"To describe the action of nerve as integrative is, although true, hardly sufficient for a definition. If nature of an animal be accepted as being that of a whole presupposed by all its parts, then each and every part of the animal is integrative." Sir Charles Sherrington

Timing counts for everything. Balance is at the centre of it all.

The effect of a segmental, localized lower limb cooling protocol on muscular strength and balance

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Submitted in partial fulfillment of the requirements for the degree of:

Master of Science in Applied Health Sciences (Kinesiology)

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Abstract

The human neuromuscular system is susceptible to changes within the thermal environment. Cold extrinsic temperatures can significantly reduce muscle and nervous system function and communication, which can have consequences for motor performance. A repeated measures design protocol exposed participants to a 12°C cold water immersion (CWI) up to the ankle, knee, and hip to determine the effect that reduced skin and muscle temperature had on balance and strength task execution. Although a linear reduction in the ability to perform balance tasks was seen from the control condition through to the hip CWI, results from the study indicated a significant reduction in dynamic balance (Star Excursion Balance Test reach distance) performance from only the hip CWI ($P<0.05$). This reduced performance could have been due to an increase in joint stiffness, increased agonist-antagonist co-contraction, and/or reduced isokinetic muscular strength. Reduced physical performance due to cold temperature could negatively impact outdoor recreational athletics.

Acknowledgements

The final product of a Master's thesis rarely is the result of one individual's effort. This manuscript was only made possible by many, the following, whom I would like to thank:

I would first like to thank my friends and family whom I am indebted to for your unwavering support in my academic endeavour and resolute understanding for my reclusiveness at times as I have worked hard to complete my Masters in a timely manner. I hope to spend more moments with all of you over the coming years.

Within the Environmental Ergonomics Lab at Brock, I would like to thank: Cody Watson, Greg McGarr, Amanda Milburn, Nick Stanov and Clark Robertson for their assistance in data collection, participant recruitment, and friendship as we collaborated to complete this project. A special thanks to Geoff Hartley. His help with data collection and data processing, as well as his wealth of insightful guidance was greatly appreciated and crucial to the completion of this research. Finally, thanks to Mike Taber for your counsel and logistical support. Your help with acquiring the immersion suits made the protocol possible.

Thank you to the participants of the study. Willing to undergo the rigors of the trials displayed your altruistic character and commitment to science.

Thanks to those in the Applied Physiology Lab across the hall for your help with the isokinetic testing. I am grateful for your expertise and advice.

Thanks to Greig Inglis for taking care of the muscle temperature probe sterilization. I'm glad no serious explosions resulted!

Thanks to my advisory committee members, Craig Tokuno and Rene Vandenboom. Your assistance in establishing a scientifically sound methodology and your ongoing academic support has been a source of motivation for me to strive for success as a scholar.

Finally, a thank you to my M.Sc. supervisor, Stephen Cheung. Your openness to my research idea and your advisory approach to allow me a large degree of independence in my academic pursuit was greatly appreciated and has helped me grow more as a researcher and as an individual.

Over the past 2 years, my experience at Brock University has been a challenging, yet rewarding one. From responding to calls with the Toronto Fire Service, helping Mark’s test new clothing designs, and participating in a History Channel documentary, to ultimately completing my own research, I have immensely enjoyed all of the opportunities and look forward to the way ahead…

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List of abbreviations and symbols used	
A/D	Analogue / Digital
ANOVA	Analysis of variance
ASIS	Anterior superior iliac spine
BOS	Base of support
CI	Co-contraction index
CNS	Central nervous system
COG	Centre of gravity
COM	Centre of mass
COP	Centre of pressure
CWI	Cold water immersion
DAQ	Data aquisistion
EEL	Environmental Ergonomics Lab
EMG	Electromyography
EPC	Equilibrium point control (model)
IC	Internal control (model)
ICC	Interclass correlation coefficient
LED	Light emitting diode
MVC	Maximal voluntary contraction
NMS	Neuromuscular system
PNS	Peripheral nervous system
ROM	Range of motion
SEBT	Star excursion balance test (Dynamic balance)

List of abbreviations and symbols used (Cont’d)	
SENIAM	Surface Electromyography for the Non-Invasive Assessment of Muscles
SS	Stork stand test (Static balance)
TTL	Transistor-transistor logic
°C	Degrees Celsius
°/S	Degrees per second
Hz	Hertz
O_2	Oxygen
T_{mu}	Muscle temperature
T_{re}	Core (rectal) temperature

Introduction

Dynamic postural control is of fundamental importance in recreational sports where both internal and external perturbations can elicit severe challenge to an individual's equilibrium. Dynamic balance not only requires that an individual has sufficient muscular strength and a well-functioning visual and vestibular systems but a strong somatosensory system as well (89). The somatosensory system is integrated within the body's neuromuscular network, and includes muscle spindle and other various mechanoreceptors such as Pacinian corpuscles that assist in touch discrimination, muscular coordination and contraction to help the body remain upright. It is also the somatosensory system that can be influenced by environmental conditions, most notably cold temperatures, which can disrupt muscle and nerve communication (150). For example, direct cooling of skeletal muscle seems to result in a drop in muscle spindle firing rates, which can lead to abnormal levels of muscle tension (35). This phenomenon, in addition to decreases in nerve conduction velocity (150), may result in an impaired ability to remain balanced and to generate vigorous muscular contractions with the lower extremities in athletic endeavours. This may make injuries more likely. For instance, a greater amount of knee injuries occur in female alpine skiers when ambient temperatures are relatively cold (125).

The lower extremities are comprised of a complex network of muscle, joints, bones, nerves and other anatomical structures which operate synergistically to produce muscular force and assist in posture, propulsion and balance. The lower extremities also act as a shell to insulate the body's vital organs from cold ambient temperature (76). Therefore, it is often the case that when the body is exposed to a cold medium that leg temperature becomes highly susceptible to a reduction compared to other bodily regions. Subsequently the muscles and somatosensory organs housed within the legs are at increased risk to be influenced by the cold. Due to the complexity and temperature reactivity of the lower extremities it is important to understand how they respond and adapt to fluctuating localized temperature.

Cold temperature's effect on the somatosensory system has been well documented with respect to general physiological changes (4, 35, 39), balance (95, 121, 138), and muscular strength (131, 25, 26, 27). For example, it has been shown that postural sway during standing increases with cold exposure (95), and antagonist muscle activity follows a negative, linear correlation with localized drops in muscle temperature (111). When it comes to dynamic balance and muscle strength research with respect to cold exposure, the research tends to focus on one specific joint (i.e., ankle or knee) and/or one specific muscle group (i.e., quadriceps femoris) (144, 149, 121) and narrow in on either elite athletic populations or those with limited balance (104, 27). What has been less researched is the fundamental effect that cold poses to the lower limbs of the recreational athlete with regards to challenging dynamic balance tasks in the anterior-posterior direction. Additionally, the idea that different lower limb segments, and their associated joints, may be more or less of an influencing factor on dynamic balance when cooled down has not been published. For instance, the plantar aspect of the foot is populated by a greater density of pressure sensitive mechanoreceptors than similar skin surface areas on the shank or thigh (142). This may mean that cooling down just the foot could reduce relative dynamic balance to a greater extent than if a larger volume of the lower limb is cooled down. Conversely, dynamic balance relies on muscular strength. The quadriceps and hamstrings, without consideration of lever class at joints, can produce a greater magnitude of muscular force comparatively to the muscles of the shank and foot. This may mean that cooling down the thigh may have a greater relative contribution to dynamic balance performance than if just the foot was cooled alone. It is the proposed research within this document that hopes to establish if these relationships exist.

Literature Review

Overview:

The dynamic thermal relationship that exists between the human body and the external environment generates deviations in physical performance. The human body can be subdivided into systems, each which are more or less susceptible to thermal variation. One of these systems within the body that is extremely sensitive to temperature changes is the neuromuscular system (NMS). Reviews by Rutkove (129), Oksa (114), and Racinais and Oksa (123) highlight the various components of the NMS that seem to be adversely affected by swings in temperature. These authors deal specifically with ambient temperatures that create reductions in both skin, muscle and, at times, core temperature. In relation to reductions in skin, muscle and core temperature often a linear correlation is observed with regards to NMS performance issues. For example, balance (95) and dynamic strength (30) show direct relationships to muscle temperature changes while isometric, submaximal muscular endurance can be inversely influenced from temperature drops (145). Ultimately, as body temperature moves farther away from its ideal temperature range negative repercussions relating to muscle function will become manifest.

It is often taken for granted how balance and strength are integral to daily living. It is not until these kinesthetic attributes are tested to their limits, for example, during outdoor, athletic endeavours where the motor tasks can be more demanding and further confounded by the physical, and specifically thermal, environment that the integrative and complex nature of the NMS becomes most apparent. This is exemplified by the lower extremities which are of obvious importance to the execution of motor tasks associated with outdoor recreational athletics like skiing and kiteboarding. As a result of thermoregulatory mechanisms, localized leg temperature is often reduced when exposed to cold mediums. This could have the effect of reducing one's performance during leg intensive and thermally challenging activities. This review will summarize the research that has been done on cold exposure with regards to human balance and muscular strength with a focus on the lower limb and peripheral NMS mechanisms.

Neuromechanics and anatomy of the lower extremities:

Anatomy of the lower extremities:

The lower extremities are comprised of approximately 33 bones from the ischium to the first distal phalanx of the foot, and 49 muscles per limb, with the vast majority of cutaneous and muscular nerve supply stemming from the lumbar and sacral plexuses. The lower extremities provide a means of locomotion, and assist in maintenance of balance through bone structure, somatosensory detection and the voluntary contraction of skeletal muscle. Depending on the location and attachment sites to bone, each muscle provides a specific action (See appendix D). The following paragraphs will provide a brief description of the anatomical and neuromechanical characteristics that revolve around the hip, knee and ankle joints and their importance to athletic activities, specifically squatting mechanics which are integral to many forms of athletics.

Hip:

The hip is a fusion of three bones: the ischium, illium and pubis. The hip joint itself is created by the integration of these three bones that form the acetabulum which accepts the head of the femur or thigh bone. The hip joint allows for three degrees of freedom in sagittal, frontal and transverse planes (55) and yet still maintains a highly stable structure.

In a bipedal stance, the hip joint is stabilized through gravity, which presses the femoral head against the acetabulum (132). During two-legged posture, at rest, each hip is loaded with approximately one-third to one-half body weight (96). This load increases to two-to-four times body weight when standing on one leg (69). This could be due to both an increase in the physical weight that the single hip is required to bear and also the increased contraction of the surrounding musculature. During more dynamic movement the hip is subjected to forces from gravity, ground reaction force, increased muscle contraction and body segment accelerations (55). Therefore, one-legged dynamic tasks, such as one-legged squatting provide the greatest challenge to the structure of the hip.

Almost 2 dozen muscles act about the hip to cause hip flexion, extension, adduction, abduction, internal and external rotation. The gluteus muscles and adductors, which will be discussed here, as well as the biarticular muscles of the thigh, which will be discussed later under the knee sub-section, contribute to the structure and mobility of the hip joint. Within a squat, as the knees and hips flex, the gluteus maximus is recruited to control descent and contribute to ascent (127). As a squat approaches and passes 90° of knee flexion the gluteus maximus recruitment is at its greatest to compensate for a mechanically disadvantaged (shortened) hamstrings muscle group (55). Where gluteus maximus tends to act as a prime mover during the squat movment, it is the gluteus medius and adductor longus which act more to stabilize to torso, especially during one-legged stance. During one-legged squats and other unipedal athletic stances the gluteus medius is activated to a greater extent than during two-legged squats and athletic postures (100). McCurdy and colleagues state that the reason for this increased activation of gluteus medius during one-legged squats is to prevent lateral pelvic drop (100). As for adductor activity during athletic posture and exercises, a moderate level of activity (25% of a maximal voluntary contraction or MVC) was observed by a research group for the adductor longus muscle during a lunge, single-leg squat and step-up (15). They concluded that similar to gluteus medius, the adductor longus group acted in a stabilizer role during the three different lower extremity exercises to control pelvic movement in the frontal plane. Therefore, dependant on attachment points, muscles of the hip act either as prime movers, synergists or stabilizers to control lower extremity actions with increased stabilization required for more complex dynamic tasks.

Knee:

The knee joint is comprised of interacting bony surfaces of the femur, tibia, fibula and patella. The three main articulations to the knee joint include the tibiofemoral joint, patellofemoral joint and suprerior tibiofibular joint (147). It is usually the tibiofemoral joint that most recognize as the knee joint, although it is all three joints which act to create a modified hinge-like joint (55). It is this same integration of joints which allows for the two degrees of freedom of the knee through flexion/extension and axial rotation

(101). The association of bones which creates the knee joint also renders it unstable and therefore requires support from a network of ligaments and muscles to maintain its structure (55).

During isotonic squats the knee joint is exposed, through both the tibiofemoral and patellofemoral joints, to forces which can compromise knee integrity. These forces that cause compression are the same as experienced at the hip. It was found that both tibiofemoral and patellofemoral compression forces were at their maximum when participants were close to the end of and start to the lowering and lifting phase of the squat (37). This is most likely due to the resistance from posterior cruciate ligamentous support and contraction of the surrounding musculature to prevent excessive anterior tibial translation with respect to the femur (37).

Primary movers for knee flexion include biceps femoris, semitendinosus, semimembranosus and assisted by gastrocnemius while knee extension is generated through rectus femoris and the vasti muscles (55). Axial rotation in the form of supination is controlled by biceps femoris and pronation is controlled by gracilis, popliteus, sartorius, semitendinosus and semimembranosus (55). During isotonic squats, regardless of extra weight or bodyweight alone, where both hip, knee and ankle are in varying degrees of flexion and extension it is the vasti muscles which are more active in relation to the biarticular rectus as well as all other lower extremity muscles (37, 71). For example, the hamstrings activate during the lowering phase of the squat to control descent and prevent anterior tibial translation (37). Hamstring activity only achieves a relatively low level of activity (~4-20% MVC) and does not become much more active until the lifting phase of the squat to assist in hip extension and knee extension (37, 71).

However, with one-legged squats, the decreased base of support (BOS) increases neuromuscular demand and as a result increases the quadriceps:hamstring co-activation ratio closer to 1:1 (1.67:1) (100). It could be that the biceps femoris activity is increased during one-legged lower body exercise to resist knee internal rotation moments by producing knee external rotation (10).

Ankle:

The ankle and foot consist of 26 irregular shaped bones and motion is controlled across 30 synovial joints by 23 muscles (55). The majority of motion at the foot and ankle occurs at three synovial joints: the talocrural, midtarsal and subtalar joints (102). Due to the multitude of joints there are many degrees of freedom that the ankle and foot are capable of. The talocrural joint provides a great deal of stability to the ankle joint due to its shape which permits ankle plantar and dorsiflexion (55). The subtalar joint, located just distal to the talocrural joint, allows for foot pronation (eversion, abduction and dorsiflexion) and supination (inversion, adduction and plantarflexion) (55). During squat exercises, the ankle joint permits dorsiflexion to reach up to 40° to allow for movement at the knee and hip to remain balanced (55). The ankle must withstand the great majority of the body’s weight while still allowing for unencumbered movement. This is in part accomplished by the coordination of the largest muscles crossing the ankle (gastrocnemius and soleus) which are positioned in a way that they exhibit a 2nd class lever characteristic that allows for a mechanical advantage to create plantarflexion (55).

Muscles often researched with regards to muscle activity and ankle movement during squat tasks are the gastrocnemius, soleus and tibilalis anterior, which cross the talocrural joint on the posterior and anterior surfaces respectively. During the deepest part of the squat descent and early ascent, tibialis anterior and soleus/gastrocnemius co-activation is at its greatest (127). This co-activation could be a result of the tibialis anterior activating to a greater degree to assist in a posterior shift in centre of pressure (COP) (45), or point location of the vertical ground reaction force (151), while the gastrocnemius and soleus help to control the eccentric descent. Throughout the rest of the squat the tibialis anterior, soleus and gastrocnemius remain relatively silent (127). A search on one-legged squats and muscle activation of the leg muscles revealed no results. It might be possible that in a one-legged stance and squat, with the increased neuromuscular challenge, there would be an increased co-activation of the tibialis anterior and triceps surae similar to the increase seen between the knee flexors and extensors (100).

Kinetic/Kinematic Chains:

The hip, knee and ankle joints are subjected to tremendous forces during dynamic athletic activity from a variety of sources. It is therefore imperative that optimal joint mechanics is achieved through neuromuscular control to ensure that injury risk is minimized. Just as the neural network is an integrated entity so too are the skeletal muscles. The muscles and joints of the lower extremity create kinetic and kinematic chains (126), which can be defined by muscle-force relationships and additive joint degrees of freedom respectively (55). Functionally this means that when operating either in an open chain, where the distal end of the appendage is free to move, or more-so in a closed chain movement, where the distal end of the extremity is in contact with the ground or another surface, one muscle or one joint will influence how other muscles and joints behave (140). For instance biarticular muscles like the gastrocnemius, biceps femoris and rectus femoris are capable of transferring mechanical energy from their own muscular contraction to other muscles within the lower extremities (127). Additionally, during a squat, if the tibialis anterior is capable of controlling COP, which in turn can affect the body's centre of gravity (COG), which is considered a vertical projection of a body's centre of mass (COM) onto the ground (151), if the tibialis anterior were to contract and shift the COP posteriorly, this could affectively push the COG anteriorly and cause the knee extensor muscles to activate to a greater extent (80). To try and better understand this example and other neuromechanical properties of the lower extremities it is imperative to have a good grasp of the how the skeletal muscles and peripheral nerves communicate within the body.

Role, Physiology and Measurement of the Peripheral Neuromuscular System:

Transmission of information to and from the muscles and somatosensory receptors occurs through the propagation of action potentials along the axons of sensory and motor nerve cells or neurons. There can be as few as two neurons in a monosynaptic reflex or many neurons if a larger amount of the central nervous system (CNS) is involved (92). Some of the most review relevant steps to neural communication will be outlined briefly and will be followed by a discussion on outcomes of neuromuscular control, how this control can be quantified and some of the important sensors within the neuromuscular network.

Modality gated channels:

Sensory receptors and their associated neurons within the lower extremities detect and transmit sensory information such as muscle stretch and tension, or superficial skin pressure and vibration. Detection occurs through the function of modality gated ion channels. These specialized ion channels are sensitive to mechanical, chemical or thermal stimulation. Upon detection of a change in one of these modalities the receptors are able to convert this natural form of information into a form (graded receptor potentials) suitable for the initiation of action potentials through the process of transduction (13, 139). Important to this thesis, further information will be provided on the specific mechanically and thermally sensitive receptors, or mechanoreceptors and thermoreceptors later on in this literature review.

Action potential propagation:

The lower extremities house some of the longest axons in the body which can span as far as the caudal region of the spine to the big toe. Therefore, it is important that the transmission of signals be quick and efficient to allow for fluid control of the legs. The speed at which the signal propagates is termed the conduction velocity and is dependent on the diameter of the axon and whether myelination is present or not. Conduction velocity ranges from 1.7 m/sec/µm in diameter in unmyelinated axons to upwards of 6.0 m/sec/µm in diameter for the largest diameter, myelinated axons (70, 146). Most nerve fibres are myelinated, it is only some of the smaller diameter nerves which relay pain and temperature information that are not (139). Although the peripheral nerves are resilient, in that they possess viscoelastic properties to stretch and bend with the movement of the limbs, they are sensitive to ambient temperature which can impair the speed at which they can transmit information (146, 129, 79). This will be discussed later in the review.

Once the afferent signal enters the spinal cord it is usually relayed through various interneurons, either at the spinal level or higher levels of the CNS which is beyond the scope of this review. Once the signal is relayed and processed by interneurons, if required, a signal is sent back to the effector organs to be turned into an action (muscular contraction, gland secretion) (139). Neuromuscular coordination is required to maintain balance and exhibit strength.

Somatic balance control components:

Balance control is maintained through the use of visual, somatosensory and vestibular systems on effector organs (i.e. muscles). Vision is utilized to plan out routes, avoid obstacles, and provide feedback on body orientation (151). The vestibular system grants the body the ability to detect linear and angular accelerations through head movement (151). Finally, the somatosensory system provides feedback to the CNS on limb and joint angle velocity, contact with the ground and other surfaces, and orientation of the body with respect to gravity (151). Out of these three balance systems, it is the somatic senses, integrated within the NMS, that tend to be the most exposed and influenced by external temperature changes. These somatic senses include muscle spindle activity (deep mechanoreceptor), superficial mechanoreceptor signaling, skeletal muscle coordination and joint-position sense.

Muscle spindles:

Goodwin and colleagues were one of the first research groups to begin to definitively understand the relationship between muscle spindle sense organs and “kinaesthesia”, a term often used synonymously with position sense and balance (44). Muscle spindles are characterized through their afferent nerve supply. These afferents exist as both type Ia (annulospiral) and type II (flower-spray) afferent fibres that connect to bag and chain spindle fibres which relay and detect both rapid (phasic) and tonic, and tonic only muscle stretch information respectively towards the CNS (44). The actual muscle spindle sensors are fusiform capsules filled with viscous fluid and are situated within intrafusal skeletal muscle so that as muscle fibres elongate, the muscle spindles stretch as well, sending signals to elicit a stretch reflex (see figure 2.1, phasic depicted). The stretch reflex has been shown to be integral to joint position sense and coordination, and which is imperative for maintenance of balance (95). It is known that the number of human muscle spindles increases with respect to the amount of muscle mass by a power law relationship in the form of $y = 0.48x + 1.33$ where y = spindle content and x = muscle mass (86). With implications regarding the dynamic thermal environment of skeletal muscle discussed later it is hypothesized that muscle spindles exist in greater numbers in areas dominated by oxidative muscle fibres and high vascularity (86).

