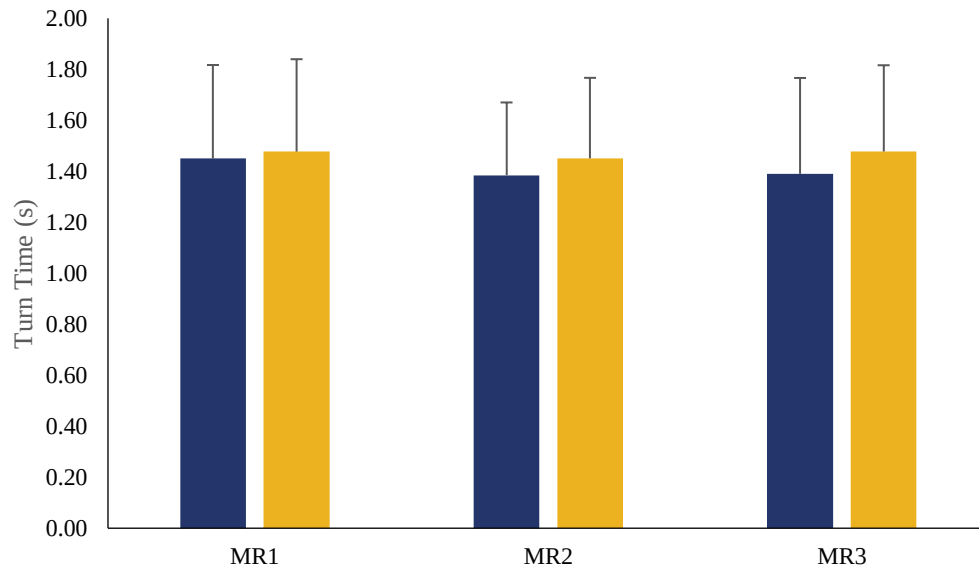
	DC		NC	
	SP1	SP2	SP1	SP2
Velocity Peak ($m \cdot s^{-1}$)	14.77±2.4	13.75±1.8	13.22±2.3	13.49±2.4
Velocity Mean ($m \cdot s^{-1}$)	8.30±2.2	7.47±1.5	7.24±1.7	7.53±2.5
HR Peak (% HR Max)	80.83±11.2	89.39±6.5	81.81±7.4	85.10±9.0
HR Mean (% HR Max)	63.03±10.1	72.70±6.9	66.56±9.8	71.67±9.5

Measurement Runs

Turn Time No condition by time interaction as observed for turn time ($p=0.313$).

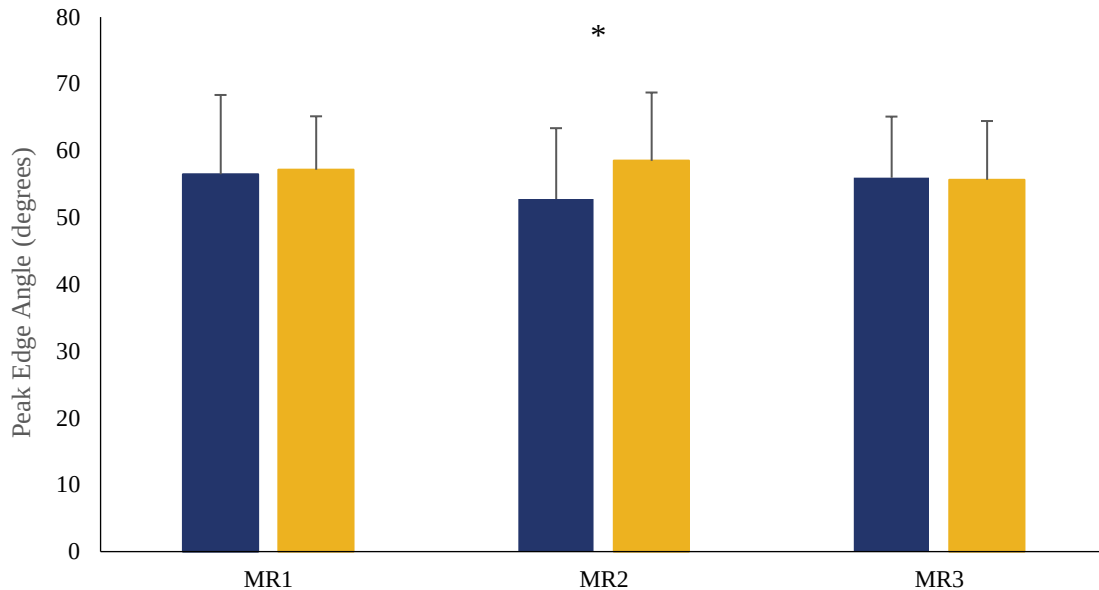
A main effect of condition was observed ($p=0.004$), where mean DC turn time (1.41 ± 0.3 s) was less than mean NC turn time (1.47 ± 0.3 s) (Figure 3.5). A main effect of time was not observed for turn time ($p=0.052$), although it approached significance. When accounting for differences in vertical skied, no condition by time interaction for turn time was observed ($p=0.115$). No main effects of condition ($p=0.225$) or time ($p=0.075$) were observed.

Figure 3.5 – Turn Time - Mean and standard deviation of turn time in the DC (blue) and NC (gold) condition.



Peak Edge Angle A condition by time interaction was observed for EA_{peak} ($p=0.000$). Post-hoc tests revealed that during MR2, EA_{peak} was significantly less the DC condition ($52.76 \pm 10.6^\circ$) than the NC condition ($58.48 \pm 10.2^\circ$) ($p=0.002$) (Figure 3.6). When controlling for vertical skied, no condition by time interactions were observed for EA_{peak} ($p=0.104$). No main effects of condition ($p=0.150$), or time ($p=0.119$) were observed.

Figure 3.6 – Peak Edge Angle - Mean and standard deviation of peak edge angle in the DC (blue) and NC (gold) condition. * indicates a significant condition by time interaction at $p \leq 0.05$.



Absolute EMG A condition by time interaction was observed for VL RMS ($p=0.044$). During MR2, VL RMS was less during the DC condition (6.74 ± 13.0 mV) than the NC condition (16.36 ± 24.3 mV) ($p=0.000$). During MR3, VL RMS was also less during the DC condition (7.67 ± 13.9) than the NC condition (17.72 ± 27.0) ($p=0.000$) (Figure 3.7). Main effects of condition were observed for all muscles tested. In the DC condition, absolute RMS was lower for all muscles tested than the NC condition (GMED $p=0.000$, GMAX $p=0.000$, RF $p=0.000$, ADL $p=0.016$, VL $p=0.000$) (Table 3.4). Main effects of condition were observed in the absolute frequency domain. RF MF was less during the DC condition than the NC condition ($p=0.009$). Median frequency of the ADL was greater during the DC condition than the NC condition ($p=0.010$). (Table 3.4)

Figure 3.7 – Mean and standard deviation of the VL in the DC condition (blue) and NC condition (yellow) during MR1, MR2 and MR3. * indicates a significant condition by time interaction at $p \leq 0.05$.