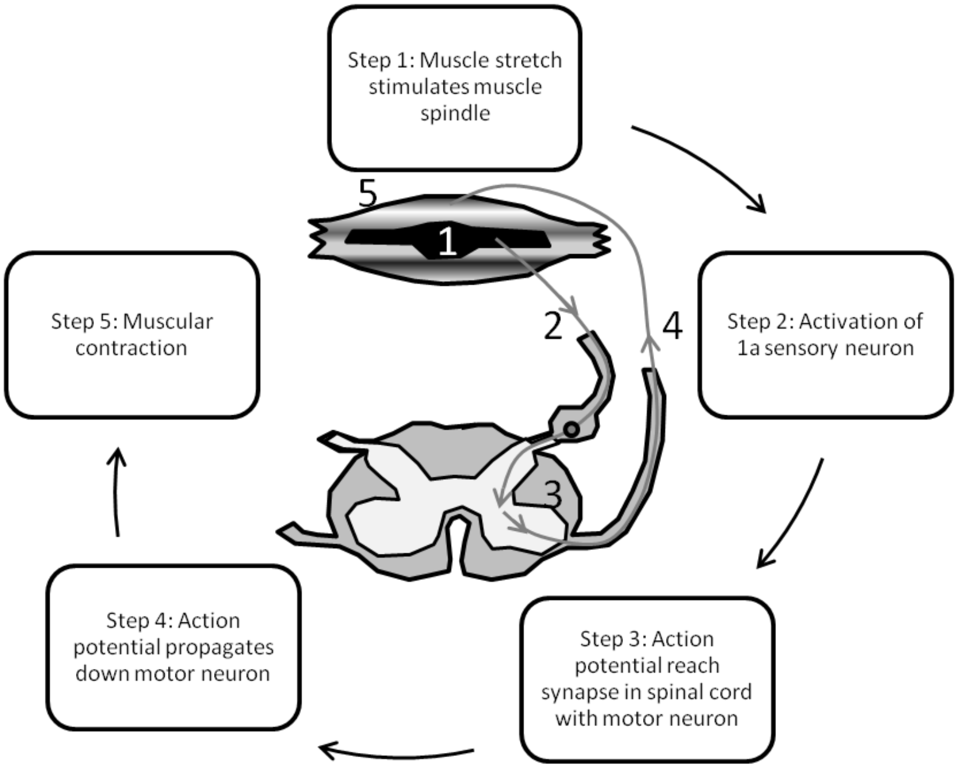


Figure 2.1: Muscle spindle and phasic stretch reflex (adapted from (97)**)**

***Superficial mechanoreceptors*:**

Beyond the proprioceptive capacity of the muscle spindles for postural control, the exteroceptive mechanoreceptors are also critical to maintaining balance. Mechanoreceptors of the glabrous skin exist as both slow (Merkel cells and Ruffini endings) and fast (Pacinian corpuscles) adapting varieties to detect position, force, acceleration and velocity of indentation on the skin from the external environment (138). Hairy skin (non-glaborous) also possesses exteroceptive mechanoreceptors similar to their glaborous counterparts to detect localized pressure on the skin and nearby joint ambulation (33). In regards to glabrous mechanoreceptors of the feet, many studies in the past had looked at these receptors with respect to balance, however, they had difficulty removing ankle joint proprioceptive organs from the equation with the exception of Nasher er al. (108), and Bloem et al. (14). These researchers were able to isolate plantar surface mechanoreceptors of the feet by using clinical populations with reduced stretch reflexes at the ankle and knee. A more recent study, Meyer et al., was able to eliminate other confounding variables and look solely at the effect of cutaneous, glabrous mechanoreceptors on balance (103). Meyer found that these mechanoreceptors provided minimal assistance for postural support with eyes open in a stable stance (103). However with a more challenging posture and with eyes closed the mechanoreceptors provided crucial feedback to the CNS for postural guidance (103). Another study found evidence that the cutaneous receptors did not purely contribute to postural support but acted primarily to protect against high regional pressures (98). Although it would seem that the feet mechanoreceptors would be the most significant contributors in the maintenance of upright posture it is also the non-glabrous mechanoreceptors of the thigh that help contribute to balance and proprioception. Edin observed that specifically slow acting receptors of the anterio-lateral thigh detected changes in knee joint angle and passive skin stretch (33). The majority of evidence (108, 25, 103, 33) seems to indicate that superficial mechanoreceptors can assist with postural control.

***Muscular co-ordination*:**

When a muscular contraction is performed by the agonist muscle, opposing, or antagonistic, muscle fibres are also activated to help control the movement. This level of antagonist to agonist muscle activation ratio is always fluctuating and can be linked to several causes. These causes include modifications to muscle spindle and Golgi tendon organ firing rates, motor learning of postural skills, or even the utilization of preferred motor unit recruitment strategies (41). As a way to quantify and compare opposing muscular contractions the agonist-to-antagonist muscle activity is often expressed as a ratio or co-activation index (CI) (41). There are multiple methods to express CI (16, 38, 41). One method by Frost demonstrated that a greater overlapping surface area of linear enveloped electromyographic (EMG) activity of the agonist versus antagonist muscles equates to a greater numeric value within the CI. This means that the higher the numeric value of CI the greater the amount of agonist-antagonist co-activation (41). Greater amounts of co-activation can be beneficial in regards to joint stability, although during dynamic movement this co-activation can reduce joint torque, and economy of motion. The amount of agonist-antagonist co-activation can be linked to two different hypothetical modes of control (115). First, an equilibrium-point control (EPC) hypothesis, where the body reacts through reflexive neural feedback mechanisms to maintain or achieve specific joint angles. It is thought that the CNS establishes specific muscle lengths that must be met, otherwise an increase in tonic reflex organ (i.e. muscle spindles) activity occurs to bring the muscle length back to the equilibrium point (24). This EPC hypothesis is used when learning new tasks or encountering new environments, which results in a greater amount of EMG activity generated (52). Second, an internal control (IC) hypothesis is based upon the learning of motor tasks to establish novel synaptic neural pathways for unique movement patterns (12). In other words the CNS governs muscle force to complete a task which has been previously learned. This 'top down' control relies less on proprioceptive spring-like properties of skeletal muscle which, in turn, results in lower levels of viscoelastic muscular forces during movement (19). These two modes of control correlate with the degree of motor learning. This means that recreational, novice athletes might rely on their somatic senses, such as muscle spindles and Golgi tendon organs, or an EPC method. Relying on an EPC method which could cause greater co-activation may allow for higher levels of protection at joints than professionals, who rely more on learned motor skills, or IC method, to allow for efficient movement and economical force production. However, generally under thermoneutral conditions, in a closed-kinetic chain posture, it is likely both IC and EPC methods are used to varying degrees to maintain the relationship between lower limb agonist and antagonist muscle groups, which ensures that there is always some degree of muscular co-activation. Opposing muscle groups, triceps surae and tibialis anterior, for example, work synergistically to keep joint locomotion of the ankle smooth, and efficient.

***Thixotropy*:**

Interrelated with muscle spindle activity, skin stretch response, and muscle agonist-antagonist co-activation is the notion of thixotropic position sense. Thixotropic muscle behaviour was first noticed by researchers who observed that during muscular contraction the initial movement of the muscle appeared stiffer compared to later time points within the same contraction (61). In general, thixotropy can be thought of as muscle stiffness variation as an effect of previous muscle contraction and length (122) and is based on Newtonian physics. Physiologically, thixotrophy is derived from the contraction characteristics of both intra- and extrafusal muscle fibres (72). For example, when myosin crossbridges are formed as the extrafusal muscle is in a shortened state there is a greater resistance to extrafusal muscle lengthening due to this myosin/actin affinity (122). Thixotropy is also present within muscle spindle sense organs which are imbedded within the intrafusal muscle fibres. Muscle spindle firing rates increase at the initiation of a voluntary contraction of their associated intrafusal muscle fibres (122). Immediately after a previous muscular contraction, a new contraction from the same muscle manifests an even greater initial burst from the muscle spindles than was witnessed during the preliminary contraction (122). This is believed to be associated with previous contraction crossbridge linkages of the intrafusal muscle fibres, similar to their extrafusal counterparts, resisting the elongation or shortening of sarcomeres (122). For instance, when the biceps brachii is contracted at a shortened length (i.e. increased elbow joint flexion), this increases the amount of stiffness when the same muscle is subsequently lengthened and is linked to increased excitability or discharge rate of 1A afferent neurons that are connected to muscle spindles (54). Thixotropy has implications for maintaining and returning to previous joint positions and must be accounted for by the NMS to ensure adequate joint control (5). With thixotropic corrections applied, the human body is able to remain in equilibrium even during dynamic postural disturbances where muscle length and tension are in constant change.

The various receptors, muscle behaviours and information pathways within the NMS are one critical component that allows individuals to perform balance and strength tasks proficiently.

Balance:

Balance is the ability to maintain COM relative to the base of support (BOS). Balance can be subdivided into two main categories: static and dynamic balance. Static balance refers to the ability to maintain COM within BOS in a stationary position while dynamic balance refers to the ability to maintain equilibrium while body segments are in motion. Static and dynamic balance can be challenged further through the introduction of unstable surfaces, or external perturbations.

Postural control, or the ability to remain in balance, can be quantified through the use of postural sway analysis, also known as posturography. Posturography includes the use of force plate and EMG technologies to measure muscular coordination with relation to remaining in a balanced position (92). This technique is often employed throughout posture oriented literature and provides a great deal of information about balance. For example, an individual may change their COP, which corresponds to changes in muscle activity across the ankle which, in turn, allows the body to remain upright during both quiet standing and dynamic balance tasks. For instance, an anterior shift in COP is a result of a greater activation of the lateral gastrocnemius while a posterior COP shift is generated by more EMG activity within the tibialis anterior (45). These fluctuations in COP and EMG activity can help to keep an individual's COM within their BOS and therefore maintain balance. There are also a great variety of field balance tests to measure one's equilibrium in both dynamic and static postures. A standard static balance test is the modified Romberg test, which challenges all components (vision, vestibular, somatosensory) of balance control (32). One recently developed test for measuring dynamic balance is the Star Excursion Balance Test (SEBT). This test involves the performance of a series of unilateral half-squats while attempting to reach with the opposite leg as far as possible in up to 8 different directions (32). Increasing the reach distance is thought to require greater range of joint motion and neuromuscular control of the lower extremity, which equates to better dynamic balance (32). The SEBT also provides a greater challenge for a healthy, athletic population compared to other dynamic balance tests that are more suited for geriatric or paediatric populations (51). The SEBT is quick to administer, with a fast learning curve of only four practice trials needed before reliable measures can be recorded with strong repeatability (interclass coefficient (ICC: 0.82 -0.94)) from session-to-session (105). In general, all balance tests ultimately help researchers and clinicians to better understand the way in which one or many components of balance control contribute to postural equilibrium.

Muscular strength:

Generally speaking, muscular strength is directly equated with the ability to produce force. Strength can be divided into three different domains: static (isometric), dynamic (isotonic, isokinetic) and ballistic (plyometric) strength (85). Although there are many physiological aspects which contribute to strength, one of the most relevant to this literature review is the neurological component. Skeletal muscle is comprised of both slow and fast twitch motor units. These motor units are functional units comprised of muscle fibres innervated by alpha efferent neurons that command the muscle fibres to contract either with slow, sustained twitch or a fast, strong burst (56). Human muscle is roughly an equal percentage of fast and slow twitch motor units with some exceptions, such as the soleus, which tends to have a much greater amount of slow twitch units (77). Interestingly, and with significant consequences regarding muscle temperature, which will be discussed later, motor unit distribution, although in most cases is evenly represented within human muscle, tends to be found in varied proportions relative to depth. Through observation of both post-mortem muscle cross-section (90) and EMG (84) it has been witnessed that fast twitch motor units are in greater abundance superficially, both within individual fascicles (20) and whole muscle (77) while conversely, slow twitch variants make up a greater percentage of the units in the deeper layers of skeletal muscle tissue (20, 84). It is possible that having the more forceful motor units towards the periphery of the muscle may assist in contraction by giving these motor units a mechanical advantage with regards to the moment compared to motor units located deeper within the muscle. Perhaps most interesting is that this pattern of larger motor units located more superficially to smaller ones follows a common pattern found throughout nature, notably the concept of granular convection, where larger objects/particles end up on top of smaller items with respect to gravity. This could mean that the main reason motor units are distributed this way is for efficiency's sake.

Neurologically, the greater the number of motor units recruited within an individual muscle, either fast or slow, to perform muscular work, the greater the amount of contractile units (sarcomeres) activated and therefore the higher level of force that is produced with that muscle. Motor units are most likely recruited systematically through the concept of Henneman's size principle which states that the order of motor unit recruitment is based on motor unit size (58). This means that smaller, slow twitch motor units are usually recruited before larger, fast twitch motor units. Strength is also based on the rate at which motor neurons discharge action potentials or rate coding, as faster discharge rates generate higher amounts of force (31). However, just like the NMS in general, the neurological component of strength is not as clear-cut as the previous statement. The body must also balance out strength with joint stability to prevent physiological damage. For example, antagonist muscles will work against the desired agonist movement to help maintain joint integrity, especially when nearing maximal exertion (42). Furthermore, similar to the communication of glaborous skin mechanoreceptors and joint receptors, it has been hypothesized that Renshaw cells, inhibitory interneurons, can also alter motor unit recruitment of both agonist and antagonist muscles to prevent excessive tension from being generated (2). It is obvious that there are a multitude of NMS sensors and motor unit input, many beyond the scope of this review, that ultimately contribute to create the end product, muscular strength.

Neurological Quantification:

Quantification of muscle neurological activity can be measured through the use of EMG, while muscular strength (joint torque) can be measured through the use of dynamometers, such as isokinetic dynamometry or other strength tests. One EMG measure often used in analysis is the root-mean-square (RMS) amplitude. The RMS value can be represented by the equation:

$$RMS = \sqrt{\frac{1}{T}\sum_{t=1}^{T} EMG^2\,(t_i).}$$

Where T = a given epoch or data window and $EMG^2(t_i)$ is the squared value of each datum of EMG within the data window. Although the RMS cannot be used to determine specific motor unit behaviour it can be used to represent the overall power behind the signal which is representative of motor unit recruitment, firing rate and sarcolemmal conduction velocity, or in essence the overall activity level of the muscle (78). RMS also has the added advantage when it comes to testing under different environmental conditions as it is less affected by temperature than other measures such as the frequency content (120). Integration of both EMG and isokinetic testing can give researchers an idea of what types, and quantity of motor units that are being recruited and link that with strength performance (21). Beyond just the raw measures of muscular recruitment and strength, these tools are powerful modes to detect: changes in strength due to training (1), pathological conditions (6), and most relevant to this review, environmental stress (22, 25, 145, 30). It must be noted that one concern with the use of surface EMG, one commonly used non-invasive EMG modality, and muscle force within a cold environment is the fact that changes in tissue temperature may alter the EMG signal without a change in actual muscle activity (150). This makes it difficult to discern if motor unit recruitment patterns have changed or if changes in the EMG signal came as a result of a reduction in nerve conduction velocity or a modification to the low pass filter characteristics of the underlying tissue (150). It is possible to employ correction factors or use more invasive EMG techniques to help adjust for temperature, although the ideal temperature range for lower limbs and surface EMG analysis remains 32-34˚C (129).

Therefore the researcher using surface EMG in colder situations needs to be cognizant of the limitations of such data collection tools when drawing conclusions.

Correlation between strength and balance:

Although both muscular strength and balance ability are important to the successful execution of motor tasks the actual relationship between strength and balance ability is not clear. It is suggested that the two variables are linked such that as strength improves so too does mastery of balance (57, 11, 65, 66). Conversely other evidence shows that regardless of balance ability, strength plays a limited role in balance performance (46, 47, 91, 99). It has been hinted at that there might be a minimum threshold of strength, that once attained and maintained, is enough to keep balance proficiency from dropping (99). Perhaps it is only with advanced age, or certain medical conditions associated with skeletal muscle atrophy or NMS deficit that will cause a drop below this minimum level of strength, which then negatively impacts balance. More research is needed to clarify if there is indeed a connection between balance and strength. It could be that developing more studies similar to Dewhurst and colleagues (28), which looks at both older and younger populations, as well as individuals in sedentary versus strength trained states could be advantageous. These types of studies could pinpoint if there is a definitive correlation between balance and strength and, if this correlation exists, if it is specific to all individuals or only select populations.

The NMS operates in a thermally diverse environment, the following section deals with the interaction of temperature and the NMS.

Thermal relationships between the lower extremities, body and external environment:

The human body can be thought of as an open system with regards to the concept of modern thermodynamics (87). This open system concept is defined by the exchange of matter between the external and the body's internal environment as well as the thermal gradients that exist between individual structures within the body, and between the body and the external environment whereby energy flows from areas of high energy (temperature) to low energy (temperature).

There are several pathways for which energy is received and exchanged between the human body and the external environment. This is represented by the heat balance equation:

$$\dot{S} = \dot{M} \pm \dot{W}_k \pm \dot{R} \pm \dot{C} \pm \dot{K} - \dot{E}\ (W \cdot m^{-2})$$

Where heat storage, $\dot{\boldsymbol{S}}$ in $W \cdot m^{-2}$ is solved for by the addition of $\dot{\boldsymbol{M}}$, or the metabolic heat production, the subtraction of $\dot{\boldsymbol{E}}$, or wet and dry evaporative heat exchange, and the subtraction or addition of $\dot{\boldsymbol{W}}_{\boldsymbol{k}}$ (external work), $\dot{\boldsymbol{R}}$ (radiation), $\dot{\boldsymbol{C}}$ (conduction), and $\dot{\boldsymbol{K}}$ (convection). It is the goal of human physiology to maintain a balanced state of heat storage to prevent or minimize states of hyperthermia or hypothermia.

When exposed to cold ambient temperatures, a negative $\dot{\boldsymbol{C}}$ and $\dot{\boldsymbol{K}}$ draw energy away from the body and can potentially create a negative heat storage value which can lead to hypothermia. As the body attempts to keep heat storage as balanced as possible it is often the tissue temperature of the legs and arms that are sacrificed to maintain the temperature of the body's core (133). This physiological change due to fluctuations in ambient temperatures has been come to be known as the core-shell model of temperature distribution which was introduced by Aschoff and Wever in 1958 (3) and verified by Webb in 1992 (148). By reducing localized limb tissue temperature, this has the effect of increasing the body's thermal resistance, due to a smaller temperature gradient for heat to flow from the core to the external environment. This increased resistance slows down energy loss. This thermal resistance can be represented by the equation:

$$R = \frac{Temperature\ gradient}{Heat\ flow} \frac{°C}{W \cdot m^{-2}}$$

Where R = resistance or the amount of insulation (76). A primary reason as to why this increased resistance occurs could be that it helps to protect against rapid energy loss so that essential bodily functions (i.e. liver enzymatic activity, cardiac cellular functions) remain within optimal temperature ranges.

This reduction in shell tissue temperature is primarily accomplished by passive conduction and convective energies and through active changes in circulation due to two physiological mechanisms, these being changes in localized nitric oxide production and adrenergic alterations:

One: when skin, subcutaneous tissue and skeletal muscle are exposed to cold ambient temperatures blood vessels react by changing the rate at which nitric oxide is produced. With cold stimulus, blood vessels vasoconstrict due to an inhibition of the enzyme nitric oxide synthase (NOS) (63, 152). This in turn reduces the amount of blood capable of flowing through the affected vascular network and mitigates the potential for heat transfer from the blood to the surrounding tissues.

Two: thermally sensitive afferent neurons detect changes in temperature that signal an andrenergic response in the body to vasoconstrict blood vessels. Specifically, it is during the initial 10 minutes of cold exposure that these afferent neurons trigger a constriction of blood vessels (62). It could be as a result of neural fatigue, desensitization to the thermal stimulus, or a reduction in the thermal gradient that causes these afferent cold sensitive neurons to lose their ability to contribute to the adrenergic vasoconstrictor response after 10 minutes (62). During later stages of cold exposure it has been shown that these afferents do not assist in constriction and that is it most likely NOS inhibition or other unknown mechanisms which maintain vasoconstriction with long-term exposure (62). A modest amount of additional information will be provided on peripheral thermal afferents later in this literature review.

Whether or not the lower extremities are exposed to a cold stimulus that also threatens the core, mechanisms are in place which reduces the conductance of heat from the core to the shell tissues and from the deep to superficial layers of the body. Although the ultimate goal of minimizing heat loss may be achieved with this physiological countermeasure, the subunits of the peripheral neuromuscular complex in the lower extremities, which are important for maintenance of balance and muscular strength, can be compromised.

Neuromuscular Interaction with Cold Exposure:

Balance and cold exposure:

Balance, or postural control, can be challenged by cold temperatures, through cold inflicting impairment on the intrinsic somatosensory components of the NMS, and through an increased likelihood of exposure to extrinsic factors such as slippery, icy surfaces (43). Of substantial importance with respect to somatosensory and NMS involvement are the alteration of the stretch reflex (112, 9, 35), superficial mechanoreceptors (94, 7, 138, 34), joint-position sense (23, 136), and muscle agonist-antagonist relationships of the lower extremities (111, 113). The interaction with cold temperature on these balance mechanisms will be outlined over the next few pages:

Deep mechanoreceptors (muscle spindles):

The stretch reflex, a muscular contraction due to passive stretching of the same musculature, has long been suspected to play a role in the decrease of postural stability with cold exposure. A linear relationship between the firing rates of muscle spindles and muscle temperature has been observed (35). Annulospiral and flower-spray muscle spindle configurations, when cooled, decreased their firing rate compared to the same muscle tension within thermoneutral conditions (35). Eldred and colleagues found that a 10˚C drop in muscle temperature elicited a drop in muscle spindle firing rates of between 10 to 30 pulses per second (35). Bell and colleague later reinforced this finding through demonstrating a drop in muscle spindle activity through a reduction in response from the tendon-tap test with skin and intramuscular temperature of 18.4˚C and 12.1˚C below their normal, room temperature values respectively (9). This reduction in spindle communication could be thought of as a decrease in the sampling frequency of the continuous monitoring of muscle length. This ultimately leads to a reduction in the flow of accurate information to the CNS about muscle length and has the effect of hindering control of the affected muscle. It has also been shown that the afferent nerve fibres which integrate the muscle spindles with the NMS are influenced by temperature. Conduction velocity slows down as nerve temperature decreases, with observations most apparent for spindle group 2 (smaller) afferent fibres (135). With reductions in the muscle spindle mechanism to monitor and control muscle stretch, especially in the lower limbs, it is possible that balance, which relies on accurate afferent signals from the muscle spindles, could become impaired with lower limb cooling.

Although most evidence demonstrates a positive linear relationship of decreased temperature and decreased muscle spindle excitability, some research has shown the opposite relationship. Oksa et al. found with low-intensity repetitive work during cold exposure that the stretch reflex of the forearm extensors and flexors was increased (109). This research seems to be the exception but the results are based on solid physiological argument. It might be that the increased co-contraction of muscle groups due to cold exposure generated an increased response from the muscle spindles to maintain appropriate levels of muscle length (109). It should be noted that this research was conducted on upper limb musculature, it might be that lower limb muscle spindles behave differently with cold compared to their upper body counterparts. Even if muscle spindle activity is enhanced with cold exposure, as Oksa and colleagues have found, it is still possible that this increased activity could still affect balance by changing muscular coordination from what the body is familiar with when under room temperature conditions.

Superficial mechanoreceptors:

Mechanoreceptor ability to help guide limbs due to changes in compression forces on the skin and joint ambulation are altered under localized cold. The behaviour of mechanoreceptors to varying temperatures was first scientifically examined by Hensel and Zotterman in 1951 (59). They found that while thermoreceptors, temperature sensitive receptors, responded to minute changes in local temperature, mechanoreceptors also responded to temperature changes (59). However, these changes needed to occur much more rapidly and of a greater magnitude temperature drop than with thermoreceptors to elicit a change in mechanoreceptor firing rates (59). More recently, mechanoreceptors on the plantar surface of the feet have received most of the attention with respect to balance, as the feet contain a higher density of dermal mechanoreceptors than the rest of the legs, and are the only parts of the human body in direct contact with the ground when individuals are trying to remain upright. Magnusson and colleagues were one of the first research groups to look at the direct effect of cold temperatures on the plantar mechanoreceptors of the feet (94, 93). Their research uncovered that, while holding a static position, anterior-posterior postural sway velocity increased significantly when subjects were in colder than normal temperature conditions regardless of visual feedback (94). Magnusson et al. also found that lateral sway increased to a great extent with mechanoreceptors that had been cooled down (93). Stål and colleagues found similar results, in that increased localized cold to the feet caused an increase in postural sway (138).

Not only static, but dynamic postural control is affected by mechanoreceptor activity modification due to temperature drops. By cooling down the plantar aspect of the feet, individuals are prone to maintain a more cautious walking pattern (34). This would indicate that the ability to accurately adjust COP while the body is in motion is reduced with colder feet.

Recalling that there are both slow and fast acting mechanoreceptors, with the fast mechanoreceptors generally being responsible for reactionary alterations to maintain balance in more dynamic situations (139). Perry et al. measured reactionary postural shifts to unpredictable, multidirectional perturbations (118). Cooling down the soles of the feet with ice water for 20 minutes generated a significant reduction in this compensatory sway mechanic that created poorer reactionary countermeasures to the postural disturbances (118). Therefore, with colder extremities, it is possible that the sudden, unexpected challenges to posture may have a greater chance of overwhelming the body's ability to remain upright.

To further complicate matters, it can easily be forgotten that the body's thermal environment is not only reacting to the surrounding ambient air/water conditions but to the heat generated from within as a byproduct of metabolic and mechanical work as expressed in the heat balance equation $(\dot{\boldsymbol{M}} \pm \dot{\boldsymbol{W}}_{\boldsymbol{k}})$. This balancing act between internal and external temperatures sets up dynamic temperature gradients that allow for heat flow and cause superficial to deep layers of muscle, adipose, and skin tissues to vary relative to one another temperature-wise. Furthermore, temperature gradients can be affected by blood vessel architecture where localized regions of muscle, adipose and skin tissue might be warmer due to greater volumes of blood flow (82). For instance, recalling that muscle spindles tend to exist in greater abundance near blood vessels it could be that muscle spindles are more resistive to the effects of cold compared to superficial mechanoreceptors when it comes to environmental cold exposure.

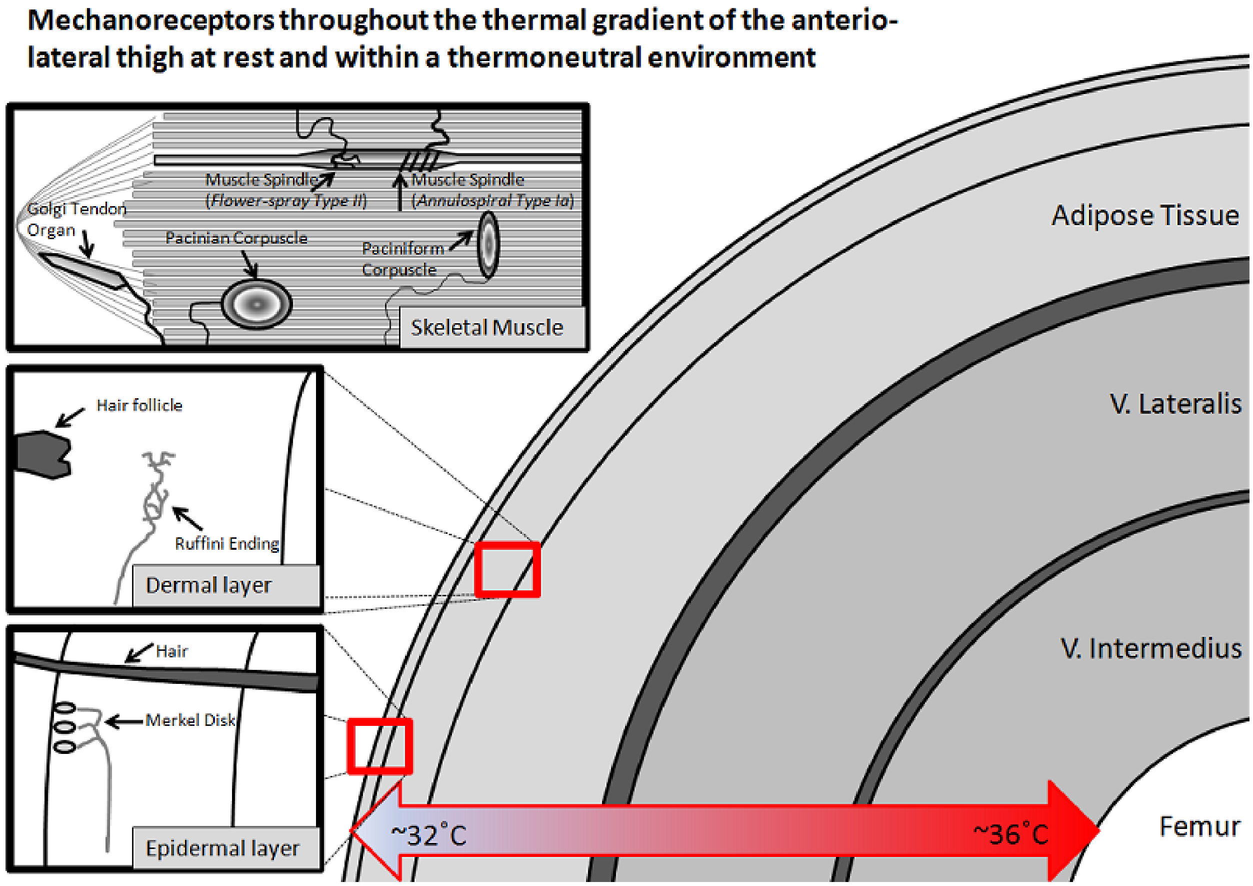


Figure 2.2: Mechanoreceptors throughout the thermal gradient of the anterio-lateral thigh at rest and within a thermoneutral environment

It is generally accepted that at rest and at temperatures ranging from room temperature (~21-24°C) to cold water immersion temperature of 8°C, muscle temperature (T_{mu}) gradients tend to follow a parabolic pattern, with the deep and middle regions of muscle significantly warmer than superficial areas (See figure 2.2) (17, 82, 130). For example, Kenny et al. observed that, with a multi-sensor temperature probe, thigh musculature T_{mu} at 10 mm and 25 mm from the femur were quite similar (~36°C) while at 40 mm distance from the femur T_{mu} had dropped off by 1°C compared to the deeper T_{mu} (82). During aerobic exercise, with the increased perfusion of blood to supply working muscles with O_2 and nutrients, remove waste, and manage elevated core temperature, the parabolic pattern is replaced with a linear one where T_{mu} is similar throughout all depths even in colder environmental conditions (130). It has yet to be looked at whether anaerobic exercise, which creates ischemic conditions within the muscle, creates this linear T_{mu} pattern.

Thixotropy:

It is often the case that individuals remark on feeling that their joints and muscles are stiffer when their limbs are cooled down during cold exposure. This increased stiffness has the potential to alter proprioceptive ability, specifically the sense of the affected joints and muscles. This could, in turn, evoke problematic reductions in balance control during dynamic tasks. Sekihara and associates found by cooling the biceps brachii muscle down to 5˚C that, after a maximal contraction of the biceps brachii at a predetermined joint angle, the individual sensed that their limb was in a significantly different position than in actuality (136). This being said, a subsequent study on the thixotropic position sense of the knee joint failed to show any sign of increased position sense error with joint cooling (23). The author states that it is possible that there was some degree of position sense error incurred by the cold application in this second study. This is due to the design of the study which was built to show only large discrepancies in joint angle (23). Balance, and especially dynamic postural control, requires the individual to have as precise a control over limb positioning as possible. With reductions in position sense to control for thixotropy, balance may become more precarious or create an increased injury risk due to modifications in joint angle at other regions in the kinematic chain to maintain equilibrium.

Agonist-antagonist Ratio:

Muscle co-activation helps to keep joints stable, helping to maintain posture, especially when learning a new motor task (115). During dynamic balance activities, the human body relies on this relationship of muscles to learn and maintain correct joint/body position. When exposed to cold temperatures, the neural activity and coordination between muscles are altered. These cold temperatures increase the degree of co-activation through agonist-antagonist relation (123). For example, Bawa and colleagues observed that with general cooling the extension of the forearm was accompanied by greater amounts of antagonist (biceps brachii) EMG activity (7). Further research by Oksa and colleagues found that, in both the lower and upper extremities, with cold air exposure ranging from 27˚C to 10˚C, the colder air caused a drop in agonist activity and an increase in the antagonist EMG pattern (113, 111). This physiological response is known as the "braking effect" and is a documented source for decreases in muscular performance (111). An increase in this counter-productive muscle activity with regards to fluid and efficient movement patterns could affect dynamic balance tasks. Hypothetically, with a decrease in leg temperature, an increase in biceps femoris activity during hip flexion would result in reducing an individual's ability to extend a leg in the SEBT, having the possible effect of decreasing their maximal reach distance.

Thermal detection and thermal sensitivity of skeletal muscle:

Although this review focuses on the effect that temperature has on the NMS it should briefly be noted that peripheral thermal detection is a crucial ability that enables individuals to react to external and internal energy variations. Unmyelinated free nerve endings that are scattered throughout the skin layers, at some places projecting into the epidermis, form the majority of body's external thermal receptor compliment (134). Both cold and hot sensitive thermal receptors have been identified which arguably are closely linked, or potentially one-and-the-same, with pain sensitive nociceptors (49). It makes practical sense that the human body is founded on the principle of efficiency. This principle is exemplified by the observation of Sir Charles Sherrington, that most thermal detection is invested towards the periphery of the organism (137). Following this pattern it appears that deeper skeletal muscle does have limited capacity to detect changes in temperature. High-threshold warm sensitive thermoreceptors within muscle have been shown to respond to injected saline solution of varying temperatures (48). Interested readers should consult the 2004 literature review by Green (49) and 2010 review by Schepers (134) to gain more insight into human peripheral thermoreception.

Additional information and contrasting evidence:

In addition to these potential sources for decreased balance, increased synovial fluid viscosity, deviations in the viscoelastic properties of muscle and general joint stiffness have also been researched with regards to cold exposure, although with only passing remarks regarding balance (121). It is feasible that increased joint and muscle stiffness could result in a reduced ability to respond to postural challenges.

The vast majority of research revolving around cold exposure and balance impairment suggest that there is a positive relationship where decreases in temperature lead to decreases in the ability to remain upright. One study which did not show this relationship was by Dewhurst et al. (28). Comparing a younger female population to an older female population, no significant decrease was noted in postural sway for either groups when their lower limb muscles were cooled to 31°C (28). This result went against their initial hypothesis, based off of previous research (29), which showed increases in neuronal excitability with cold exposure among youthful participants. It is possible that the T_{mu} of 31°C was not sufficient to impair balance and that lower temperatures would have been needed to show a significant effect.

Muscular strength and cold exposure:

Recall that human muscle is often found to contain a greater percentage of fast twitch relative to slow twitch motor units within more superficial relative to deeper regions of skeletal muscle tissue. Due to their closer proximity to the external environment, it could be that fast twitch motor units are more often affected by temperature changes than their slower counterpart. This could be a potential reason as to why it seems that forceful and rapid contractions, that tend to utilize more fast twitch fibres, are impaired to a greater extent than slower, more sustained muscle activity. This pattern of cold exposure and muscle strength will be outlined briefly over the next several paragraphs:

Isometric strength and muscular endurance and cold exposure:

Beyond fatigue associated with muscle activity, exposure to cold environments, with the potential for reductions in T_{mu}, can modify isometric muscle mechanics. A study in 1958 found that maximal isometric contraction was reduced when the muscle was cooled below 27˚C (22). Since that study, more have been published (25) and summarized (123) which show the same pattern. While maximal isometric contraction seems to be reduced with muscle cooling, endurance of submaximal isometric contraction appears to increase. Davies et al., (25) and Thornley et al. (145) both showed that, with local muscle and skin cooling, there was a significant increase in time to exhaustion for a submaximal isometric contraction.

Dynamic strength and cold exposure:

Reductions in T_{mu} do appear to cause impairments to dynamic contractions. For instance, cooling by each degree Celsius can reduce the peak strength of dynamic contractions by as much as 2-5% (129). It is thought that this drop in force could be due to slowing down of metabolic pathways, and/or desynchronization of individual motor units (129). Explosive movement of the leg muscles also shows increments of impairment with cold. Asmussen et al. used a vertical jump test and found that with reduced T_{mu} (~33°C) that jump height was considerably reduced (4). However, Asmussen also found that a greater amount of elastic energy could be released under these same cold conditions, allowing for a gain in height from a drop jump compared to thermoneutral T_{mu} (4). It is argued that this improved ability to store and release elastic energy within the series elastic component of the muscle is due to reduced cross-bridge breaking at lower temperatures (4). Although there are potential strength mechanisms that seem to improve with decreasing temperatures the overall NMS pattern shows reduced performance with a colder thermal environment.

Nerve conduction velocity:

One common physiological measure between balance and strength performance is the magnitude at which messages travel in both afferent and efferent directions. It has been established that it is important that nerve pulses travel at a fast enough speed to create the desired level of muscular contraction and overcome inhibitive interneurons through temporal and spatial summation (92). As tissue temperature drops the speed at which nerves are capable of transmitting action potentials also decreases. At room temperature (skin temperature of ~32-34°C) nerve action potentials are conducted at 72-120 m/sec., 35-120 m/sec., 35-75 m/sec. and 0.5-30 m/sec for extrafusal muscle fiber, muscle spindles, cutaenous mechanoreceptors, and thermoreceptors respectively (146). With every degree Celsius drop in skin temperature it is thought that nerve conduction velocity is impaired by 1.5-2 m/sec. with larger, myenlinated axons more affected than smaller non-myelinated axons (129). This value takes into account the thermal gradient and that the near-nerve temperature can be substantially different from skin temperature (129). Several physiological parameters can account for this drop in nerve conduction velocity with cooling. Action potentials rely on the speed at which sodium gates open and close to allow for depolarization along the length of the axon (139). As nerve temperature drops so too does the speed at which these sodium gates open and close which translates to a slower depolarization and repolarization and therefore slower conduction velocity (64). This decrease in conduction velocity of the axon can carry over to the sarcolemmal action potential where a decrease in muscle temperature also decreases the velocity of the depolarizing wave along the outer membrane of skeletal muscle (18). A drop in conduction velocity could be a reason as to why both sensory information and effector performance can be reduced with the cold.

Conclusion:

The pattern of integration that the nervous system possesses extends to all parts of the human body, as Sir Charles Sherrington proclaimed in his 1906 publication: The Integrative Action of the Nervous System. This much is clear, as the body is built on a foundation of kinematic and kinetic chains, where transmission of forces and energies from one segment of the body to another allow for human movement and athletic activities (126). Muscular strength and balance are the end result of various components, from muscle spindles and Pacinian corpuscles to synergistic and antgonistic muscle contraction, forging and maintaining an intricate communication network. Integration extends beyond the boundaries of the human body as it obeys the universal laws of thermodynamics. External temperature variations influence the body's internal climate from minute-to-minute. Cold temperatures can draw energy away from the body at faster rates slowing down nerve conduction (129) and impairing muscle activity (111). Apart from the possible philosophical implications of the above sentences there is an obvious practical importance as well. Outdoor athletic endeavours can expose participants to temperatures which can hinder their ability to produce force and maintain equilibrium thereby reducing performance and increasing chance of injury. Past research has looked at full body cold air exposure (112), or a specific amount of CWI (i.e. up to the knee) (104), but none have researched what the impact of varying amounts of CWI relative to the segments of the lower extremities have on balance and strength performance. The rest of this thesis is dedicated to this research question.

Statement of the Problem:

Through peripheral mechanisms, both balance and muscular strength have been shown to be altered when the limbs are exposed to frigid temperatures. Most research demonstrates a positive linear relationship for balance and strength, with progressively colder temperatures. The majority of this research has been done without consideration of the lower limb as an integrative machine where an effect on one component can influence other mechanisms that ultimately lead to a change in kinesthetic performance outcome.

Little research has been conducted to look at the relative contributions of different limb segments (foot, shank, and thigh), and associated joints to dynamic balance with respect to cold exposure. For example, is it the reduction in temperature of the foot and ankle that contribute the most to possible dynamic balance impairments or does cooling down the entire limb have even greater consequences for balance mechanics. Previous research has suggested that more scientific focus needs to be invested in observing more challenging dynamic balance tasks and their interaction with cold exposure.

Purpose:

The novel experiment outlined within this document hopes to fill a gap in the scientific understanding of the interaction between the integrative nature of the NMS and the thermal environment. The primary purpose of this research is to determine the effect that cold exposure has on the performance of a challenging dynamic balance task. The SEBT is a balance task which not only requires precise neuromuscular control but a high degree of muscular strength to be successfully executed. Secondary objectives include uncovering any connections that may exist between muscle groups and peripheral nervous system receptors through indirect exposure to the cold stimulus. For example, does cooling up to the ankle impact the agonist-antagonist ratio of the thigh musculature or is direct cooling of the muscle required to elicit this effect.

Hypotheses:

By utilizing the SEBT, stork stand test and isokinetic knee extension/flexion tests on young, recreationally active males with segmental limb cooling; there are several null hypotheses that will be investigated:

1. A decrease in muscle, skin and joint temperature of the foot and ankle will not contribute to a greater relative decrease in balance performance (SEBT reach distance, SS time) compared to cooling down a greater volume of the lower limbs in the SEBT and SS tasks.
2. Peak torque of the quadriceps and hamstrings will not be reduced to the greatest extent with entire lower limb cooling compared to knee and/or ankle cooling.
3. In regards to EMG, there will be no significant increase in muscular co-activation between agonist and antagonist pairings with cold exposure across all conditions during maximal reach of the SEBT. The greatest amount of co-activation in a muscle pairing will not occur when the muscle temperature is directly influenced by the CWI (i.e. there will be no difference in the co-activation between biceps femoris and vastus lateralis across all conditions).

Methods:

Participants:

The study enlisted 10, non-acclimated, recreationally active males, (age 22.8 ± 3.4 years; body mass 76.5 ± 9.1 kg; height 1.76 ± 0.06 m; body fat 12.8 ± 7.7% mean ± SD). Participants were excluded from the study if they currently had body fat percentage above ~25% (119). Participants had a shank fat volume of 671.7 ± 349.4 cm^3 and a thigh fat volume of 1173.2 ± 756.9 cm^3 (exclusion criteria of shank and thigh fat volume > 1500 cm^3 and >2500 cm^3 respectively). These volumetric values were recorded to ensure that participants would be cooled consistently with the established CWI protocol. Subjects were free from Raynaud's Syndrome, neurological, neuromuscular and balance (vision, vestibular, somatosensory) related disorders determined through the administration of a health questionnaire (adapted from Physical Activity and Readiness Questionnaire, CSEP). Upon an initial familiarization visit to the lab, subjects were asked for their written, informed consent (see appendix F) and provided with a written and oral presentation on the nature and purpose of the experiment, along with the potential risks involved. During experimental trials participants were asked to refrain from caffeine consumption on the day of the trial and avoid alcohol and excessive lower body exercise 24 hours prior to each test session. Ethical approval was obtained through the Brock University Research Ethics Board (REB# 11-030) and the study complied with the declaration of Helsinki for human research.

Familiarization:

Body Dimension Analysis:

Each participant had their subcutaneous adiposity measured through the use of 3-site (Jackson & Pollock) (74, 73) skinfold caliper (Harpenden, Baty International, West Sussex, England) test plus a calf skinfold measure to gauge lower limb subcutaneous adiposity. Subject height and weight was also recorded. Participants had their dominant leg measured for height from the anterior superior iliac spine (ASIS) to medial malleolus to normalize reach distance values for the dynamic balance task (51). Leg dominance was determined through asking what leg the participant would kick a ball with. 9 participants were right leg dominant and 1 participant favoured their left leg. Finally, anthropometric segmental limb volume was calculated through measuring both the length and girth of lower limb segments. Limb volume was used to help determine fat versus fat free volume of the thigh and shank (81) and for a volumetric reach analysis. Limb segment length coupled with limb volume was used to gauge water level within the immersion tank for each of the experimental trials (i.e. appropriate water level for knee cold water immersion versus ankle cold water immersion)

Protocol Familiarization:

Participants were seated in the Biodex® 3 isokinetic dynamometer (Biodex Corp., Shirley, NY, USA) and the equipment adjusted to conform to the subject body dimensions. These settings were recorded for use during the experimental trials. Participants were allowed to perform as many contractions of the knee extensors and flexors at both concentric and eccentric settings to ensure that they were proficient and comfortable with the movement. Participants were shown the balance tasks, both verbally and through demonstration, by the investigator. Participants were allowed to practice balance tests, SEBT and Stork Stand Test, to ensure that they understood how to perform these field measures of dynamic and static balance.