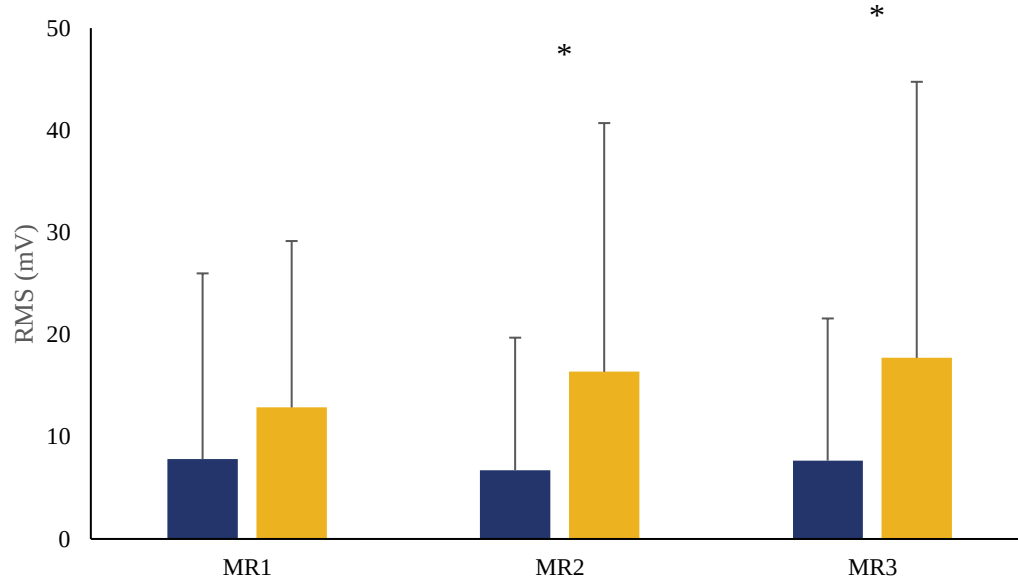


Table 3.3 – Absolute EMG Response – Mean and standard deviation of absolute whole turn RMS and MF. * Indicates a main effect of condition at $p \leq 0.05$. ** Indicates a condition by time interaction at $p \leq 0.05$.

		DC				NC				<i>p</i>
		MR1	MR2	MR3	Mean	MR1	MR2	MR3	Mean	
GMED	RMS (mV)	3.95 ±8.8	4.67 ±10.1	5.09 ±10.4	4.57 ±9.8*	8.35 ±14.36	8.69 ±13.1	9.49 ±16.9	8.89 ±14.8	0.000
	MF (Hz)	73.63 ±24.0	43.45 ±23.4	66.82 ±23.7	71.30 ±23.8	71.81 ±29.55	70.07 ±26.1	69.24 ±25.4	70.44 ±27.0	0.729
GMAX	RMS (mV)	1.58 ±11.1	1.69 ±3.6	2.00 ±4.7	1.76 ±3.9*	2.68 ±4.58	3.05 ±5.0	3.27 ±4.0	3.00 ±4.8	0.000
	MF (Hz)	38.86 ±12.1	39.19 ±11.7	38.02 ±10.1	38.69 ±11.3*	41.62 ±11.95	41.26 ±12.0	39.37 ±10.7	40.75 ±12.6	0.065
RF	RMS (mV)	6.21 ±12.6	6.72 ±13.3	7.45 ±13.0	6.80 ±12.9*	15.52 ±21.52	16.43 ±24.4	14.50 ±23.8	15.41 ±23.9	0.000
	MF (Hz)	64.04 ±15.9	65.61 ±12.7	66.70 ±13.7	65.45 ±14.1*	69.62 ±15.13	68.91 ±13.8	68.24 ±14.3	68.92 ±14.4	0.009
ADL	RMS (mV)	5.70 ±11.1	6.26 ±13.2	6.06 ±11.6	6.00 ±11.0*	9.01 ±13.19	8.30 ±11.5	7.16 ±11.7	8.16±12.3	0.016
	MF (Hz)	45.97 ±11.6	45.25 ±9.0	46.48 ±11.1	45.90 ±10.6*	44.77 ±12.34	42.65 ±11.2	43.60 ±10.7	43.67 ±10.6	0.010
VL	RMS (mV)	7.82 ±18.2	6.74 ±13.0**	7.67 ±13.9**	8.75 ±28.4*	12.38 ±1.55	16.36 ±24.3	17.72 ±27.0	15.65 ±12.3	0.000
	MF (Hz)	62.45 ±14.8	64.89 ±15.4	63.96 ±15.6	64.77 ±15.2	45.31 ±1.38	63.94 ±16.1	62.65 ±15.6	64.11 ±17.1	0.817

When accounting for differences in vertical skied between condition, there was a condition by time interaction for GMED RMS ($p=0.016$, Figure 3.8), GMAX RMS ($p=0.046$, Figure 3.9), RF RMS ($p=0.005$, Figure 3.10) and VL RMS ($p=0.014$, Figure 3.11). A main effect of condition was observed for ADL RMS ($p=0.008$), where ADL RMS was less in the DC condition (6.00 ± 11.8 mV) than the NC condition (8.16 ± 12.1 mV).

Figure 3.8 – Adjusted GMED RMS – Adjusted mean and 95% confidence interval for GMED RMS during the DC and NC conditions. * Indicates a significant condition by time interaction at $p\leq0.05$.