Experimental Trial Protocol:

The experiment consisted of 4 trials administered in a randomized order. Trials were conducted at minimum a 3 days span between each other to minimize the potential for acclimation to the CWI. For each subject, trials took place at the same time of day to account for normal diurnal variation in circadian rhythm on core temperature (88) and balance performance (53). The trials varied only by the amount of lower limb exposure to the 12˚C water bath. Each trial followed a dual-phase, multi-step protocol (see figure 3.1). The first phase included participant instrumentation, followed by a cold water immersion (CWI), T_{mu} measurement and finally isokinetic strength measurement. The second phase, which began immediately following the strength testing, included re-instrumentation, a second CWI, a second muscle temperature measurement, isometric EMG normalization, and finally a balance field test battery performed with bare feet. Each dual-phase trial spanned approximately 2 hours in duration (see figure 3.1). All testing took place in climate controlled laboratories with an average room temperature of 22.4 ± 0.8°C, relative humidity of 38.8 ± 12.4% and barometric pressure of 754 ± 5.3 mmHg. The majority of testing occurred between the months of February and May 2012 with an average outdoor temperature of 9.5 ± 6.4°C on trial days.

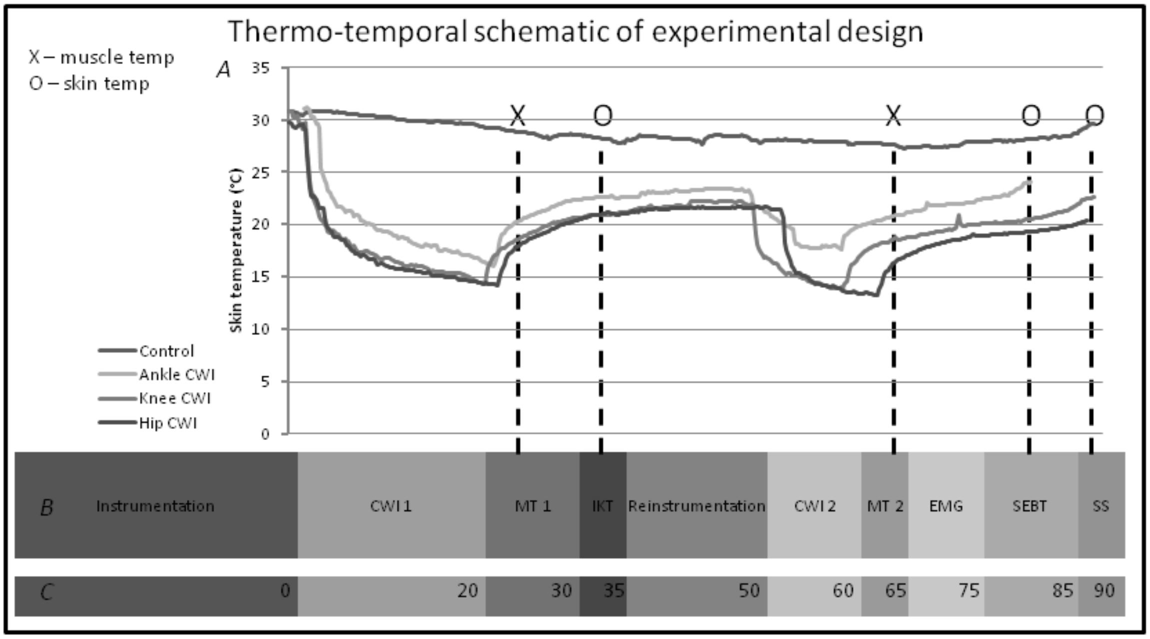


Figure 3.1: Thermo-temporal schematic of experimental design. A: representative raw skin temperature plot from 1 participant with indicated time points for muscle temperature and skin temperature measurements. (note that there is a time discrepancy between the trials (took longer to enter/exit cooling tank, etc.) **B:** experimental segments. CWI = cold water immersion, MT = muscle temperature, IKT = isokinetic testing, EMG = electromyographic normalization, SEBT = star excursion balance test, SS = stork stand. **C:** cumulative trial time (min.), 0 min = start of data recording

Phase 1: Strength Testing

Core temperature:

Upon arrival to the Environmental Ergonomics Lab (EEL) (Brock University, Canada) participants were asked to insert their rectal core temperature probe (400 series, Mallinckrodt Medical) 15 cm beyond the anal sphincter within the privacy of a private changeroom.

Electromyographic recording:

Once the core probe was inserted participants returned to the EEL where EMG sensor sites, 6 in total, were located with SENIAM (www.seniam.org) recommendations. In order to ensure electrodes were not placed directly over motor points, researchers, through use of low-intensity, evoked stimulation located skeletal muscle motor points, and if necessary, shifted electrode placement away from them, towards the muscle tendon. Motor points were determined as the location of the cathode yielding the strongest contraction with the lowest evoked pulse amplitude. The evoked stimulation was accomplished with the use of stimulating electrodes that were connected in series with an isolation unit (Grass Telefactor SIU8T, Astro-Med, Inc., West Warwick RI, USA) to a peripheral nerve stimulator (Grass Telefactor S88, Astro-Med, Inc., West Warwick, RI, USA) that delivered a square-wave pulse 0.5 ms in duration. These sites, 6 in total, (non-dominant and dominant limb vastus lateralis and biceps femoris, and dominant limb tibialis anterior and lateral gastrocnemius) were then shaved, with the non-dominant limb muscle sites further prepared with light abrasion, isopropyl alcohol and skin prep gel (Nuprep®, Weaver and Company, Aurora CO, USA). Conductive gel (Signagel®, Parker Laboratories Inc., Fairfield NJ, USA) was then applied to the electrodes which were then attached to the 2 non-dominant limb sites and a ground electrode adhered to the non-dominant limb ASIS. EMG electrodes were placed on the bulk of the muscle belly and away from motor points. Transpore™ tape (3M™, St. Paul MN, USA) was placed over top of the electrodes in addition to the electrode adhesive to help keep the electrodes in place during each trial.

The study utilized a hard-wired 4-channel EMG system (Delsys Inc., Boston, MA., USA). Muscle activity was picked-up through active, single differential electrodes (DE-2.1, Delsys Inc., Boston, MA., USA) with a 10 mm inter-electrode distance and transmitted via wires to the Bagnoli amplifier (Delsys Inc., Boston, MA., USA) where the information was band pass filtered at 20-450Hz and then sampled and digitized by the

16-bit multiplex A/D DAQ card (National Instruments Corp., Austin TX, USA) which was set to a sampling rate of 2500Hz. EMG analysis was performed on the filtered EMG signal by means of a root mean square (RMS) mathematical protocol through a custom script in MATLAB® (Mathworks Inc., Natick MA, USA)

Skin Temperature:

Skin temperature was recorded at 5 sites through the use of wired skin thermistors. These 5 sites included chest, posterior upper arm, lateral thigh, lateral shank, and dorsal aspect of the foot. The 4 former thermistor locations were used to calculate mean skin temperature with the Ramamathan equation for mean skin temperature (124).

$$\overline{\mathrm{T}}_{\mathrm{sk}} = 0.3\ t_{\mathrm{chest}} + 0.3\ t_{\mathrm{arm}} + 0.2\ t_{\mathrm{thigh}} + 0.2\ t_{\mathrm{leg}}$$

Transpore™ tape (3M™, St. Paul MN, USA) was placed over top of the thermistors to help keep the thermistors in place during each trial.

Data Logger:

The 5 skin thermistors and 1 core temperature probe were tethered to a portable data logger (Smart Reader Plus, ACR Systems, Surrey, BC, CAN.). Throughout each trial this data logger was either carried by the participant or placed on the ground while conducting the strength and balance measures.

Cooling Protocol #1:

After instrumentation of rectal temperature probe, skin thermistors, and EMG electrodes, subjects, seated within a hard plastic tank (120 cm x75 cm x72 cm), were either exposed to no cold water (thermoneutral) or exposed to cold water up to the ankle (lateral malleolus), knee (lateral condyle) or hip (ASIS) while seated for 20 minutes.

Subjects were seated in a position such that when the water level was up to the lateral condyle that their thigh remained relatively out of contact with the water to keep the thigh musculature a neutral temperature. Subjects remained dry during water exposure through the use of a waterproof barrier (Ocean Commander immersion suit *outer shell*, Mustang Survival, Bellingham, WA, USA). Water temperature was regulated at 12˚C through the use of a recirculating chiller (Model 5202, Polyscience, Niles, IL, USA).

Once 20 minutes of lower body environmental exposure had elapsed, the participant exited the cooling tank under their own power, removed the immersion suit shell and seated themselves in a transport chair (Airgo™, AMG Medical, QC, CAN). They were then wheeled to the muscle temperature station within the EEL and then the nearby Applied Physiology Laboratory by the researchers.

Muscle Temperature Measurement #1:

5 minutes after the cold water immersion and approximately 5 minutes before the isokinetic strength testing, participant T_{mu} of the non-dominant limb vastus lateralis and lateral gastrocnemius was measured with sterilized 26 gauge muscle temperature probes (Model MT-26/2, Physitemp Instruments, NJ, USA). Probes were inserted by the researcher into the bulk of the muscle belly within 5 cm of EMG electrodes, if present, and to a depth of 3 mm beyond the epimysium. Probes were held for ~5 s, until a stable temperature was recorded.

Isokinetic Muscle Strength Test:

Isokinetic, concentric and eccentric, knee extension/flexion torque and EMG activity of the non-dominant vastus lateralis and biceps femoris was measured with the use of an isokinetic Biodex 3 dynamometer (Biodex Corp., Shirley, NY, USA) and Delsys 4-channel surface EMG (Delsys Inc., Boston, MA., USA). Subjects seated themselves in the Biodex seat and had their knee angle set to 90˚ and hip angle set to 110˚ based on familiarization measurements. Straps were secured across the chest, waist and non-dominant thigh to minimize extraneous movements. The rotational centre of the lever arm was aligned to the lateral femoral epicondyle of the knee. The lever arm was secured to the lower leg with the resistance pad around the ankle. Range of motion (ROM) limits were set (~170° knee extension, 180° = full knee extension) and then participants completed 3 sub-maximal ‘warm-up’ isokinetic, concentric contractions of the knee extensors and flexors at a velocity of 45˚/s through 90% of their constrained knee range of motion (5% of participant ROM was taken away from both start position (90°) and end position (170°) of knee movement). This reduction in ROM was done to assist during the eccentric repetitions which placed the muscles in a more advantageous mechanical position (i.e. length/tension relationship) to be able to produce enough torque to trigger the dynamometer to begin lever arm motion. Once the warm-up set was completed the participant rested for 30 seconds and then performed either 3 maximal isokinetic concentric knee extension and knee flexion contractions at a velocity of 45˚/s or 3 maximal isokinetic, eccentric knee extension and knee flexion contractions at a velocity of 45˚/s. Participants then rested for 60 seconds and then performed the contraction type which they hadn’t performed during their first set (concentric/eccentric). This order of concentric and eccentric sets was kept constant for each participant, for all four of their trials, but was randomized between participants. 10 seconds of rest was maintained between each repetition, while 60 seconds of rest was maintained between maximal concentric and eccentric sets to minimize fatigue, and maintain agreement between the rest periods used during dynamic balance testing. During each repetition, participants were verbally encouraged by the tester to contract as forcefully as possible. If an error occurred during a set (equipment, tester or, participant error) then a further 60 second rest period was allowed followed by another 3 repetitions of the set that contained the error. Isokinetic torque was recorded at a frequency of 100 Hz, with the highest value between the three contractions for each maximal set used for further analysis. EMG activity was recorded with EMGworks 3.5® (Delsys Inc., Boston, MA, USA).

Once isokinetic testing was completed participants were then wheeled via transport chair back to the EEL to continue the trial.

Phase 2: Balance Testing

Instrumentation #2:

The 2 EMG electrodes were removed from the non-dominant limb, and cleaned with isopropyl alcohol to prepare their use for further EMG recording. The 4 previously located EMG sites on the dominant limb were then prepared through shaving, and light abrading with isopropyl alcohol and skin prep gel (Nuprep®, Weaver and Company, Aurora CO, USA). The ground electrode was switched to the dominant limb ASIS. 4 electrodes (DE-2.1, Delsys Inc., Boston, MA., USA) were prepped with conductive gel and fixed to the predetermined locations on the dominant limb (vastus lateralis, biceps femoris, tibialis anterior, lateral gastrocnemius). These electrodes were secured to the skin with electrode adhesive and Transpore™ tape (3M™, St. Paul MN, USA).

Cooling Protocol #2:

Participants re-entered the cooling tank and were exposed to the same environmental condition as previously exposed during phase 1 of the trial. Participants remained in the tank for 10 minutes to counteract any potential rewarming and therefore allow for similar muscle and skin temperature during both phases of the experiment (isokinetic strength testing and balance testing). Participants then exited the tank, removed immersion suit shell and seated themselves back in the transport chair to have their muscle temperature re-measured.

Muscle Temperature Measurement #2:

Just prior to the EMG normalization procedure test, participant T_{mu} of the dominant limb vastus lateralis and lateral gastrocnemius was measured with sterilized 26 gauge muscle temperature probes (Model MT-26/2, Physitemp Instruments, NJ, USA). Probes were inserted by the researcher into the bulk of the muscle belly and within 5 cm of EMG electrodes and to a depth of 3 mm beyond the epimysium, and probes were held in place for ~5 s until a stable temperature was recorded.

EMG Normalization:

Subjects sat on the edge of a padded bench with their dominant leg secured with padded straps and knee flexed at ~120˚ (180° = full knee extension) with the assistance of a custom built wooden apparatus (see appendix B). Subjects performed maximal isometric voluntary contractions (MVC) of tibialis anterior, lateral gastrocnemius , vastus lateralis, and biceps femoris by executing ankle dorsiflexion, ankle plantarflexion, knee extension and knee flexion respectively. Participants were verbally encouraged by the researchers to contract as forcefully as possible for 3 seconds against the MVC device for each muscle tested. If clipping of the EMG signal occurred during normalization, amplification was adjusted and another 3 second isometric MVC was performed. EMG data for normalization was collected with DASYlab (Ver. 10.0, Measurement Computing, Norton, MA, USA). A 250 ms data window of this isometric MVC EMG data was used to normalize the activity of the recorded muscles during the balance tasks.

Motion Capture:

Once the isometric MVCs were completed, passive reflective markers were adhered with 3M™ Transpore™ tape to specific bony landmarks on the participant (over skin where possible). These landmarks, 8 in total, were the dominant limb: head of 5th metatarsal, lateral malleolus, lateral femoral condyle, greater trochanter, ipsilateral acromion process, and non-dominant limb: head of 1st metatarsal, medial malleolus and medial femoral condyle. As the participant walked over to the balance testing area within the EEL, the camera (HDR-CX110 Handycam, Sony Electronics Inc., CA, USA) was turned on to record 2-dimensional kinematics for the balance exercises. The camera was positioned ~4.7 m away from the participant and at a height of ~0.9 m. Video was recorded at 60 Hz and synchronized to EMG data through the use of an LED/trigger system. As participants performed the balance tasks the researcher depressed a trigger switch which activated the LED and sent a square wave TTL pulse through the 16-bit multiplex A/D DAQ card (National Instruments Corp., Austin, TX, USA) and ultimately synchronized to the EMG signal within the EEL computer (DASYLab Ver. 10.0, Measurement Computing, Norton, MA, USA) for analysis.

Dynamic Stability Test:

The Star Excursion Balance Test (SEBT) measures dynamic postural control. It is a test that has been shown to have a relatively strong intra-rater reliability of [ICC (2,1): 0.67 to 0.87] (83) and [ICC (2,1): 0.81 to 0.96] with coefficients higher or lower depending on reach direction (60). Within approximately 10 minutes of completion of the CWI, subjects took up position where the floor was taped with either their big toe or heel adjacent to the start line depending on direction of reach. EMG instrumentation was connected to data acquisition equipment. Subjects then performed the SEBT reaching task with their non-dominant leg in anterior, and posterior directions while remaining balanced on their dominant leg (see appendix C). Which direction participants performed first for the SEBT was kept the same within each subject throughout the 4 experimental trials although the order of direction was randomized between subjects. 10 seconds of rest was maintained between each reach attempt and 1 minute of rest was maintained when switching between reach directions. This timing was maintained with a stop watch (Fisher Scientific, Waltham, MA, USA) by the researchers. Subjects were instructed to keep their hands on their hips throughout all balance testing. The two SEBT directions included, at minimum, 4 practice trials to minimize any learning effect (128), followed by, at minimum, 3 test trials, with the maximal excursion distances recorded through the use of visual spotting, marking with tape, and at the completion of the trial, measuring with a steel measuring tape to establish achieved distance. The 3 properly executed test trial distances were then averaged. Participants performed more than 4 practice trials and more than 3 test trials if they lost their balance as 4 properly executed practice trials and 3 properly executed measured test trials were needed for data analysis. The averaged excursion distance was normalized to individual participant leg length (ASIS → medial malleolus) (51). Other standardizing procedures (i.e. maintain balance, no heel raise, rest between excursions) that are associated with the SEBT were also adhered to (60). EMG activity was recorded within a 250 ms data window that was established around the participant's maximal reach during each excursion. The RMS of the EMG signal during the SEBT was calculated and normalized to the RMS of the EMG signal during the maximal isometric voluntary contraction (MVC).

Static Balance Test:

After 1 minute of rest had elapsed post-SEBT testing, subjects completed a stork stand test on their dominant leg. The stork stand test is a measure of static balance with an inter-rater reliability coefficient of .76 (143). Participants placed their hands on their hips and non-dominant foot against the inside of their supporting knee. On the test administrator's command, the participant rose up onto the ball of the dominant foot and maintained the position until they were unable to continue. The participant completed the test 3 times with the longest time recorded and used for analysis. 30 second rest was allowed in between each of the 3 attempts. Timing was accomplished with the use of a stop watch (Fisher Scientific, Waltham, MA, USA).

Statistical analysis:

Data screening:

Prior to running statistical analysis all data pertaining to the study was screened to detect if assumptions were met for repeated measures design:

Thermal data:

Muscle, skin and core temperature met the assumptions of normal distribution, sphericity and independent random sampling. The equal cell sizes assumption was violated as at times during testing as it was not always possible to obtain a muscle temperature reading or thermistors malfunctioned. Where possible, trial data was smoothed though MATLAB® or discarded to obtain equal cell sizes.

Cold water immersion (CWI) data from skin thermistors was recorded every 10 seconds and averaged into 1 minute intervals and leg thermistor information analyzed with two-factor (condition x time) repeated measures analysis of variance (ANOVA). It was also important to determine that skin temperature of exposed limb segments dropped to similar temperatures with each CWI depth. Therefore at minute 20 and minute 10 of each exposure a repeated measures ANOVA was used to show any main effects and, if found, post-hoc pairwise comparisons were ran to find where the differences were.

Three 1 minute time points of interest for each trial were highlighted to investigate skin temperature and how it was affected by the varying environmental conditions. Separate repeated measures ANOVA were performed for thigh, shank and foot temperature during the isokinetic strength, SEBT and SS tasks to compare skin temperature between control, ankle CWI, knee CWI and hip CWI. Where significant main effects were detected, post-hoc pairwise comparisons with Bonferonni adjustments were utilized.

Superficial muscle temperatures of the vastus lateralis and lateral gastrocnemius were obtained after both cold water immersions. A 3 factor (muscle x exposure x condition) repeated measures ANOVA were used to determine the effect that the two immersions had on the thermal profile of the two muscles. Secondary 1 factor repeated measures ANOVA for the vastus lateralis and lateral gastrocnemius were used to determine the exact effect that each thermal condition had on the respective muscle temperature.

Using a 4-site model (see appendix A or *skin temperature* section in methods), mean skin temperature ($\overline{T}_{sk}$) was measured across trials using a single repeated measures ANOVA.

SEBT and stork stand:

Reach distance during SEBT and stork stand time violated normal distribution, as the data set was slightly kurtotic and skewed in several instances. This violation should be expected due to the relatively small sample size (10) and the fact that these tests are field tests and contain a greater potential for variability due to tester error and variation in reach and balance technique than other measurement tests. Since this variation was expected these values were left untreated. For SEBT condition interaction sphericity was violated, a greenhouse-geiser adjustment was used. Assumptions on equal cell sizes, and independent random sampling were met.

A two-factor (reach direction x condition) repeated measures ANOVA was used to look at the change in excursion distance during the SEBT in relation to cold exposure. Post-hoc pairwise comparisons within each reach direction were used to find significant reach differences between conditions.

A single repeated measures ANOVA was utilized to look at stork stand time in relation to cold exposure.

Joint kinematics:

Normal distribution assumption was violated due to a large standard deviation within the data set. This large standard deviation was as a result of different reaching strategies creating large variation in joint angle of the ankle, knee and hip on the supporting limb. As this was a biomechanically expected phenomenon, the values were left untreated. Equal cell size, sphericity and independent random sampling assumptions were met.

A three-factor (reach-direction x joint x condition) repeated measures ANOVA was used to detect for significant variation within the SEBT joint kinematic data set (ankle, knee, hip). With each analysis, if significant main effects were detected, post-hoc (tukey) pairwise comparisons were utilized with Bonferonni adjustments. Reach distance was correlated to joint angle at maximum reach with Pearson squared correlations.

Muscle activation:

In general, the muscle activity data met the assumptions associated with ANOVA. Specific violations included: violation of sphericity for comparison of normalized root mean square (RMS) activity between muscles, and comparison of normalized RMS activity between muscles and reach direction. Additionally, several normalized RMS statistical distributions were slightly kurtotic.

A three factor (reach direction x muscle x condition) repeated measures ANOVA and separate two factor (reach direction x condition) repeated measures ANOVA for each individual muscle were utilized to examine any potential significant main effects and interactions on the muscle activity of the vastus lateralis, biceps femoris, tibialis anterior and lateral gastrocnemius during the maximal reach of the SEBT. Where significant main effects were found, post-hoc analysis, with pairwise comparisons with Bonferonni adjustment were used. One participant's data set was removed due to a higher degree of variability. This participant was unsure of their limb dominance which may have been a reason as to this higher amount of RMS variability.