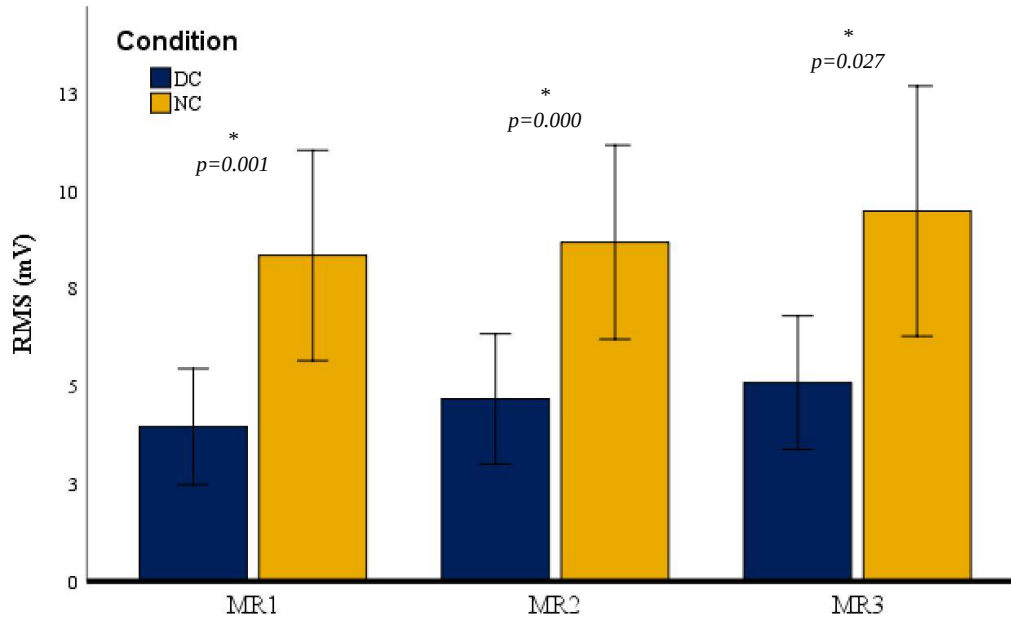


Figure 3.9 – Adjusted GMAX RMS – Adjusted mean and 95% confidence interval for GMAX RMS during the DC and NC conditions. * Indicates a significant condition by time interaction at $p \leq 0.05$.

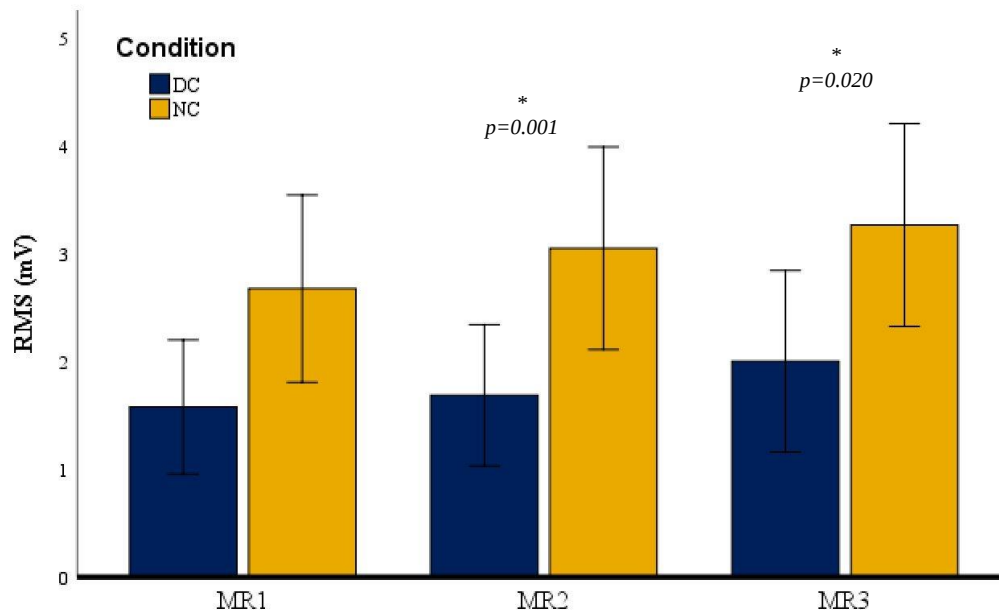


Figure 3.10 – Adjusted RF RMS – Adjusted mean and 95% confidence interval for GMED RMS during the DC and NC conditions. * Indicates a significant condition by time interaction at $p \leq 0.05$.

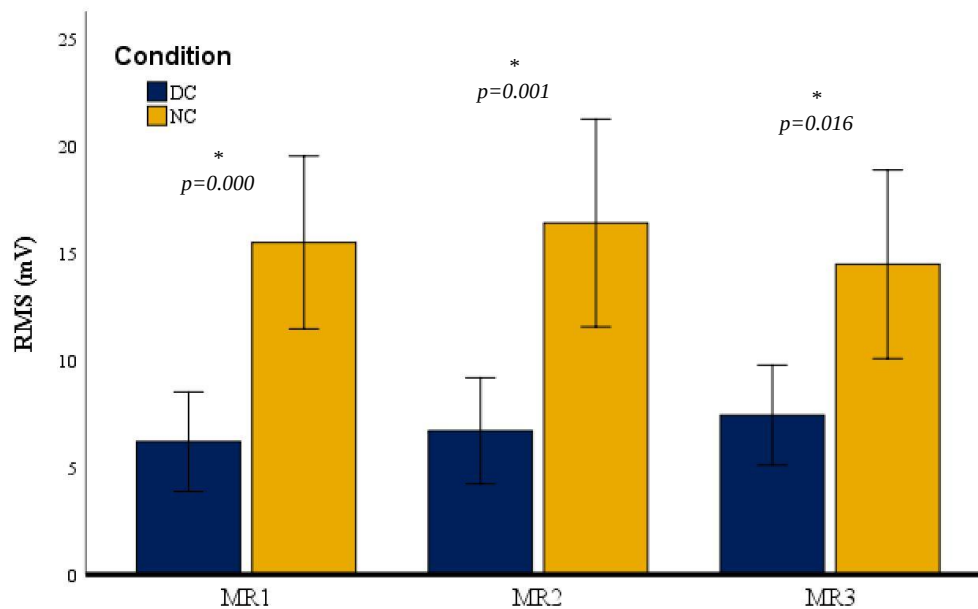
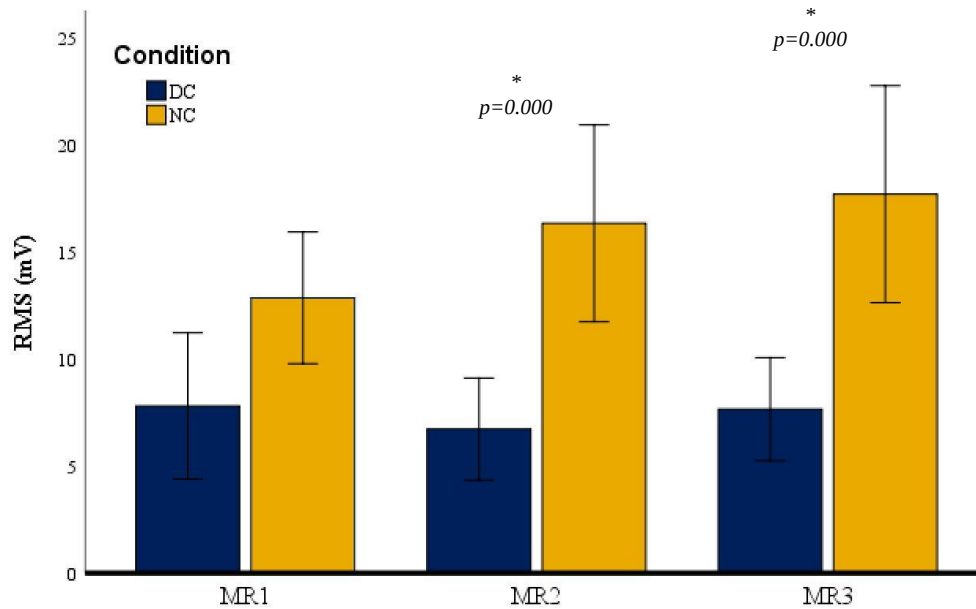