Muscle agonist/antagonist co-activation between the vastus lateralis and biceps femoris and the tibialis anterior and lateral gastrocnemius was determined through the following calculation (68):

$$CI = \left[\frac{Less\ active\ EMG_{RMS}}{More\ active\ EMG_{RMS}} \times (Less\ active\ EMG_{RMS} + \ More\ active\ EMG_{RMS})\right]$$

A two factor (reach direction x condition) repeated measures ANOVA was used to analyze for any significant main effects for the CI across different conditions.

Peak isokinetic torque:

All assumptions were met for ANOVA with the exception of slight kurtosis in the peak torque data set.

A three factor (muscle x contraction type x condition) was used to look for main effects and interactions.

All statistical analyses were conducted with SPSS 16.0 (SPSS Inc., Chicago, Illinois). Statistical significance was set at P<0.05.

Results:

Cooling protocol:

During each of the 4 trials, participants were exposed to a different environmental condition. Additionally, within each trial, participants underwent two exposures: First, a 20 minute seated exposure to room air, ankle, knee, or hip high 12°C water (CWI1); and second, a 10 minute seated exposure to the same condition as during the first exposure (CWI2). In general, with each different depth of cold water immersion (CWI), the skin of the immersed lower limb segment (foot, shank, thigh) was significantly cooled. This cooling effect followed a parabolic pattern with the quickest cooling occurring within the first half of the immersion duration. During the hip CWI 1 & 2 the thigh skin temperature was significantly cooled from 31.9 ± 1.3°C to 21.5 ± 3.7°C ($P<0.001$) (Figure 4.1A) and 28.8 ± 1.2°C to 22.7 ± 4.0°C ($P\leq0.012$) (Figure 4.1B) respectively:

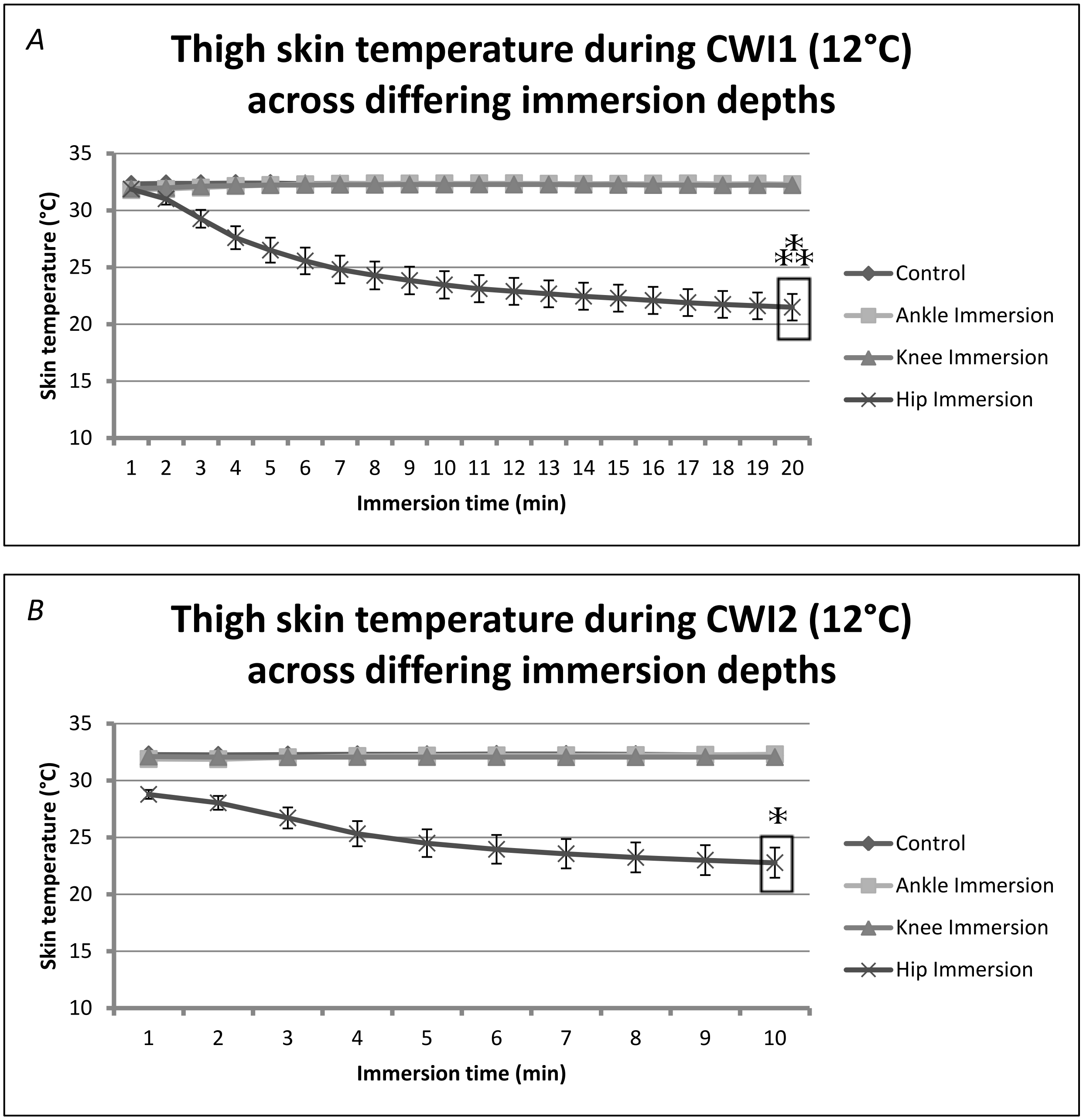
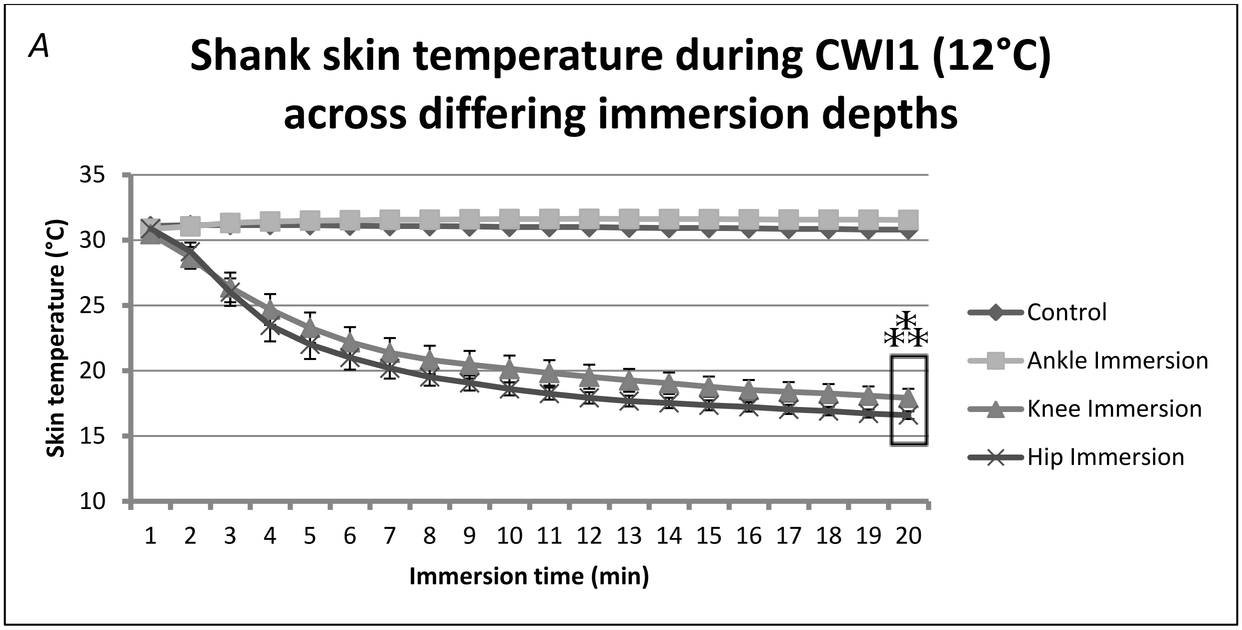


Figure 4.1: Thigh skin temperature (A: Top panel, 20 min. CWI) A repeated measures ANOVA was performed on the final minute of the CWI (Min 20). After a greenhouse-geisser adjustment, a significant main effect was found for the thigh skin temperature in relation to thermal conditions ($F(1.09, 7.65)=51.49$, $P<0.001$, $\eta^2=.880$). With Bonferroni adjustments, post-hoc pairwise comparisons showed a significant difference between hip CWI compared to control and ankle and knee CWI ⁂ ($P<0.001$). Data points represent 1 min. averages. Error bars represent ± 1 SE. **(B: Bottom panel, 10 min. CWI)** A repeated measures ANOVA was performed on the final minute of the CWI (Min 10). After a greenhouse-geisser adjustment, a significant main effect for thigh skin temperature was found ($F(1.14, 6.81)=28.04$, $P=0.001$, $\eta^2=.824$). With a Bonferonni adjustment, post-hoc analysis revealed that the thigh skin cooling was significantly lower for the hip immersions compared to the control, ankle and knee CWI * ($P\leq0.012$). Data points represent 1 min. averages. Error bars represent ± 1 SE.



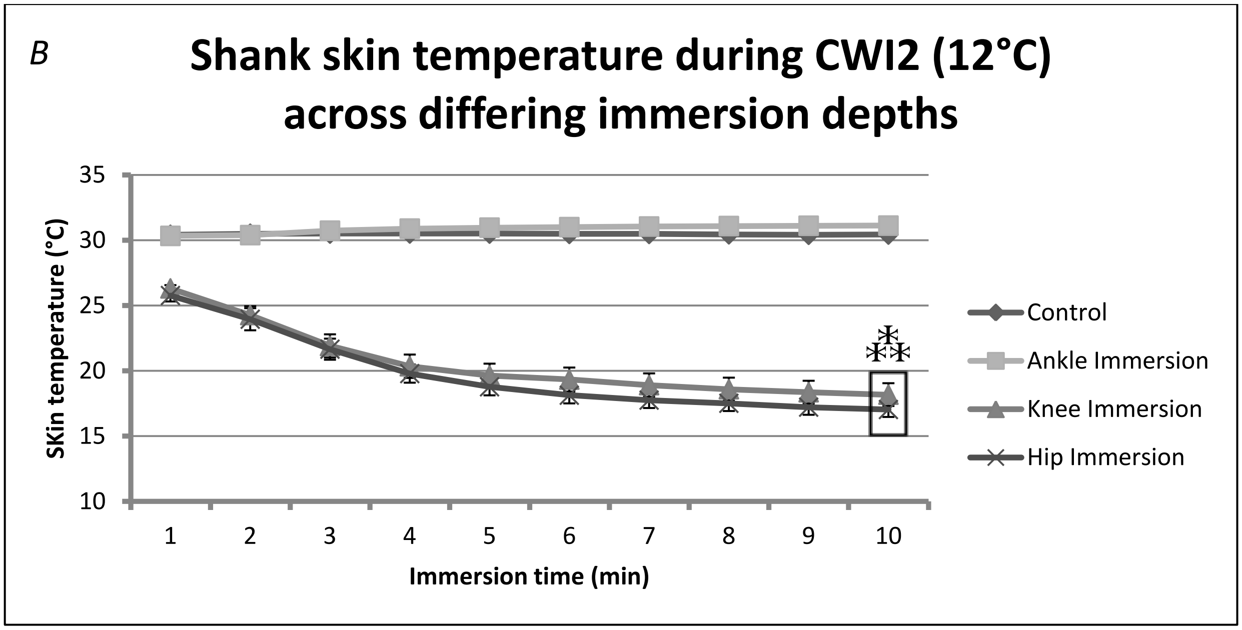


Figure 4.2: Shank skin temperature (A: Top panel, 20 min. CWI) A repeated measures ANOVA was performed on the final minute of the CWI (Min 20). After a greenhouse-geisser adjustment, a significant main effect was found for the shank skin temperature in relation to thermal conditions (F(1.33, 9.29)=310.1, $P<0.001$, $\eta^2=.978$). With Bonferroni adjustments, post-hoc pairwise comparisons showed a significant difference between knee and hip CWI compared to control and ankle CWI ⁂ ($P<0.001$). Data points represent 1 min. averages. Error bars represent ± 1 SE. **(B: Bottom panel, 10 min. CWI)** A repeated measures ANOVA was performed on the final minute of the CWI (Min 10). After a greenhouse-geisser adjustment, a significant main effect for shank skin temperature was found (F(1.60, 12.76)=236.83, $P<0.001$, $\eta^2=.967$). With a Bonferonni adjustment, post-hoc analysis revealed that the skin cooling was significantly lower for the knee and hip immersions compared to the control and ankle CWI ⁂ ($P<0.001$). Data points represent 1 min. averages. Error bars represent ± 1 SE.

During the hip and knee CWI, shank skin temperature was significantly cooled. As a result of CWI1 and CWI2, shank skin temperature dropped from 30.7 ± 1.1°C to 17.3 ± 1.5°C (P<0.001) (Figure 4.2A) and 26.0 ± 1.1°C to 17.6 ± 2.3°C (P<0.001) (Figure 4.2B) respectively **see previous page for figures*.

During the ankle, knee and hip CWI, dorsal foot skin temperature was significantly cooled. Due to CWI1 and CWI2, dorsal foot skin temperature dropped from 29.7 ± 1.5°C to 16.2 ± 1.6°C (P<0.001) (Figure 4.3A) and 22.2 ± 1.8°C to 15.3 ± 1.0°C (P<0.001) (Figure 4.3B) respectively * *see next page for figures*:

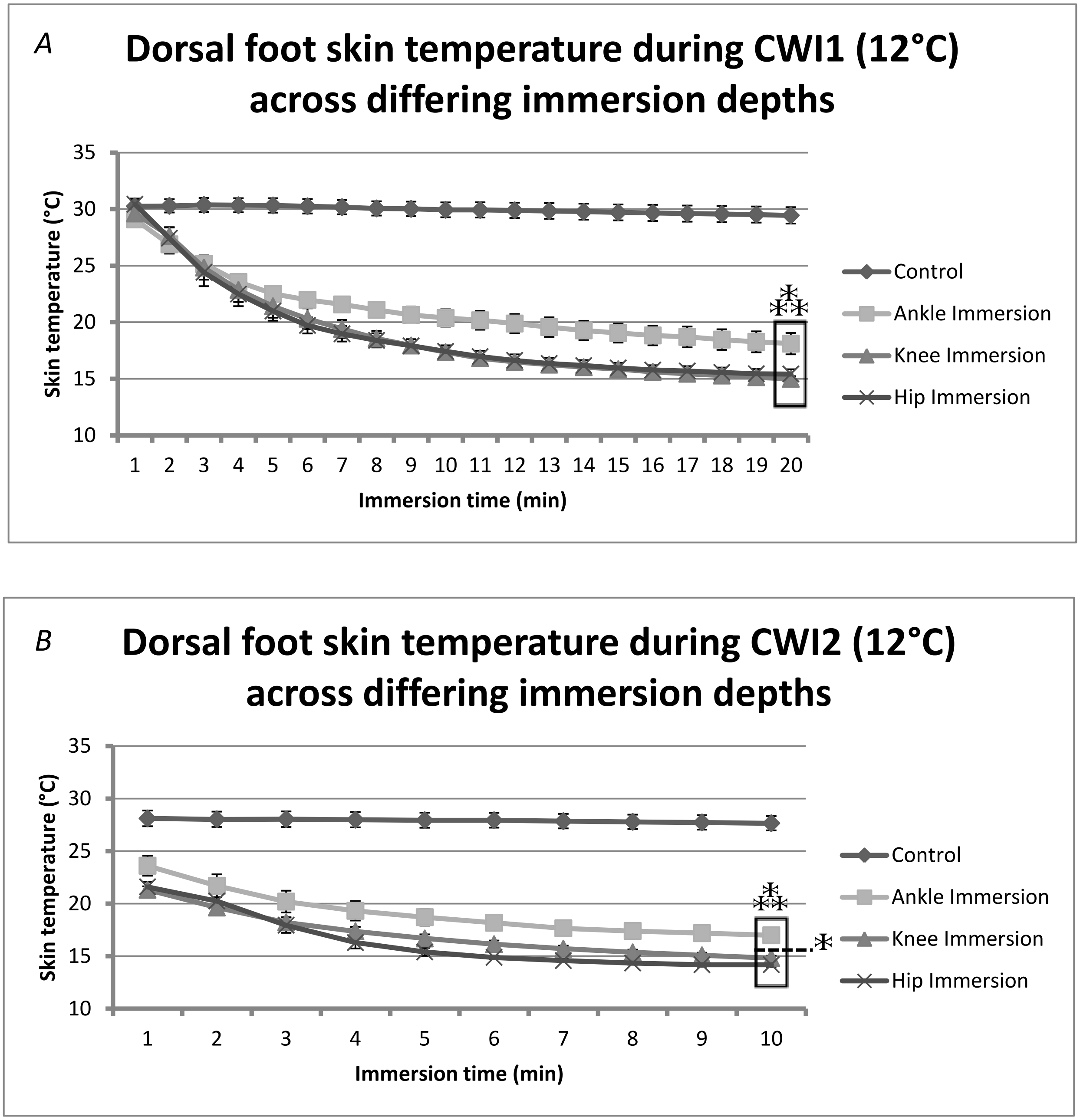


Figure 4.3: Dorsal foot skin temperature (A: Top panel, 20 min. CWI) A repeated measures ANOVA was performed on the final minute of the CWI (Min 20). A significant main effect was found for the dorsal foot skin temperature in relation to thermal conditions (F(3,18)=136.37, P<0.001, η^2=.958). With Bonferroni adjustments, post-hoc pairwise comparisons showed a significant difference between all 3 CWI compared to control ⁂ (P<0.001). The ankle CWI compared to the hip CWI approached but was not significant at P=0.077. Data points represent 1 min. averages. Error bars represent ± 1 SE. **(B: Bottom panel, 10 min. CWI)** A repeated measures ANOVA was performed on the final minute of the CWI (Min 10). A Significant main effect for dorsal foot skin temperature was found (F(3,18)=165.43, P<0.001, η^2=.965). With a Bonferonni adjustment, post-hoc analysis revealed that the skin cooling was significantly different for the ankle, knee and hip immersions compared to the control. Effect was similar for knee and hip immersion ⁂ (P<0.001). Additionally, after the 10 minute CWI, foot skin temperature was significantly warmer after the ankle CWI compared to the hip CWI * (P=0.021). Error bars represent ± 1 SE.

Muscle temperature:

In addition to skin cooling from the CWI, superficial T_{mu} of the thigh (vastus lateralis) and shank (lateral gastrocnemius) was impacted. T_{mu} measurements were taken on participants within 5-7 minutes of them exiting the cooling tank. Vastus lateralis was cooled only with the hip CWI ($P<0.001$) where T_{mu} dropped to an average temperature of 27.8 ± 1.7°C compared to the other 3 test conditions which averaged a vastus lateralis T_{mu} of 32.9 ± 0.9°C (Figure 4.4A, top panel). The lateral gastrocnemius was cooled from both the hip and knee CWI ($P<0.001$) where T_{mu} dropped to an average temperature of 22.9 ± 1.0°C compared to the ankle CWI and control conditions which averaged a lateral gastrocnemius T_{mu} of 31.0 ± 1.0°C (Figure 4.4B, bottom panel).

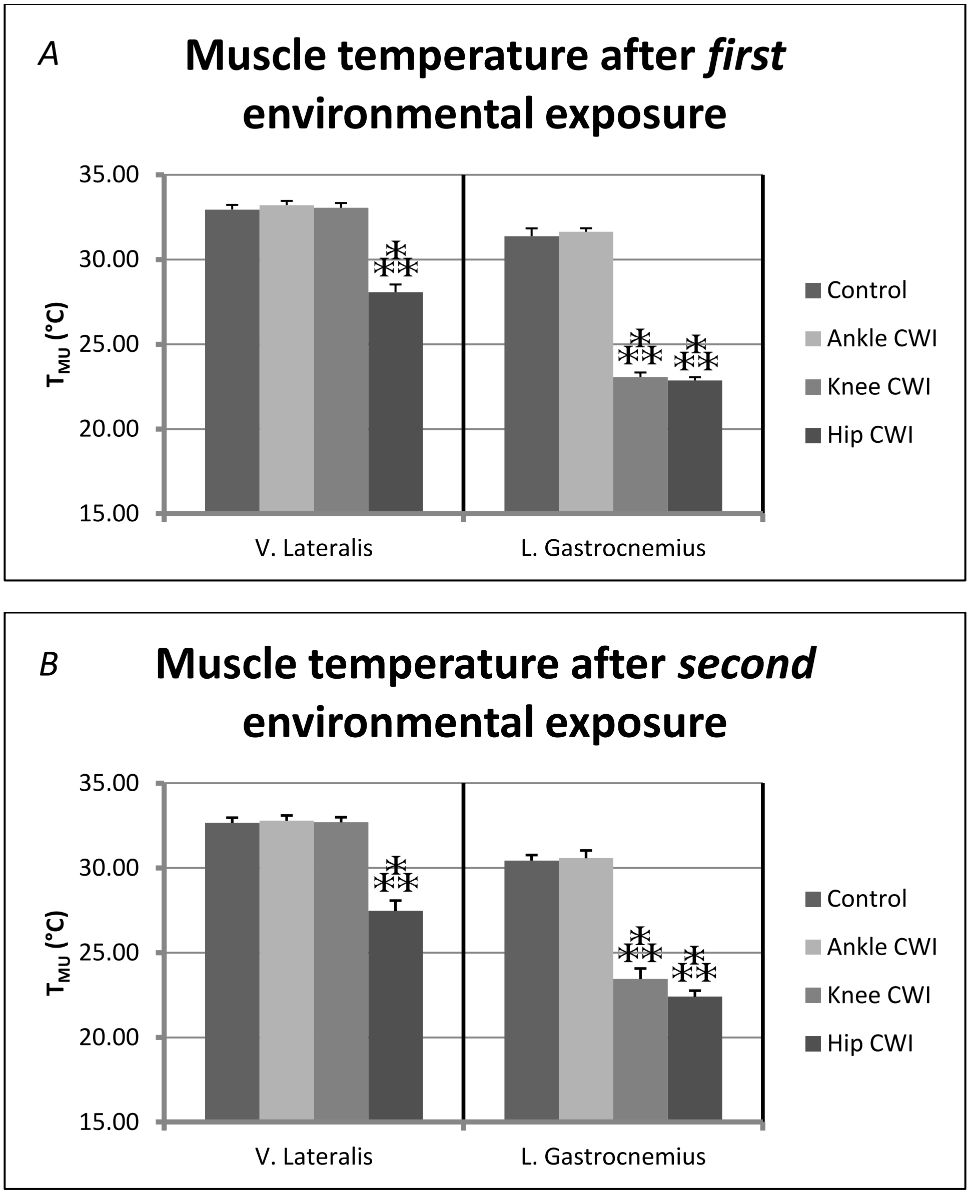


Figure 4.4: Muscle temperature (A. Top panel: first exposure) and **(B. Bottom panel: second exposure)** muscle temperature. A 3 factor (muscle x exposure x condition) repeated measures ANOVA was performed on all muscle temperature measurements for the vastus lateralis and lateral gastrocnemius. A significant main effect for condition was found (F(3,12)=161.97, P<0.001, η^2=.976). A significant interaction between muscle and condition was found (F(3,12)=106.47, P<0.001), η^2=.964). Follow-up repeated measures ANOVA for vastus lateralis and lateral gastrocnemius against conditions were performed which both had significant main effects (F(1.93,28.87)=94.77, P<0.001, η^2=.863) and (F(3,30)=335.49, P<0.001, η^2=.971) respectively. With Bonferonni adjustments significance was found with pairwise comparisons. Hip immersion had a significant cooling effect on the vastus lateralis ⁂ (P<0.001) while knee and hip immersion had a significant cooling effect on the lateral gastrocnemius ⁂ (P<0.001). Bars represent mean. Error bars represent ± 1 SE

Skin temperature during strength and balance tasks:

Balance and strength tasks were completed within approximately 10 minutes of muscle temperature measures. It is likely that muscle temperature was slightly elevated during strength and balance tests beyond what was quantified, although given the technical challenges of the experimental design (i.e. testing in separate labs, EMG normalization) this temporal deficit could not have been diminished to any greater level without compromising data collection or safety of the participant.

Skin temperature of the thigh, shank and dorsal foot were measured during the balance and strength tasks. Although, like the potential muscle rewarming, skin temperature was warmer than when measured post CWI but was still significantly cooler than when the skin was not exposed to the cold water immersion. In certain conditions, there was also a difference due to rewarming across the balance and strength tasks, again, as a result of skin rewarming after CWI in room temperature air.

Thigh skin temperature:

During the hip immersion condition at the strength and balance task time points, the thigh temperature was significantly colder compared to all 3 other thermal conditions at the same time points (Figure 4.5). The temperature dropped from an average of 32.2 ± 0.6°C to 27.7 ± 2.0°C (P<0.01). There was also approximately 1.0°C difference of thigh skin temperature when cooled during the hip immersion between the dynamic and static balance tests due to rewarming (P=0.11).

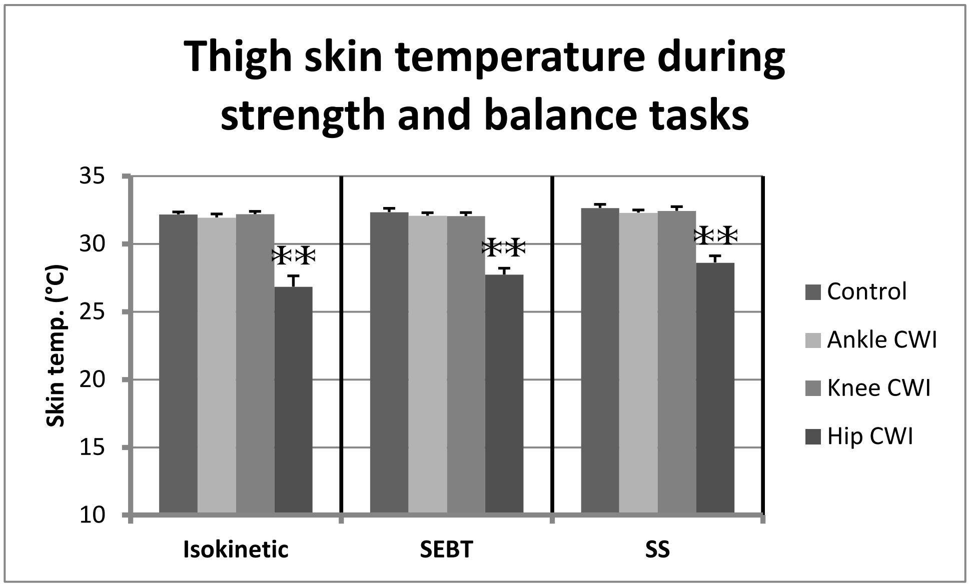


Figure 4.5: Task thigh skin temperature: A repeated measures ANOVA revealed a significant main effect for all thigh skin temperature during the strength and balance tasks after environmental exposures (F(11, 99)=37.52, P<0.001, η^2=.807). Bonferonni adjusted pairwise comparisons revealed significant differences in thigh skin temperature during the isokinetic, SEBT and SS tests after exposed to the hip CWI compared to all other conditions ** (P<0.01). There was also a significant difference between the thigh skin temperature between the SEBT and SS during the hip immersion trial (P=0.011). Bars represent mean. Error bars represent ± 1 SE.

Shank skin temperature:

After the knee and hip CWI shank skin temperature was significantly lower during the strength and balance tasks when compared to the same time points after the control and ankle CWI conditions (P<0.05) (Figure 4.6). The shank temperature dropped from an average of 30.8 ± 0.9°C during the ankle CWI and control conditions to an average of 26.1 ± 1.0°C during the knee and hip CWI tasks. There were also some significant differences of ~2.0°C between the tasks during the knee (P<0.05) and hip CWI (P<0.01) as the skin warmed back up.

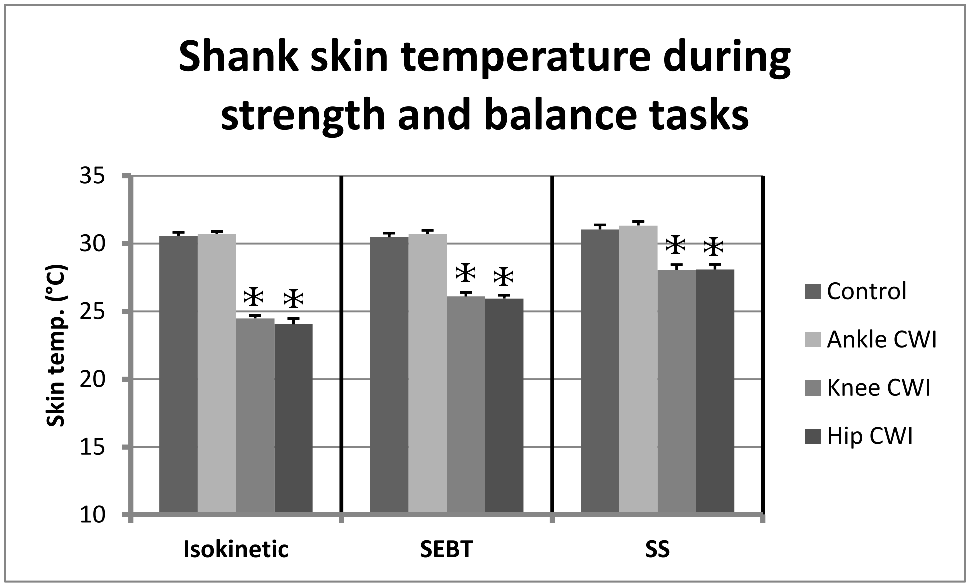


Figure 4.6: Task shank skin temperature: A repeated measures ANOVA revealed a significant main effect for all shank skin temperatures during the strength and balance tasks after environmental exposures (F(11, 99)=128.41, P<0.001, η^2=.935). Bonferonni adjusted pairwise comparisons revealed significant differences in shank skin temperature during the isokinetic, SEBT and SS tests after exposed to knee and hip CWI compared to ankle CWI and control conditions * (P<0.05). After the knee CWI, shank skin temperature was significantly different during isokinetic, SEBT and SS tasks do to the temporal effect of rewarming in ambient room air * (P<0.05). During the hip CWI SS task, shank skin temperature was significantly different from both SEBT and isokinetic tasks, again due to rewarming (P<0.01). Bars represent mean. Error bars represent ± 1 SE.

Dorsal foot skin temperature:

After the ankle, knee and hip CWI dorsal foot skin temperature was significantly lower during the strength and balance tasks when compared to the same time points after the control condition (P<0.01) (Figure 4.7). The dorsal foot skin temperature dropped from a mean of 28.2 ± 1.9°C during the control temperature tasks to an average of 21.2 ± 1.5°C during the ankle, knee and hip CWI tasks. There was also a ~ 1.0°C difference between the dorsal foot skin temperatures during the two balance tasks after the foot had been submerged which appeared as significant (P<0.01).

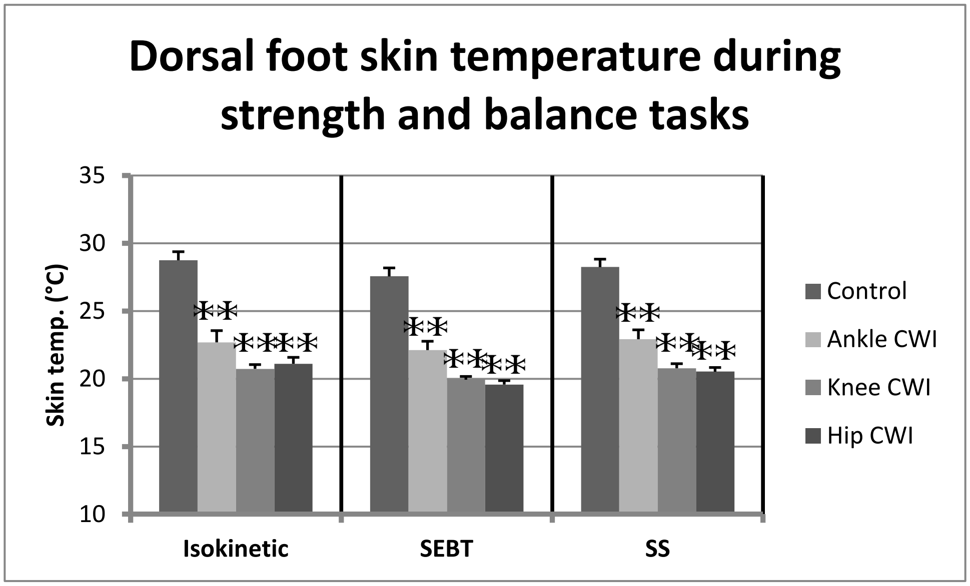


Figure 4.7: Dorsal foot skin temperature: A repeated measures ANOVA revealed a significant main effect for all dorsal foot skin temperature during the strength and balance tasks after environmental exposures (F(11, 99)=75.09, P<0.001, η^2=.893). Bonferonni adjusted pairwise comparisons revealed significant differences in dorsal foot skin temperature during the isokinetic, SEBT, and SS tests after exposed to ankle, knee and hip CWI compared to the control condition ** (P<0.01). During the control condition dorsal foot skin temperature was significantly different between the isokinetic and SEBT testing (P=0.016). During the ankle, knee and hip CWI dorsal foot skin temperature was significantly different between the SEBT and SS testing (P=0.003, 0.007, 0.001). During the SEBT, skin temperature was significantly lower during hip immersion than ankle immersion (P=0.03). Bars represent mean. Error bars represent ± 1 SE.

Core temperature:

A 1 minute average of core temperature (T_{re}) was measured during the first and last minute of both environmental exposures (control, CWI1 & 2). A 1 minute average was also measured during the time point in each trial when isokinetic, dynamic and static balance testing occurred. No significant change in T_{re} was detected across environmental exposures during CWI and strength and dynamic balance tasks. Within knee and hip CWI1 and knee CWI2 a significant rise (0.1 ± 0.02°C) in T_{re} was noticed between the first and last minutes of exposure ($P<0.01$). Within the static balance task a significant main effect across conditions was observed ($P<0.05$).

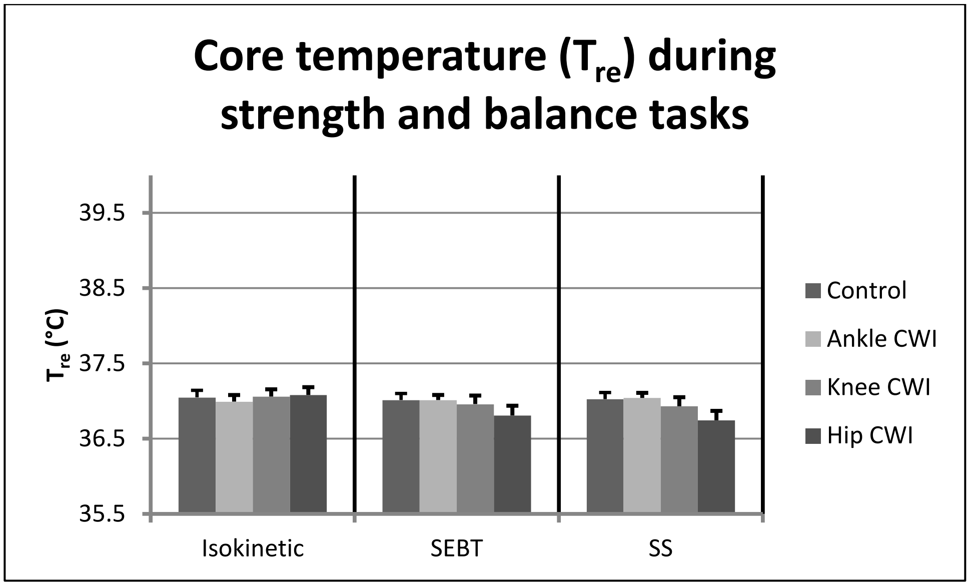


Figure 4.8: T_{re} during critical trial time points: With a repeated measures ANOVA a significant main effect during SS was observed ($F(3, 27)=3.19$, $P<0.05$, $\eta^2=.262$). No pairwise comparisons were significant. Bars represent mean. Error bars represent 1 ± SE.

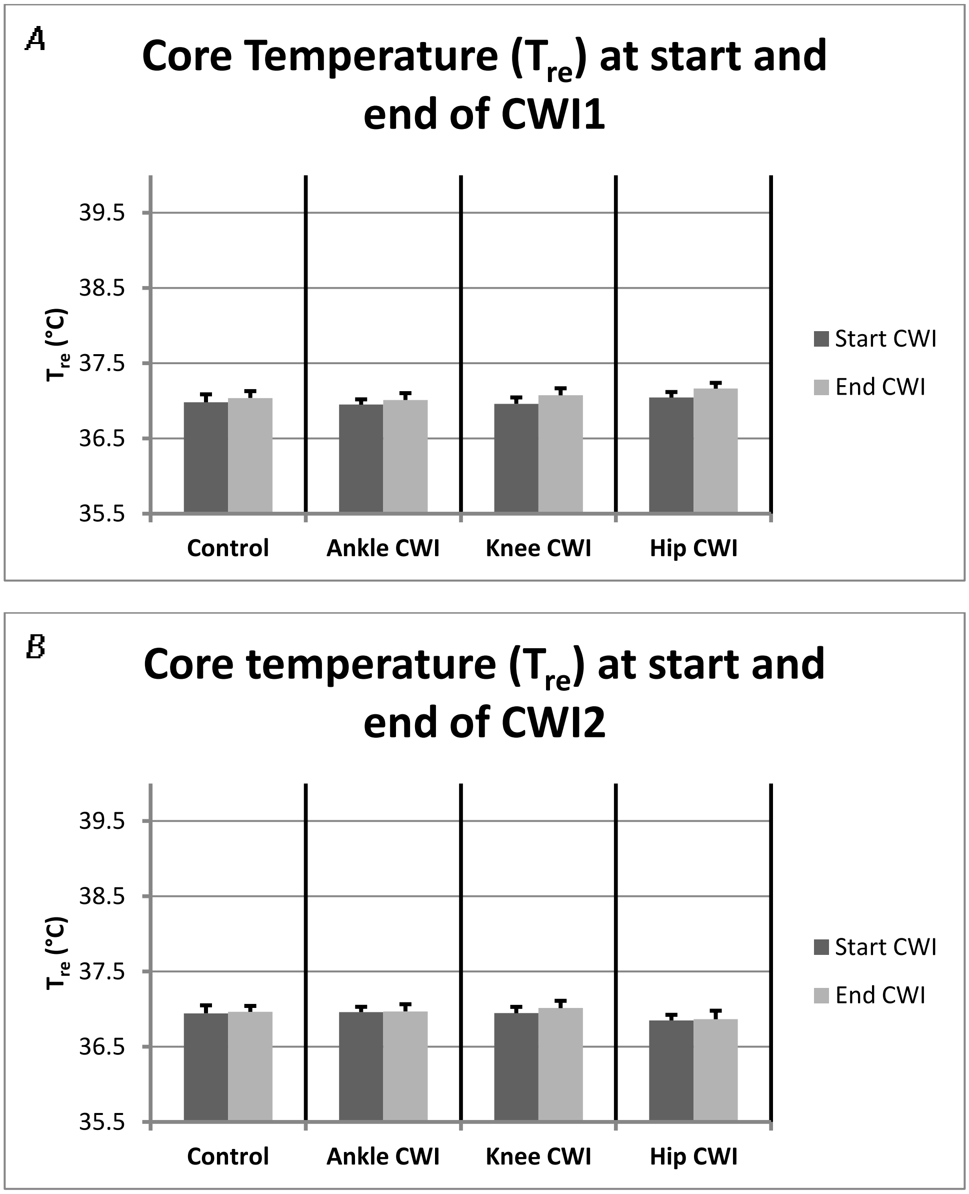


Figure 4.9: Core (T_{re}) temperature start/end of CWI1 (A: Top panel) and CWI2 **(B: Bottom panel):** Individual repeated measures ANOVA within conditions detected a significant main effect for T_{re} for the knee ($F(1, 9)=25.31$, $P<0.01$, $\eta^2=.738$) and hip ($F(1, 9)=19.17$, $P<0.01$, $\eta^2=.680$) CWI1 and knee ($F(1, 9)=11.84$, $P<0.01$, $\eta^2=.568$) CWI2. Bars represent mean. Error bars represent ± 1 SE.

Trial Mean skin temperature:

A 4-site model for mean body skin temperature was used to monitor thermal variation (see appendix A). Although the CWI did directly impact temperature of the exposed body segments, the upper body remained largely unaffected which resulted in a moderated effect on mean skin temperature throughout the trials. Despite this moderation there was still a significant drop in mean skin temperature between the knee and hip immersion trials compared to the control and ankle CWI trials ($P<0.05$) (Table 4.1).

Table 4.1: Mean skin temperature ($\overline{T}_{sk}$). A significant main effect was found across environmental conditions ($F(3,18)=15.40$, $P<0.001$, $\eta^2=.720$). Pairwise comparisons with Bonferonni adjustment applied revealed a significant difference between mean skin temperature during the knee and hip CWI trials compared to the ankle CWI and control conditions ($P<0.05$). *Significance accepted at $P<0.05$.

Mean skin temperature ($\overline{T}_{sk}$) during experimental trials				
	Control	**Ankle CWI**	**Knee CWI**	**Hip CWI**
Mean (°C)	**31.50**	**31.62**	**30.77** *	**29.73** *
± 1 SE	**0.08**	**0.07**	**0.09**	**0.11**

Isokinetic peak torque:

No significant changes in peak concentric and eccentric torque for the quadriceps femoris and hamstrings muscle groups were found across conditions. See figure 4.10 A and B for peak torque values.

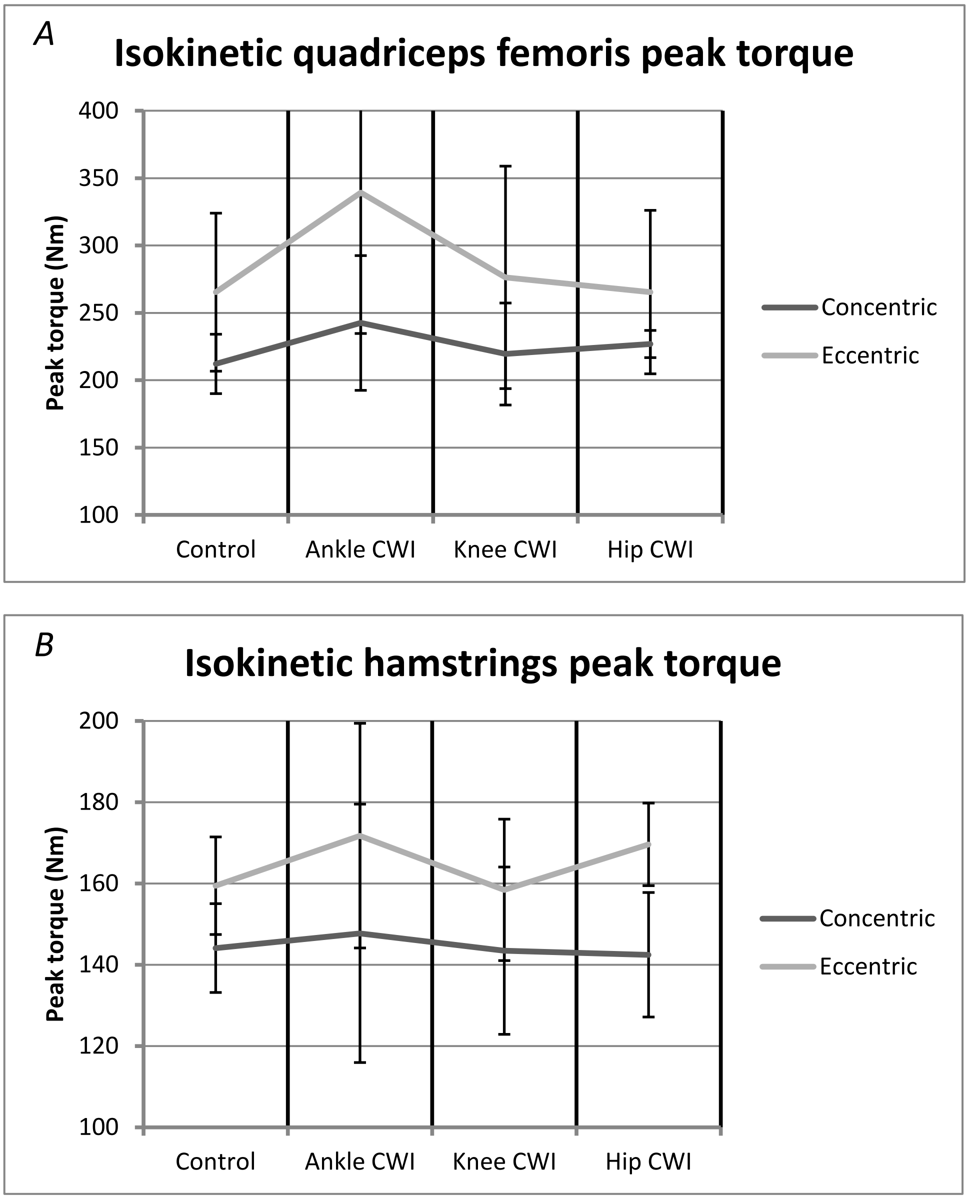


Figure 4.10 (A: Top panel) Isokinetic quadriceps femoris peak torque. **(B: Bottom panel) Isokinetic hamstrings peak torque**. Values represent mean. Error bars represent ± 1 SE.