Figure 3.11 – Adjusted VL RMS – Mean and 95% confidence interval for VL RMS during the DC and NC conditions. * Indicates a significant condition by time interaction at $p \leq 0.05$.



Relative EMG No significant interactions or main effects were observed for

relative EMG response in either the amplitude or frequency domain.

Table 3.4 – Relative EMG Response – Mean and standard deviation of relative whole-turn EMG RMS and MF.

		DC		NC	
		MR2	MR3	MR2	MR3
GMED	RMS (%)	106.79 ±59.9	114.22 ±64.8	106.32±59.0	111.63 ±67.1
	MF (%)	100.23 ±31.0	92.05 ±32.6	98.23 ±27.3	97.40 ±27.2
GMAX	RMS (%)	103.32 ±59.5	108.7 ±67.7	108.20 ±61.4	100.55 ±54.8
	MF (%)	101.97±26.0	99.81 ±24.7	99.61 ±20.9	95.37 ±20.6
RF	RMS (%)	103.92 ±54.4	101.98 ±51.43	93.00 ±41.3	96.23 ±43.7
	MF (%)	103.69 ±19.0	105.52±22.4	99.11 ±15.7	98.38 ±16.1
ADL	RMS (%)	95.37 ±51.6	87.24 ±45.1	89.99 ±41.3	96.93 ±59.1
	MF (%)	98.99 ±17.1	102.15 ±24.5	95.30 ±18.7	97.97 ±19.6
VL	RMS (%)	112.52 ±63.5	138.36±51.3	111.61 ±58.6	121.30 ±72.6
	MF (%)	104.26 ±21.9	102.99±20.9	98.92 ±23.3	97.07 ±25.7

Figure 3.12 – Total Muscle Activation Patterns - Mean muscle activation patterns and MF for the DC (blue) and NC (gold) treatments during a representative double turn. Time windows 1-10 represent the right leg as the inside leg (right turn), and time windows 11-20 represent the right leg as the outside leg (left turn).

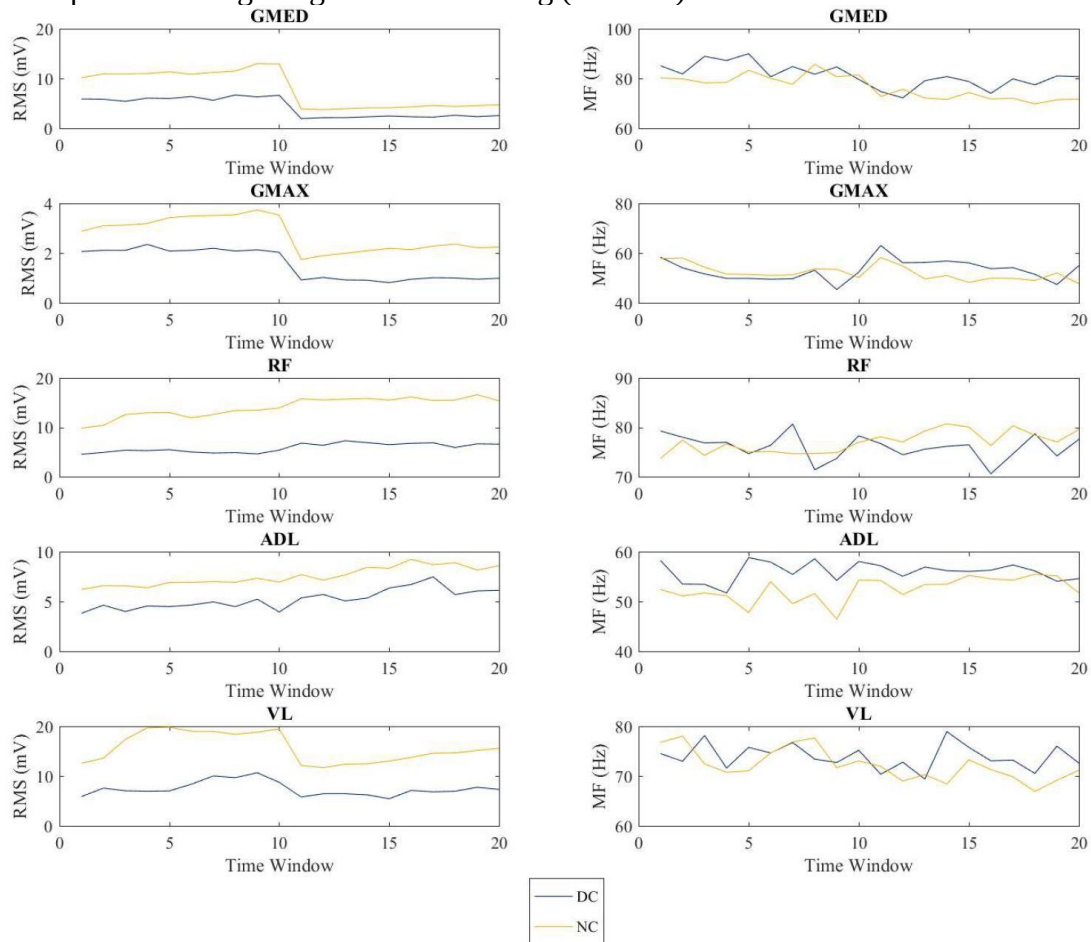
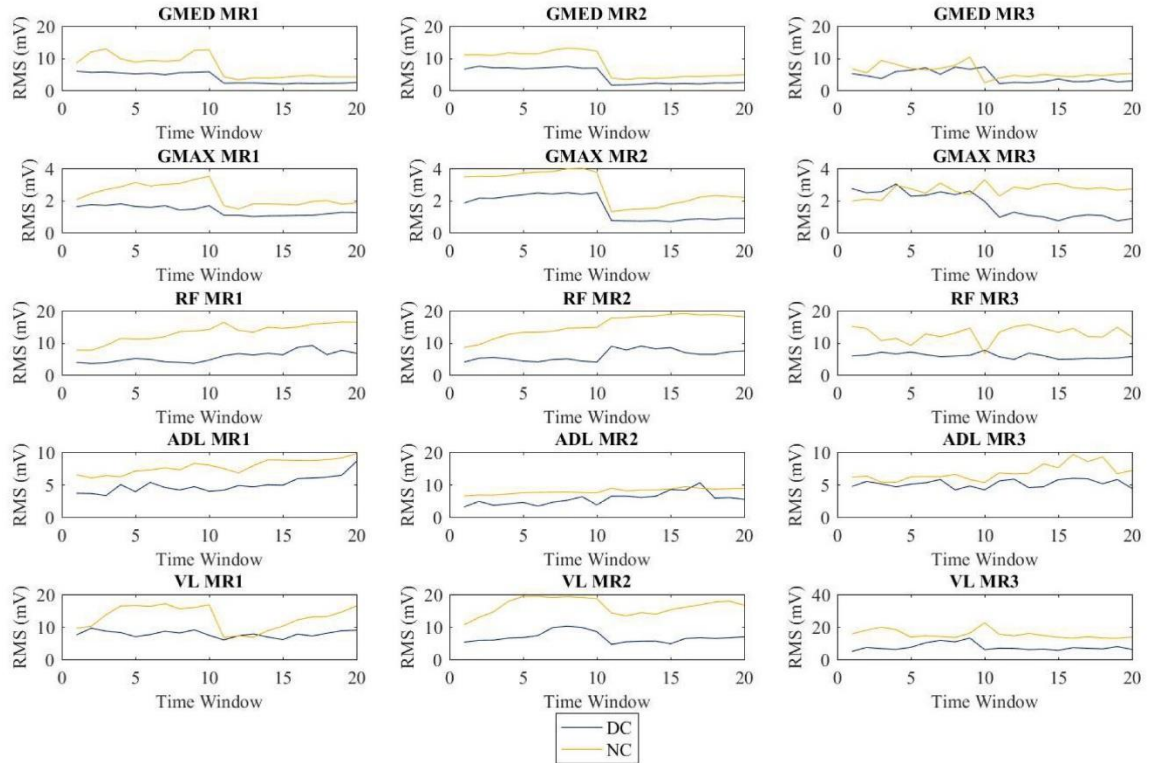