Balance performance:

SEBT:

Across the different thermal conditions, a significant drop in reach distance for both anterior (Figure 4.11A, top panel) and posterior (Figure 4.11B, bottom panel) directions of the SEBT was observed ($P<0.05$). This significant value was for the hip immersion reach distances versus the control and ankle conditions. Across all 4 conditions, the mean SEBT reach distance showed a decreased reach distance each time more of the lower limb was exposed to the cold water immersion.

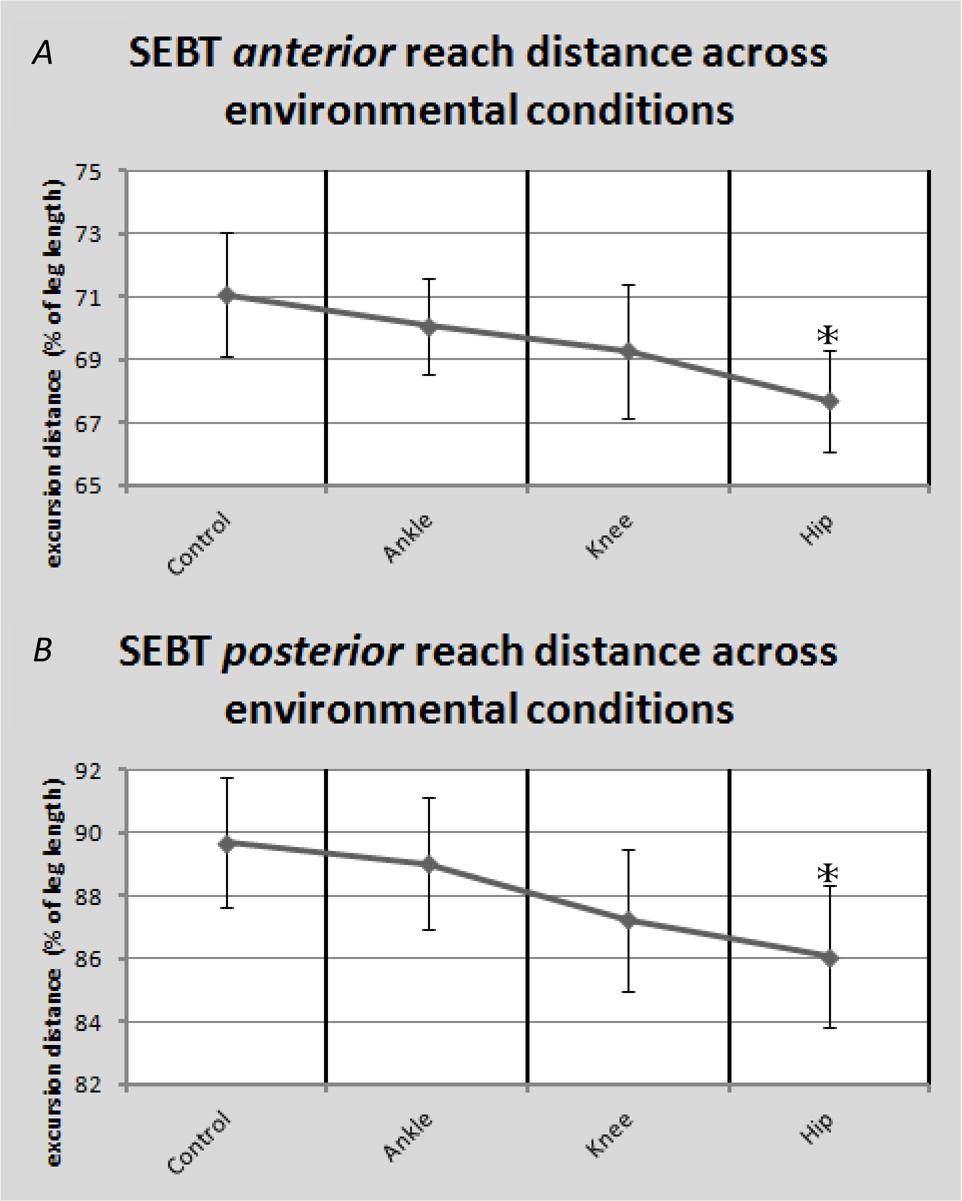


Figure 4.11 (A: Anterior reach, Top panel) (B: Posterior reach, Bottom panel) SEBT Reach distance and across environmental conditions. A significant main effect was found for reach distance comparing anterior to posterior reach ($F(1,9)=92.72$, $P<0.0001$, $\eta^2=.912$). After a greenhouse-geisser adjustment was performed a significant main effect was found for reach distance across thermal conditions ($F(1.695,15.252)=5.62$, $P=0.018$, $\eta^2=.385$). With Bonferroni adjustment for multiple comparisons, post-hoc analysis of this thermal condition main effect revealed a significant difference in reach distance between the control and hip CWI ($P=0.01$) and ankle CWI and hip CWI conditions ($P=.025$). Error bars represent ± 1 SE.
* Significance accepted at $P<0.05$

When layering mean reach distance with the relative volumes of the affected limb segment during each different immersion depth it becomes apparent that, although the ankle CWI did not significantly impair reach distance, hypothetically it did have the most significant impact on reach distance if we compare the relative volume of the foot to that of the shank and thigh as a weighted mean (See below, Figure 4.12 and Table 4.2, See Equation 6 in Appendix A for weighted mean calculation).

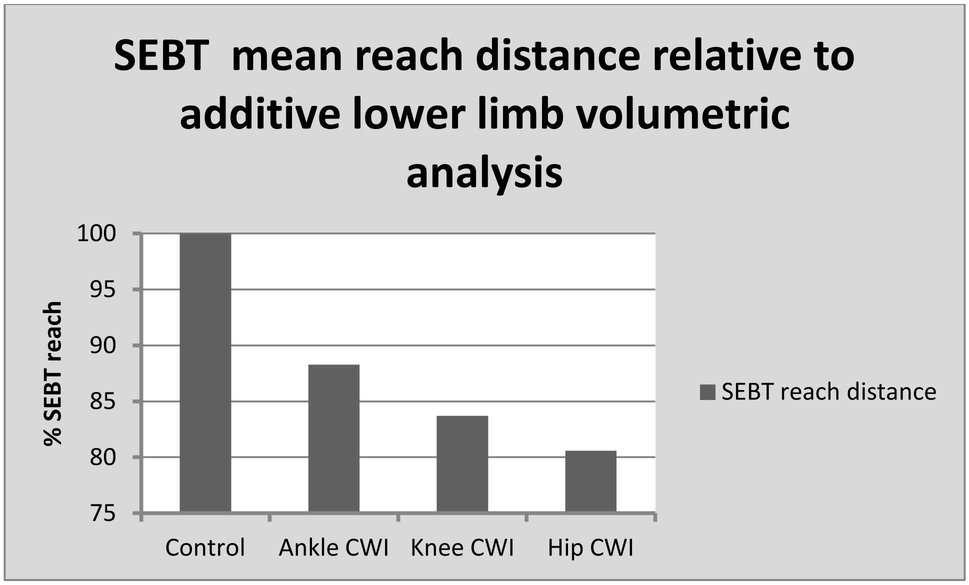


Figure 4.12: SEBT **mean reach distance relative to additive lower limb volumetric analysis**. The percentage change in SEBT reach relative to maximal SEBT reach during control condition was adjusted through the relative segmental (foot, shank, thigh) volumetric contribution to overall lower limb volume.

Table 4.2: Relative segmental contribution to volume of lower limb.

Relative segmental contribution to volume of lower limb		
Thigh volume *(cm³)*	**Shank volume *(cm³)***	**Foot volume *(cm³)***
6480.19 ± 1326.83	3858.76 ± 579.51	1027.80 ± 66.91
Thigh volume / total volume (%)	**Shank volume / total volume (%)**	**Foot volume / total volume (%)**
57.01	33.95	9.04

Joint kinematics:

Joint angles of the dominant leg were recorded and analyzed during the maximum reach distance during SEBT of each participant. No statistically significant effects were found.

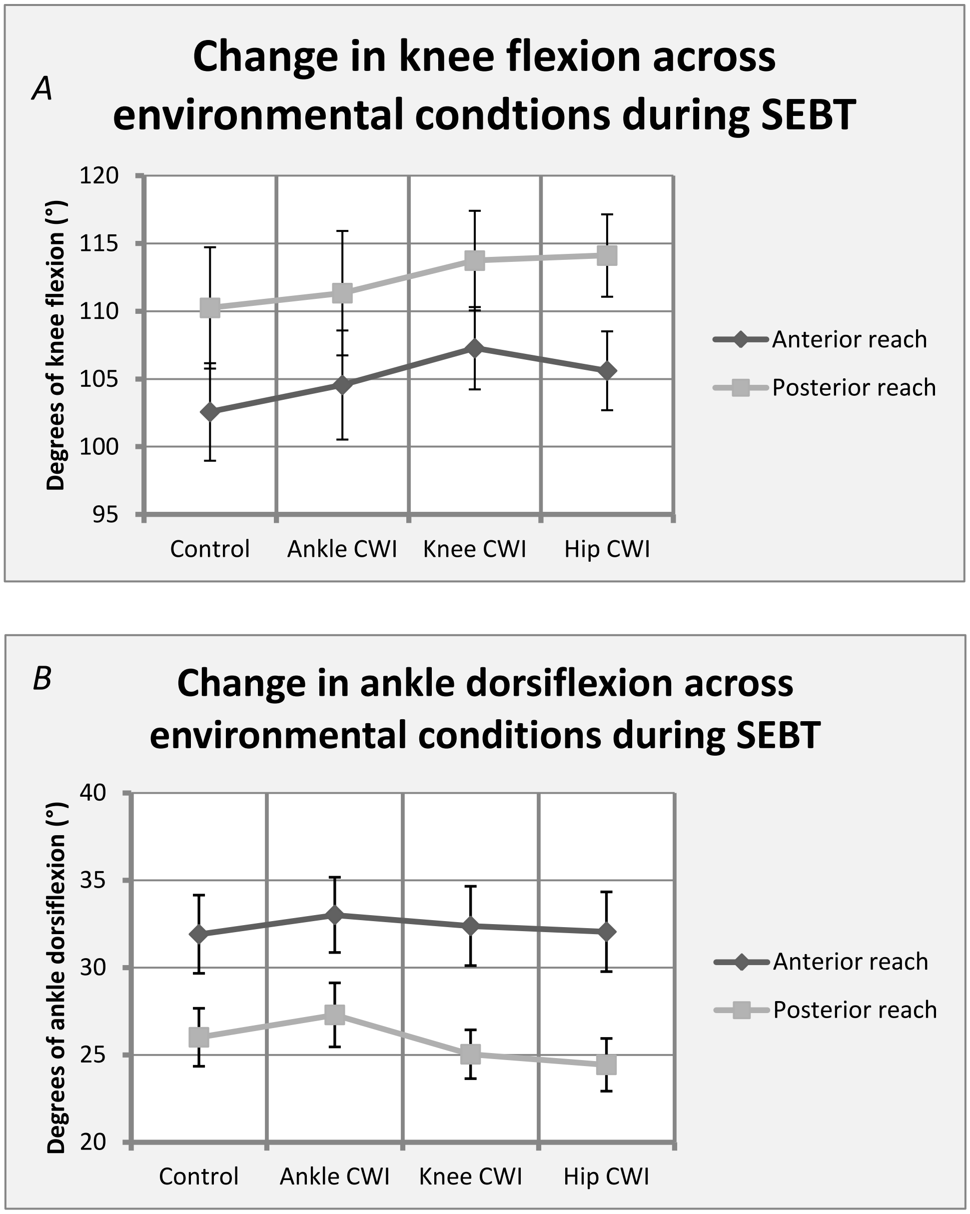


Figure 4.13 (A: Top panel) Knee flexion angle at maximum reach distance across environmental conditions (180° = full knee extension). (**B: Bottom panel) Ankle dorsiflexion at maximum reach distance across environmental conditions** (0° = neutral ankle posture). Error bars represent ± 1 SE.

Maximum reach distance of the SEBT can be correlated to the amount of ankle and knee flexion achieved. Through a Pearson's r correlation it was found that knee flexion (Figure 4.14A) did not correlate in the anterior direction, although there were medium positive correlations (r=.358 & .385) between ankle dorsiflexion in both anterior (Figure 4.14B) and posterior (Figure 4.15B) SEBT directions as well as a strong negative correlation (r=-.556) between reach distance and knee flexion when reaching backwards during the SEBT (Figure 4.15A). The data set although slightly kurtotic did not violate assumptions greatly enough to utilize Spearman's rho (although these values were quite similar when analyzed)

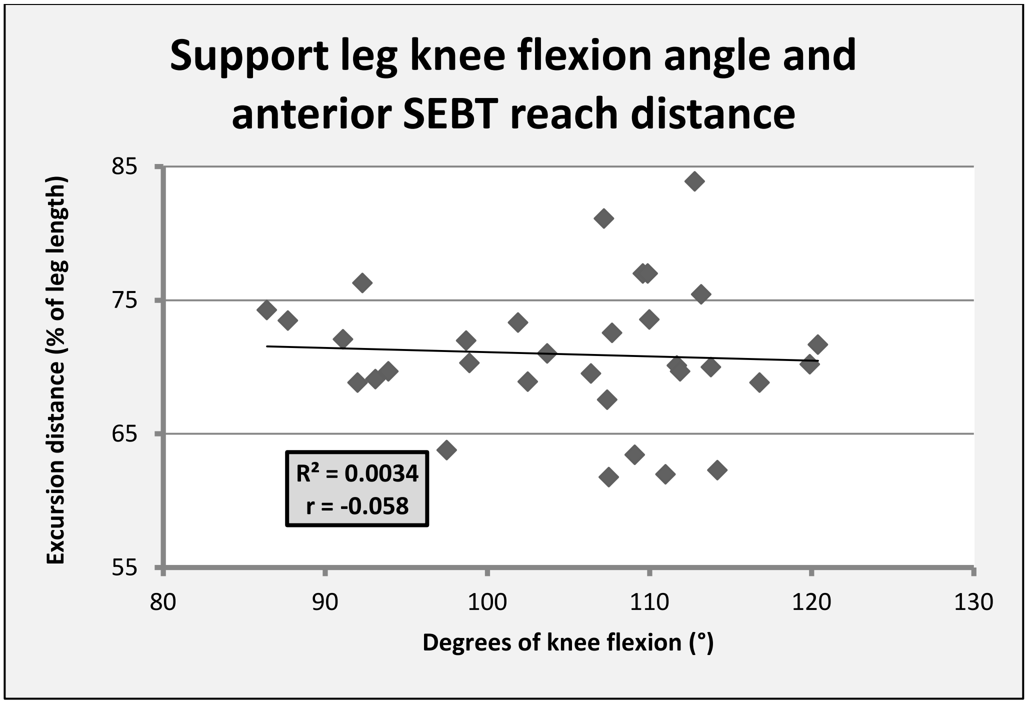


Figure 4.14A: Support leg knee flexion angle and maximal anterior SEBT reach distance. (r=-.058).

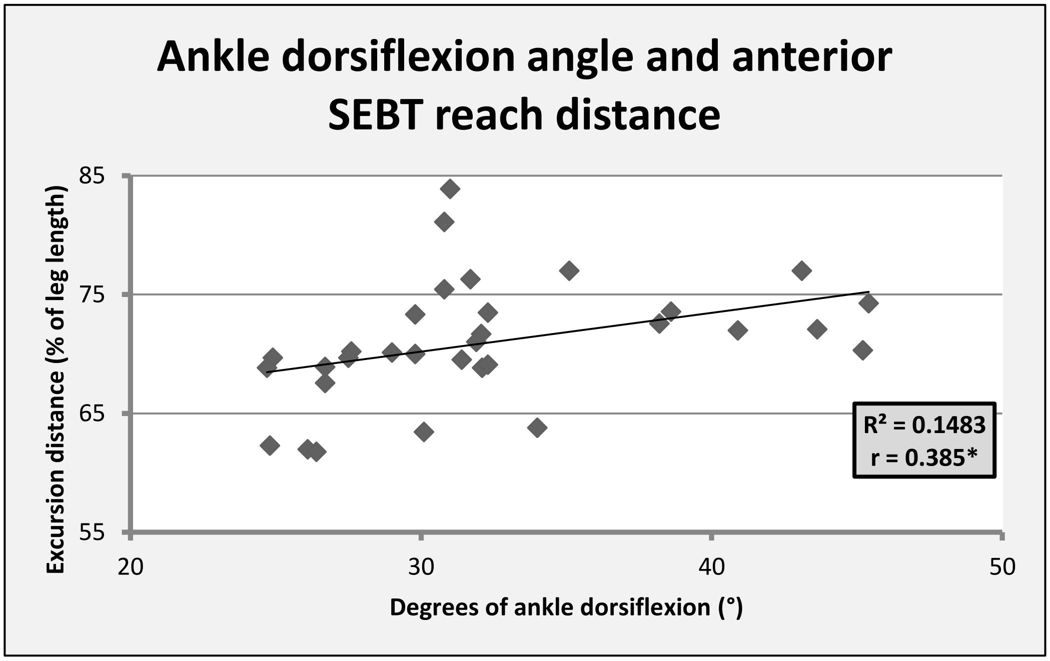


Figure 4.14B: Support leg ankle dorsiflexion angle and maximal anterior SEBT reach distance. (r=.385) * significant at P<0.05.

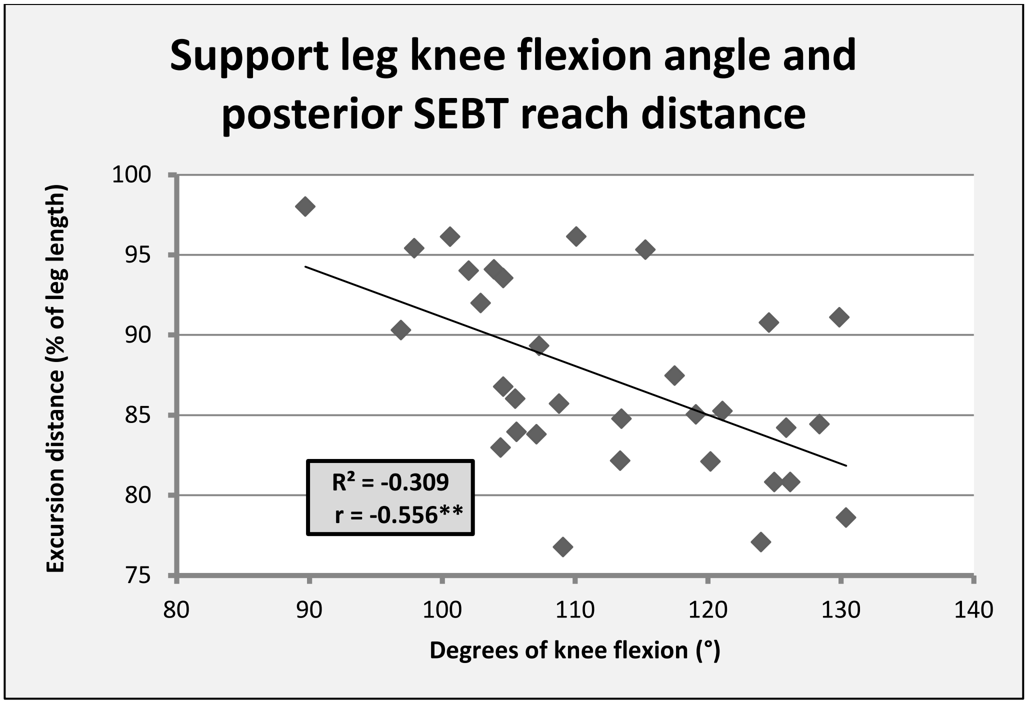


Figure 4.15A: Support leg knee flexion angle at maximal reach during posterior SEBT excursion attempt. (r=-.556) ** significant at P<0.01.

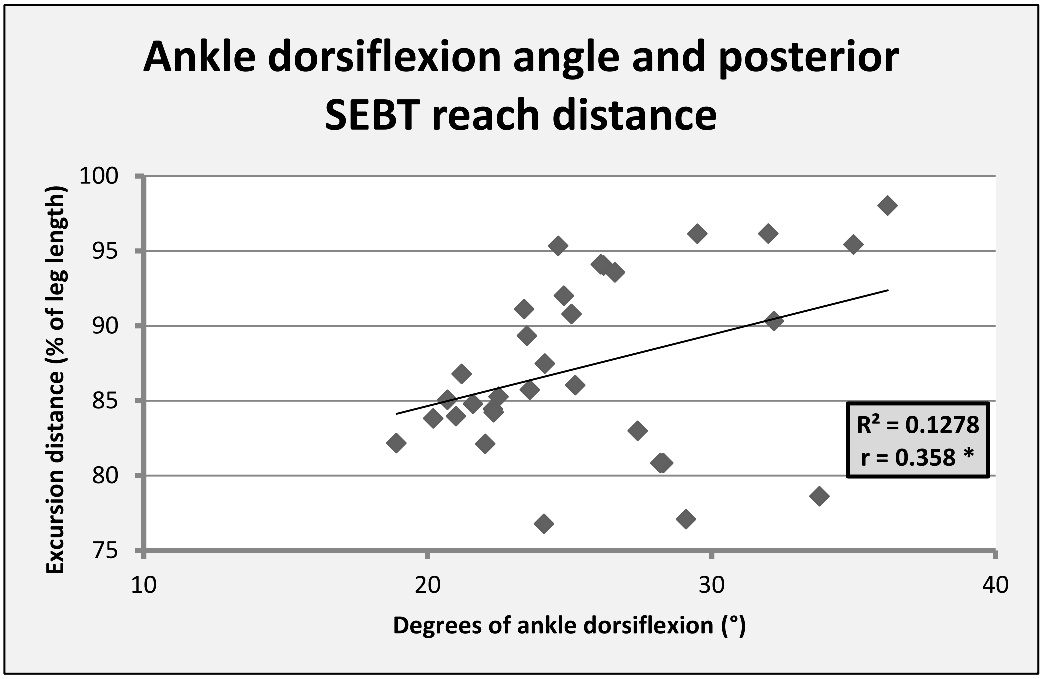


Figure 4.15B: Support leg ankle dorsiflexion angle at maximal reach during posterior SEBT excursion attempt. (r=.358) * significant at P<0.05.