Figure 3.13 – Absolute Muscle Activation Patterns - Mean muscle activation patterns for the DC (blue) and NC (gold) treatments during a representative double turn in each condition. Time windows 1-10 represent the right leg as the inside leg (left turn), and time windows 11-20 represent the right leg as the outside leg (right turn).



Discussion

One of the main interests of this study was to investigate the influence of DC on recreational alpine skiing performance, specifically vertical and runs skied during a simulated ski day. In the current study, subjects completed more runs, skied more vertical meters, had faster turn times, and demonstrated lower muscle activity patterns in the DC condition than the NC condition. While the fact that the subjects in this study completed more runs during this study is not a direct measure of RPE, it does provide an indirect observation of how our subjects perceived their skiing. Since the study design

required subjects to report when they felt like they had 1-2 runs left, and the subjects completed more runs in the DC condition, we can hypothesize that the subjects in the current study perceived that they could ski longer in the DC condition.

Since number of runs and vertical skied were not controlled, only guided in this study. The absence of a condition by time interaction indicates that there were no differences in individual self-paced skiing sessions (SP1 vs SP2) between conditions. Skiing load is determined by the mass of the skier, the skier's velocity, and the radius of the turn the skier is completing. Mass of the skiers was not different between conditions, and no differences in velocity were observed between self-paced skiing sessions, unless subjects chose to alter turning radius without altering skiing velocity, skiing load was likely similar between conditions. To that note, skiers received verbal encouragement during self-paced skiing sessions from an investigator to maintain a constant turning radius. Thus, it is probable that skiing load was not different between conditions. This conclusion is supported by the absence of condition by time interactions or main effect of condition on both HR_{peak} and HR_{mean} (Seifert et al, 2009). However, the skiers in the current study completed more runs, so the total load applied during the DC condition was greater than the NC condition.

A condition by time interaction was observed for EA_{peak} . During MR2, peak edge angle was 9.78% lower, on average, in the DC condition than the NC condition. While this difference was small, even a small increase in turning effectiveness could make a large difference in skiing performance over the course of an entire day of skiing. When accounting for the difference in vertical skied, no treatment by condition or main effects

were observed. Thus, changes in EA_{peak} cannot be attributed to DC garments or increased vertical alone. If recreational alpine skiers were able to ski more vertical while also maintaining a more effective, or at least not experiencing load related decreases in turning technique, it is possible that the use of DC garments may allow recreational alpine skiers to achieve improved recreational skiing performance, without increasing their risk for injury due to turning technique. Improved turning technique could also serve as another indicator of performance since turn time was faster in the DC condition. Given that they skied more vertical, average turn time in the measurement runs should have been slower in the DC condition.

Without considering the additional skiing completed in the DC condition, there was a main effect of condition observed in absolute RMS for all muscles. Absolute RMS was lower in the DC condition than the NC condition. Previous studies have produced similar results in isokinetic and isometric contractions (Fu et al., 2011, Wang et al., 2016), running (Coza and Nigg., 2008, Kerherve et al., 2017, Li et al., 2011), cutting maneuvers (Chaudhari et al, 2014), strength training exercises (Miyamoto et al., 2010, Zhang et al., 2016,) using traditional compression. Without adjusting for the additional vertical completed in the DC condition, a condition by time interaction was observed for absolute VL RMS. During MR2 and MR3, RMS was less in the DC condition than the NC condition. When considering the additional vertical skied in the DC condition, these results become clearer. Significant interactions were observed for GMED, GMAX, RF, and as well as VL. Adjusted RMS, through an ANCOVA, was lower in during all three measurement runs for GMED and RF, while in GMAX and VL interactions were only

observed during MR2 and MR3. While the methods utilized in the current study are not detailed enough to observed subtle changes in muscle function during alpine skiing, these results, especially the interactions observed when adjusting for the additional vertical skied are indicative of improved performance in the DC condition.

The improvement in skiing volume and performance may be related to subtle shifts in the muscle activity controlling ski technique. It is possible that this increase in RMS amplitude during the later measurement runs is indicative of altered turning technique. The observations of turn time and edge angle indicate that turning technique was different between conditions. Previous studies have shown that small changes in motor unit recruitment are related to altered movement patterns (Wakeling, 2004). This effect has been previously demonstrated in sustained alpine skiing (Kröll et al., 2011). They found that skiers tend to shift from bi-lateral loading of both legs (prominent during carving turns) towards unilateral loading of the outside leg (prominent during parallel ski steering turns). While this shift is most obvious in the rectus femoris, it was also observed as an increase in the vastus lateralis of the outside leg. It is possible that the increase in VL and RF RMS observed during later measurement runs without DC could be related to the shift toward increased loading of the outside leg observed by previous studies (Kröll et al. 2010, Kröll et al. 2011).

While this was not a mechanistic study, it has been proposed that compression garments can reduce the pre-synaptic inhibition of cutaneous tactile mechanoreceptors, possibly providing increased sensory feedback about the location of the extremity in space (Iles et al., 1996). While other studies have demonstrated this effect, it is not yet

known if or how it is linked to reduced muscle activity in compression conditions (Bernhardt and Anderson, 2005). It is possible that simply by using DC garments, the effectiveness of motor unit recruitment is improved. While performance was slightly better in the measurement runs, skiers dramatically improved their performance in the self-paced skiing sessions, completing ~40% more vertical, a critical outcome for the recreational skiing population.

There was a high degree of variation in responses between subjects as well as within subjects. It is likely that although self-selected skiing intensity was similar between subjects, that when forced to ski a standardized course, some subjects were able to complete the measurement run in a more consistent pattern while others were not. All the subjects in the current study can be considered recreational alpine skiers and no subjects were actively training and competing in alpine ski racing. However, some subjects had extensive previous experience in competitive alpine skiing. One subject was a retired international level skier. While this subject had been retired for over twenty years, their familiarity with standardized turns is far more than another subject who was in intermediate level skier with ten years of skiing experience, and almost no experience completing standardized turns. When using more detailed analysis techniques, future studies should consider a more homogenous sample in order to gain better insight into the influence of DC garments on muscle activity.

Conclusion

In conclusion, subjects were able to ski more vertical, have lower muscle activity patterns, and ski through a standardized course faster despite completing more runs throughout a simulated day of recreational skiing in a directional compression garment. It is also likely that self-paced skiing intensity was not different between conditions. Despite completing a greater skiing load, at a similar intensity, absolute muscle activity was lower in the DC condition than the NC condition.

Based on the results of this study, wearing DC garments did allow recreational alpine skiers to complete more vertical runs of skiing, possibly achieving greater value perception during a day of skiing. It is also possible that DC garments could attenuate or prolong shifts towards less controlled, more risky skiing styles during a day of skiing. Further studies should investigate these trends using more detailed techniques such as windowed, and wavelet analysis to better quantify specific changes in myoelectric intensity during alpine skiing while wearing DC garments. Further investigations should also explore how DC garments might influence muscle activity patterns and physiologic response during consecutive days of recreational alpine skiing.

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APPENDICES

APPENDIX A

INSTITUTIONAL REVIEW BOARD APPLICATION

Full Committee Review ☐Expedited Review ☒

MONTANA STATE UNIVERSITY
Institutional Review Board Application for Review
(revised 06/01/15)

**THIS AREA IS FOR INSTITUTIONAL REVIEW BOARD USE ONLY. DO NOT
WRITE IN THIS AREA**

Application Number:

Approval Date:

Disapproved:

IRB Chair's Signature:

Date: 9 December 2016

I. Investigators and Associates (**Cory Snyder, John Seifert, Samantha Bessert, Phillip Ferrara, Louie Blood, Celine Valentin**; application will be filed under name of first person listed)

NAME: **Cory Snyder**TITLE: **Graduate Student**DEPT: **HHD**PHONE #: **603-667-6428**COMPLETE ADDRESS: **3157 Summer View Lane, Bozeman MT, 59715**E-MAIL ADDRESS: **cosnyd@me.com**DATE TRAINING COMPLETED: **January 2016**

SIGNATURE (PI or ADVISOR): _____

NAME: **John Seifert**TITLE: **Associate Professor**DEPT: **HHD**PHONE #: **994-7154**COMPLETE ADDRESS: **103A Romney Gym, PO Box 173360, MSU**E-MAIL ADDRESS: **john.seifert@montana.edu**DATE TRAINING COMPLETED: **October 2008**

SIGNATURE (PI or ADVISOR): _____

NAME: **Samantha Bessert**TITLE: **Graduate Student**DEPT: **HHD**PHONE #: **(360) 852-0312**

COMPLETE ADDRESS: **Romney Gym, PO Box 173360, MSU**
 E-MAIL ADDRESS: **Samantha.bessert@gmail.com**
 DATE TRAINING COMPLETED: **December 2016**

NAME: **Louie Blood** TITLE: **Graduate Student**
 DEPT: **HHD** PHONE #:
 COMPLETE ADDRESS: **Romney Gym, PO Box 173360, MSU**
 E-MAIL ADDRESS: **lblood57@gmail.com**
 DATE TRAINING COMPLETED: **February 2016**

NAME: **Phillip Ferrara** TITLE: **Graduate Student**
 DEPT: **HHD** PHONE #:
 COMPLETE ADDRESS: **Romney Gym, PO Box 173360, MSU**
 E-MAIL ADDRESS: **PhilFerrara3@gmail.com**
 DATE TRAINING COMPLETED: **July 2016**

NAME: **Celine Valentin** TITLE: **Graduate Student**
 DEPT: **HHD** PHONE #:
 COMPLETE ADDRESS: **Romney Gym, PO Box 173360, MSU**
 E-MAIL ADDRESS: **valentine.celine@gmail.com**
 DATE TRAINING COMPLETED: **February 2016**

Do you as PI, any family member or any of the involved researchers or their family members have consulting agreements, management responsibilities or substantial equity (greater than \$10,000 in value or greater than 5% total equity) in the sponsor, subcontractor or in the technology, or serve on the Board of the Sponsor? NO X

If you answered Yes, you will need to contact Pamela Merrell, Assistant Legal Counsel-JD at 406-994-3480.

II. Title of Proposal:

The Influence of a Directional Compression Garment on Muscle Activity and Performance in Recreational Alpine Skiers

III. Beginning Date for Use of Human Subjects:
December 2016

IV. Type of Grant and/or Project (if applicable)

Research Grant: **N/A**

Contract: **N/A**

Training Grant: **N/A**

Classroom Experiments/Projects: **N/A**

Thesis Project: **X**

Other (Specify): **N/A**

- V. Name of Funding Agency to which Proposal is Being Submitted (if applicable):
Rocky Mountain Sports Research Consortium

VI. Signatures

Submitted by Investigator
 Typed Name: **Cory Snyder**
 Signature:
 Date:

Faculty sponsor (for student)
 Typed Name: **John Seifert**
 Signature:
 Date:

VII. Summary of Activity. Provide answers to each section and add space as needed. Do not refer to an accompanying grant or contract proposal.

A. RATIONALE AND PURPOSE OF RESEARCH. (What question is being asked?)

Skiers tend to alter movement patterns before they are in a clinically fatigued state. The use of directional compression tights may prevent changes in technique that result from altered motor unit recruitment strategies. Directional compression apparel also appears to be most effective in movements that require high-force, low-velocity contractions, such as those found in recreational alpine skiing. The unique physiological and biomechanical demands of recreational alpine skiing may put skiers at risk for fatigue as they change their movement patterns to adapt to external stressors. Directional compression tights could provide a unique stimulus to reduce or attenuate the changes in muscle activation that lead to altered movement patterns. The purpose of this study is to assess the influence of a directional compression garment (Opedix, Denver, CO) on muscle activity and performance in recreational alpine skiers.

B. RESEARCH PROCEDURES INVOLVED. Provide a short description of sequence and methods of procedures that will be performed with human subjects. Include details of painful or uncomfortable procedures, frequency of procedures, time involved, names of psychological tests, questionnaires, restrictions on usual life patterns, and follow up procedures. **If you are planning on posting flyers, posters, etc. anywhere on Campus, you must check with the building managers and/or departments located in MSU buildings and obtain their approval prior to the posting.**

Subjects will be recruited from intermediate-expert alpine skiers residing near Bozeman, MT. They will report to Bridger Bowl for two randomized days of testing. On one day, subjects will complete all skiing wearing commercially available directional compression tights, and on the other day

subjects will wear their own, non-compressive base-layer. On each day subjects will complete six measurement runs, three each of self –selected and standardized turns, as well as continuous skiing between measurement runs, to simulate a full day of recreational alpine skiing. Skiers will take a break at noon and then return to continue their skiing following lunch. Surface electromyography (sEMG), heart rate, knee joint angle and acceleration will be measured during all runs. sEMG (Delsys Inc, Boston, MA) sensors will be placed on the gluteus maximus, gluteus medius, rectus femoris, vastus lateralis, adductor longus, and bicep femoris of the right leg and attached with a piece of tape and wrapped in elastic bandage. An accelerometer (Notch Interface) will be attached to the right leg above and below the knee to record accelerations, as well as joint angle and movement velocity. A heart rate monitor will be placed next to the skin to record heart rate during runs as well as between runs. Measurement runs will occur at approximately 9:30am, 11:30am, and 3:00pm. Between all measurement runs, subjects will ski lift-accessed terrain at Bridger Bowl, excluding the Schlassman’s lift. Subjects will be required to ski identical terrain on both days. To ensure that run selection is identical on both days, an investigator will record run selection, order and time of run. Subjects will also wear a GPS watch to record this data.

- C. DECEPTION - If any deception (withholding of complete information) is required for the validity of this activity, explain why this is necessary and attach debriefing statement. **Subjects will not be aware of the hypothesis of this study in order to prevent them from intentionally skiing differently when they are in the tights or the normal base-layer. This would affect not only their skiing mechanics, but could also influence the number or runs, velocity, and other variables. In order for subjects to act as their own controls they must ski the same volume between measurement runs on both days of testing.**

D. SUBJECTS

1. Approximate number and ages

How Many Subjects: **10**

Age Range of Subjects: **18-60**

How Many Normal/Control: **10 – Crossover design – subjects will serve as their own controls**

Age Range of Normal/Control: **18-60 – Crossover design**

2. Criteria for selection:

To qualify for this study, subjects must be intermediate or expert skiers according to PSIA standards without recent injury or illness. Intermediate-expert skiers are able to execute carved turns on low and moderate grade

slopes. Skiers must also use skis that are less than 85mm wide under foot.

3. Criteria for exclusion:

Below intermediate skiers with recent injury or illness, or those who use skis greater than 85mm under foot.

4. Source of Subjects (including patients):

Purposive / snowball sampling of intermediate to expert skiers near Bozeman, MT.

5. Who will approach subjects and how? Explain steps taken to avoid coercion.

Primary Investigator

6. Will subjects receive payments, service without charge, or extra course credit?

YES

(If yes, what amount and how? Are there other ways to receive similar benefits?)

Yes, subjects will receive lift tickets for the day of testing if they do not already have a Bridger Bowl season pass, as well as a voucher for standardized meals on the day of testing. Subjects will also receive the tights they wear in the study, valued at \$250.00.

7. Location(s) where procedures will be carried out.

Bridger Bowl Ski Area, Bozeman, MT.

E. RISKS AND BENEFITS (ADVERSE EFFECTS)

1. Describe nature and amount of risk and/or adverse effects (including side effects), substantial stress, discomfort, or invasion of privacy involved.

Since subjects will ski at their own pace on self-selected slopes, the risks to participate in this study are minimal. Risks from this exercise include fatigued, sore muscles, or an injury from a fall or collision. Subjects are responsible for skiing in control and being aware of inherent hazards present on ski slopes. At the present time, there are no adverse risks to wearing directional compression apparels.

2. Will this study preclude standard procedures (e.g., medical or psychological care, school attendance, etc.)? If yes, explain.

No

2. Describe the expected benefits for individual subjects and/or society.

Results from testing will provide insight as to the possible benefits of directional compression apparels and fatigue prevention for recreational alpine skiers.

F. ADVERSE EFFECTS

1. How will possible adverse effects be handled?

By investigator(s):

Referred by investigator(s) to appropriate care: **Emergency medical treatment (Bridger Bowl ski patrol) will be called.**

Other (explain):

2. Are facilities/equipment adequate to handle possible adverse effects? Yes
or No
(If no, explain.) **Yes**

3. Describe arrangements for financial responsibility for any possible adverse effects.

MSU compensation: **None**

Sponsoring agency insurance: **None**

Subject is responsible: **Skiers will be responsible**

Other (explain):

G. CONFIDENTIALITY OF RESEARCH DATA

1. Will data be coded? **Yes**

2. Will master code be kept separate from data? **Yes**

3. Will any other agency have access to identifiable data? **No**
(If yes, explain.)

4. How will documents, data be stored and protected?

Locked file:

Computer with restricted password: **Data will be stored on a password-protected computer**

Other (explain):

VIII. Checklist to be completed by Investigator(s)

A. Will any group, agency, or organization be involved? **No**
(If yes, please confirm that appropriate permissions have been obtained.)

B. Will materials with potential radiation risk be used (e.g. x-rays, radioisotopes)?
No

1. Status of annual review by MSU Radiation Sources Committee (RSC). **N/A**
(If approved, attach one copy of approval notice.)
 2. Title of application submitted to MSU RSC (if different). **N/A**
- C. Will human blood be utilized in your proposal? **No**
(If yes, please answer the following)
1. Will blood be drawn? **N/A**
(If yes, who will draw the blood and how is the individual qualified to draw blood?
What procedure will be utilized?)
 2. Will the blood be tested for HIV? **N/A**
 3. What disposition will be made of unused blood? **N/A**
 4. Has the MSU Occupational Health Officer been contacted? **N/A**
- D. Will non-investigational drugs or other substances be used for purposes of the research? **No**
- Name:
Dose:
Source:
How Administered:
Side effects:
- E. Will any investigational new drug or other investigational substance be used? **No**
[If yes, provide information requested below and one copy of: 1) available toxicity data; 2) reports of animal studies; 3) description of studies done in humans; 4) concise review of the literature prepared by the investigator(s); and 5) the drug protocol.]
- Name:
Dose:
Source:
How Administered:
IND Number:
Phase of Testing:
- F. Will an investigational device be used? **No**

(If yes, provide name, source description of purpose, how used, and status with the U.S. Food and Drug Administration FDA). Include a statement as to whether or not device poses a significant risk. Attach any relevant material.)

G. Will academic records be used? **No**

H. Will this research involve the use of:

Medical, psychiatric and/or psychological records **No**

Health insurance records **No**

Any other records containing information regarding personal health and illness **No**

If you answered "Yes" to any of the items under "H.", you must complete the **HIPAA worksheet**.

I. Will audio-visual or tape recordings or photographs be made? **Yes**

J. Will written consent form(s) be used? **Yes** (Please use accepted format from our website. Be sure to indicate that participation is voluntary. Provide a stand-alone copy; do not include the form here.)

APPENDIX B

INFORMED CONSENT

**SUBJECT CONSENT FORM
FOR PARTICIPATION IN HUMAN RESEARCH AT
MONTANA STATE UNIVERSITY**

Investigators: Cory Snyder, John Seifert, Sam Bessert, Louie Blood, Phillip Ferrara, Celine Valentin

Title: The Influence of a Directional Compression Garment on Muscle Activity and Performance in Recreational Alpine Skiers

You have been invited to participate in a project investigating the effect of directional compression on performance and muscle activity. You will make three measurement runs in a gated course and free-skiing at designated times during a full day of recreational skiing. Between measurement runs, you will ski on lift-accessed terrain at Bridger Bowl Ski resort. Results from this project will provide insight to the effect of directional compression apparels on performance and muscle activity.

Funding Agency. Rocky Mountain Sports Research Consortium

Procedures. If you agree to participate, you will report to Bridger Bowl for two randomized days of testing at least 48 hours apart. On one day you will complete all skiing wearing commercially available directional compression tights, and on the other day you will wear your own, non-compressive base layer. On each day you compete six measurement runs, three each of self-selected and standardized turns, as well as continuous skiing between each measurement run to simulate a full day of recreational alpine skiing. Surface electromyography (sEMG, which is a measure of muscle activity), heart rate, knee joint angle and acceleration will be assessed during the measurement runs. sEMG sensors will be placed over muscles on your right gluteus maximus, gluteus medius, rectus femoris, vastus lateralis, and adductor longus muscles, biceps femoris, as well as accelerometers above and below your right knee joint, and attached with a piece of tape and wrapped in elastic bandage. A heart rate monitor will be placed next to your skin to record heart rate during runs as well as between runs. The monitor will be paired with a watch worn on your wrist. Measurement runs will occur at approximately 9:30am, 11:30am, and 3:00pm. Between all measurement runs, you will ski lift-accessed terrain at Bridger Bowl, excluding the Schlassman's lift, "high-traverse" trail, the ridge, and any run requiring hiking, or excessive poling or skating to return to the lift. You will be required to ski the same terrain on both testing days. You will take a break at noon (after the 11:30 measurement run) where you will be given a voucher for lunch. You must eat the same food on both measurement days. Following lunch, you will return to the hill to resume skiing. Finally, you will be required to ski on skis no greater than 85mm underfoot width for the entirety of this study.

Time Commitment. The total time for your participation in this testing is about sixteen hours, over two separate days. You are free to discontinue this testing at any time.

Confidentiality. Personal information and data will be kept on a password-protected computer. Data will be coded to protect your identity.

Benefits. Results from testing will provide insight as to the possible benefits of directional compression apparel, and identifying fatigue patterns for alpine skiers.

Compensation. If necessary, you will be provided with a lift ticket (if you don't have a Bridger Bowl pass) and a voucher for lunch on both days of testing at Bridger Bowl. You will also receive the tights used in testing (worth about \$250).

Risks. The risks of involvement in this study include sore or fatigued muscles from the exercise, and injury due to a fall. You should ski in control at all times during the study and be aware of hazards that may exist on the ski slopes. If complications do arise during this study, we can refer you to appropriate medical caregiver. Ski patrol will be available on the mountain as first responders in case of an accident. However, there is no compensation available from MSU for injury.

Questions. Your decision whether or not to participate will not jeopardize your relationship with the Movement Sciences Laboratory. You are free to discontinue participation at any time without negative effects on your relationship with MSU or the researchers. If you have any questions, please ask us.

If you have any additional questions later, Cory Snyder (603-667-6428) or John Seifert (406-994-7154) will be happy to answer them. Additional questions about the rights of human subjects can be answered by the Chairman of the Institutional Review Board, Mark Quinn, (406) 994-4707

The Influence of a Directional Compression Garment on Muscle Activity and Performance in Recreational Alpine Skiers

Freedom of Consent

I have been given ample opportunity to read this document in its entirety and to ask questions which have been answered to my satisfaction. I hereby consent to become a participant in this study knowing the health risks involved and that I may withdraw my consent at any time, for any reason. I also understand that project personnel may screen me from this study for any reason deemed appropriate.

AUTHORIZATION: I have read the above and understand the discomforts, inconvenience and risk of this study. I, _____ (*name of subject*), agree to participate in this research. I understand that I may later refuse to participate, and that I may withdraw from the study at any time. I have received a copy of this consent form for my own records.

Signed: _____

Witness: _____

Investigator: _____

Date: _____