SEBT Muscle activation:

Through analysis of the root mean square (RMS) of the normalized EMG activity around a 250 ms data window of the maximal reach, several observations present themselves. First, reliance on the vastus lateralis is greater than the other 3 muscles measured during the maximal reach of the SEBT. This is seen through a significant main effect ($F(1.79,14.33)=15.67$, $P<0.001$, $\eta^2 = .662$) and a significant pairwise comparison between the vastus lateralis and the 3 other muscle groups ($P<0.05$) within the three factor ANOVA. Second the muscle activation patterns differed within muscle groups depending on the reach direction. This is seen through a significant main effect of the two factor ANOVA for the biceps femoris ($F(1,9)=8.43$, $P<0.05$), $\eta^2=.484$) and tibialis anterior ($F(1,9)=8.65$, $P<0.05$, $\eta^2=.490$) For example, the tibialis anterior and biceps femoris muscles are more active during the maximal reach in the posterior reach direction than the anterior reach direction. (See figures 4.16A-B and 4.17A-B)

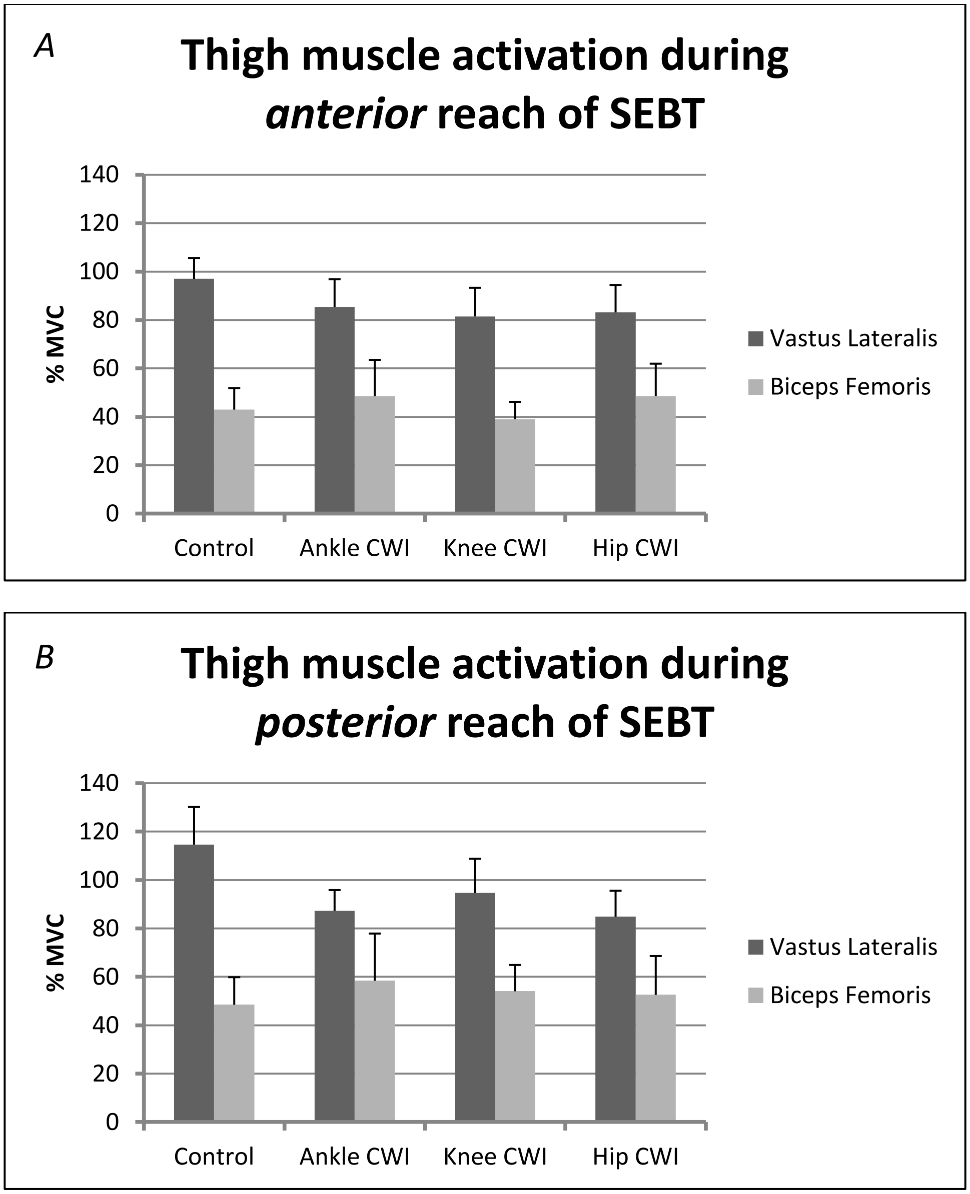
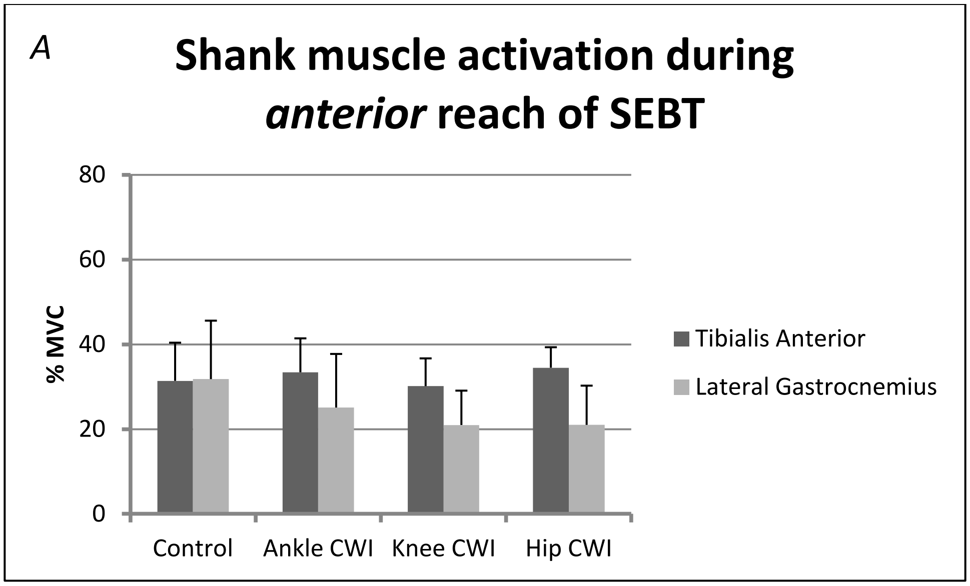


Figure 4.16 (A: Top panel) Thigh muscle activation during anterior reach of SEBT. (B: Bottom panel) Thigh muscle activation during posterior reach of SEBT. Bars represent mean. Error bars represent ± 1 SE.



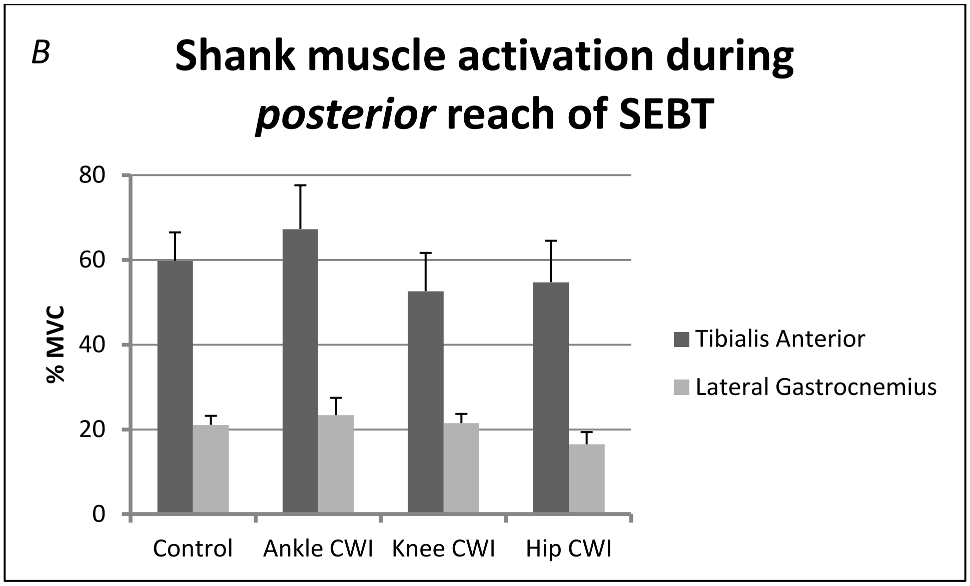


Figure 4.17 (A: Top panel) Shank muscle activation during anterior reach of SEBT. Lateral gastrocnemius activity across condition approached but was not significant (P=0.059) (**B: Bottom panel) Shank muscle activation during posterior reach of SEBT.** Bars represent mean. Error bars represent ± 1 SE.

SEBT Muscle Co-activation:

The larger the magnitude of the CI calculated, the greater the amount of co-activation that occurs. No significant changes in co-activation were seen between the vastus lateralis and biceps femoris (Table 4.3A) as well as the tibialis anterior and lateral gastrocnemius (Table 4.3B). There does appear to be marginal increase of co-activation between vastus lateralis and biceps femoris although due to the variability of reach patterns between and within individuals this data is extremely difficult to base any conclusive results.

Table 4.3A: Thigh muscle co-activation during maximal reach of SEBT. Mean ± 1 SE.

	Thigh muscle co-activation during maximal reach of SEBT			
	Control	Ankle CWI	Knee CWI	Hip CWI
Anterior reach	66.90 ± 16.20	79.53 ± 26.27	62.47 ± 14.30	80.11 ± 24.40
Posterior reach	78.65 ± 23.09	82.13 ± 28.10	85.29 ± 21.34	72.71 ± 20.88

Table 4.3B: Shank muscle co-activation during maximal reach of SEBT. Mean ± 1 SE.

	Shank muscle co-activation during maximal reach of SEBT			
	Control	Ankle CWI	Knee CWI	Hip CWI
Anterior reach	27.78 ± 3.49	29.93 ± 5.15	25.37 ± 3.09	28.71 ± 4.51
Posterior reach	31.78 ± 3.46	35.66 ± 7.72	28.67 ± 3.50	21.08 ± 3.24

Stork stand test:

Participants experienced a reduction in the time that they were able to maintain their stork stand when exposed to CWI. The data shows a decrease in time in seconds across conditions (control → hip), although the variability of the time between participants, especially within the control condition, weakened the pattern. No pairwise comparisons were observed between conditions (see figure 4.18).

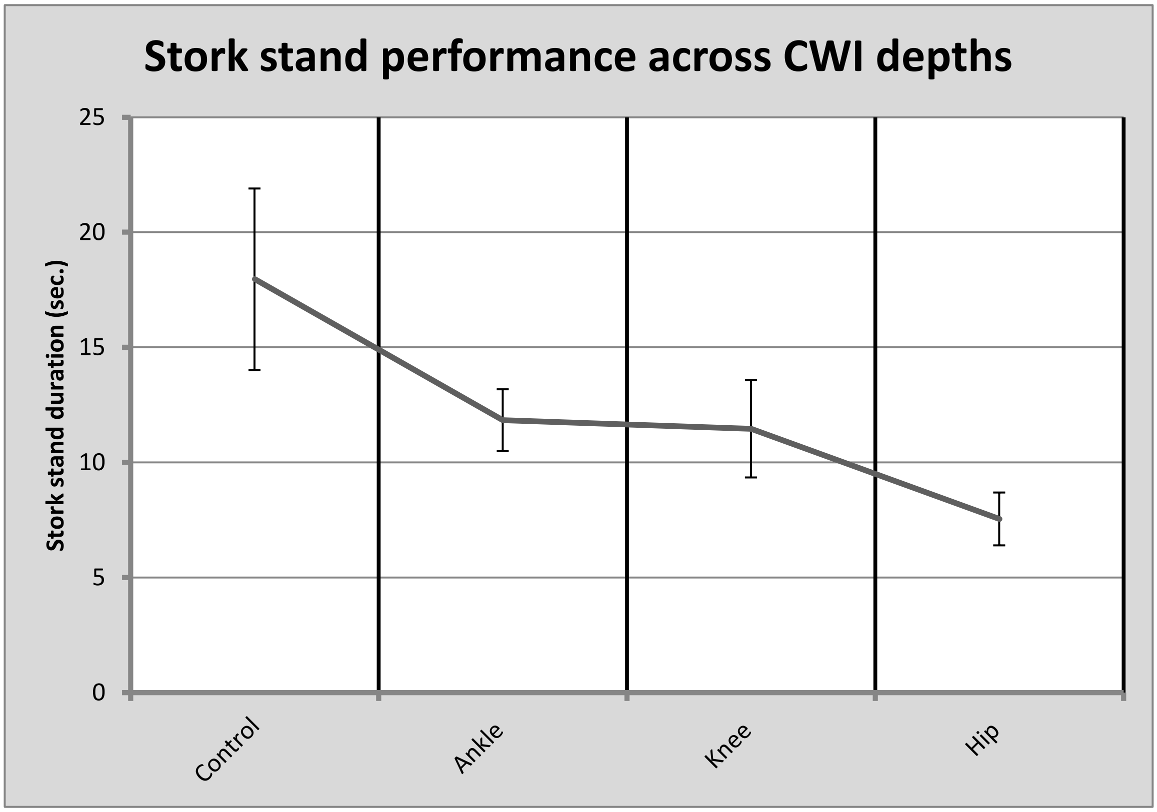


Figure 4.18: Stork stand performance. A significant main effect was found for stork stand performance across CWI depths (F(3,27)=4.89, P=0.008, η^2=.352). No significant pairwise comparisons were found. Data points represent mean SS time. Error bars represent ± 1 SE.

Discussion:

This study sought out to discover the impact that CWI has on dynamic balance performance as well as static balance and isokinetic strength involving the lower extremities. Specifically the study examined the proportional significance that each segment of the lower extremity, the foot, shank, and thigh to be exact, might have with regards to impairment from the cold and contribution to kinesthetic, test battery performance.

Three null hypotheses were established at the outset of the study which related to the environmental effect from the novel CWI protocol:

1. A decrease in muscle, skin and joint temperature of the foot and ankle will not contribute to a greater relative decrease in balance performance (SEBT reach distance, SS time) compared to cooling down a greater volume of the lower limbs in the SEBT and SS tasks.
2. Peak torque of the quadriceps and hamstrings will not be reduced to the greatest extent with entire lower limb cooling compared to knee and/or ankle cooling.
3. In regards to EMG, there will be no significant increase in muscular co-activation between agonist and antagonist pairings with cold exposure across all conditions during maximal reach of the SEBT. The greatest amount of co-activation in a muscle pairing will not occur when the muscle temperature is directly influenced by the CWI (i.e. there will be no difference in the co-activation between biceps femoris and vastus lateralis across all conditions).

These hypotheses will be addressed throughout the discussion.

Cooling protocol:

Previous research has looked at the impact of tissue cooling during and within a short time after cold water (82, 117, 119, 121), cold air (95, 110) and ice pack (36, 75) modalities and the impact of rewarming after a long post cold exposure recovery period (153). Dependent on the modality type, temperature and exposure time, as well as participant adiposity, and limb girth, which can all affect the thermal gradient, a variety of tissue temperatures result (107). This can make it difficult to generalize the effect of cold temperature on the body. The 20 minute and 10 minute 12°C CWI utilized during this study provided sufficient time and thermal stress to generate significant cooling ($P<0.001$) both of the skin and superficial skeletal muscle of the lower extremities. The room temperature environment (22.4 ± 0.8°C), after CWI exposure, allowed for significantly cooler skin temperature for the limb segment(s) exposed (thigh and foot $P<0.01$ and shank $P<0.05$) versus non-exposure during the strength and balance tasks which occurred between ~10-20 minutes after CWI. It is possible for up to 60 minutes after cold exposure for effects from that exposure to still manifest within the individual (153). It would be ideal to perform the balance and strength tasks immediately after CWI, although this wasn't possible, due to logistics and T_{mu} measurements. The balance and strength tasks were still performed within 60 minutes of CWI due to the dual phase methodology where 2 CWI were performed during each experimental trial.

Although the dual phase protocol worked sufficiently well for our purposes it would be advisable for future studies to use caution when using a dual phase cooling protocol. The dual phase cooling protocol adds an extra level of complexity where more is likely to go wrong during each trial. For example, it was a challenge to keep skin thermistors on when participants entered and exited the immersion suit. Performing a suit ingress and egress twice, provided more opportunity for wires to become ensnared and break or tape to come unstuck. The dual phase protocol also made it difficult, but not impossible, to keep consistent skin and muscle temperatures between the strength task in the first phase and balance tasks in the second phase. This could be due to the fact that it is found that muscle temperature often lags behind skin temperature both during cooling and rewarming (22). As a result, during the second T_{mu} often a lower value, although not statistically significant, was obtained compared to the first recording. This might have been due to the T_{mu} starting the second CWI in a colder than normal state and subsequently, even the shorter 10 minute CWI, still brought the T_{mu} down further than after the first CWI. Therefore if studies are trying the establish relationships based on muscle temperature and different kinesthetic tasks it might be best to have participants endure separate CWI and tasks on different days to maintain ideal T_{mu} congruence.

Isokinetic strength:

When skeletal muscle and the surrounding tissue are cooled previous research has indicated that isokinetic strength is reduced (67, 131). Therefore it was thought that peak isokinetic torque of the knee extensors and flexors would be reduced the most with the entire limb exposed to the CWI. It was thought that quadriceps femoris and hamstrings peak torque could be reduced with ankle and knee CWI as well. It was thought that perhaps cooling the ankle might influence how much force a participant could exert against the ankle pad of the isokinetic lever arm due to altered mechanoreceptor sensitivity. By cooling up to the knee it was thought that increased knee joint or patellar ligament stiffness might negatively impact isokinetic peak torque. Unfortunately the speed at which the isokinetic testing occurred in the current study might have been too slow to elicit a significant drop in peak torque regardless of CWI exposure level. This may be the case as past research shows the reduction in peak torque due to cooling is linked to the speed at which the contraction is executed (67). Howard and colleagues noticed that, at concentric isokinetic velocities reaching 180°/s and faster, peak torque was reduced by ~25-27% with muscle cooling from a 12°C water bath up to the gluteal fold (67). At a velocity of 0-30°/s no significant reduction in peak torque was found (~4-10% reduction) from the same cooling protocol (67).

Due to the small number of participants who were run through the current isokinetic testing protocol successfully (n=4) not much can confidently be stated about 12°C CWI on isokinetic peak torque at 45°/s. Inferring to the pattern established over the 4 test conditions and keeping in mind that slower isokinetic concentric velocities appear to be less influenced by cold temperatures, it is hypothesized that the relatively slow contraction speed used in this study also created a situation where no significant reduction in peak torque of the quadriceps femoris and hamstrings muscle groups occurred. It could be that the faster contraction speeds in colder conditions exaggerate the ‘braking effect’ of antagonist muscle groups which causes the drop in peak torque (114). It could also be as a result of increased joint stiffness which provides significantly increased resistance only at faster contraction velocities (131). What can be said about this current study is that the peak torque values that were obtained are similar to other studies (40, 106). At relatively slow isokinetic speeds (30-180°/sec.) a 0.5 strength ratio of the knee flexors to knee extensors has been observed (106). The current study showed an average hamstrings to quadriceps peak torque ratio of 0.64 ± 0.03 concentric and 0.58

± 0.06 eccentric across all conditions. Therefore, it could be stated that with this study that the torque ratio between the quadriceps and hamstrings was not disrupted by the cold exposure.

The reason behind including a slow speed isokinetic strength component in this study was to determine if muscular strength of the thigh, an important component to the successful execution of the SEBT (32), was influenced by cold exposure and could therefore be a reason as to why SEBT performance was reduced with lower limb cooling. No significant change in torque was seen across conditions. Therefore we must accept the null hypothesis and reject the alternative. It is plausible that, despite inconsistencies in correlating balance and strength (46, 47, 91, 99), the muscular strength needed for the SEBT, which is executed at a relatively slow joint velocity, was not severely impacted by the cold to become a factor in the impairment of the test performance when the lower limb, specifically the thigh, was cooled.

Static balance performance:

The time one is able to hold the stork stand posture for is related to how strongly their visual, vestibular and somatosensory organs can integrate to allow one to maintain their balance in a static position (143). As a greater limb volume was cooled and therefore potentially more of the somatosensory organs were impaired by the cold exposure, a greater reduction in the mean stork stand time was found. Shortest mean stork stand times were found after the entire lower limb was submerged from the hip CWI (17.96 ± 3.95s control versus 7.55 ± 1.15s hip CWI). Many participants also remarked, without query from the researchers, that they felt that the hip immersion made it more difficult for them to maintain the stork stand position.

There are several possible reasons as to why there was decreased stork stand performance across environmental conditions. Vision and vestibular balance components were not affected by the CWI, or tested in particular during the stork stand (i.e. eyes were kept open), which leaves the somatosensory component as the one part of balance that might have been influenced by the cold. Previous research has demonstrated impairment of static balance with single (93, 94) and repeated (95) cold exposure through postural sway analysis. Reasons stated as to why decreased static balance performance occurred runs parallel with this current study: One, stimulation of cutaneous afferents can influence motor recruitment patterns (recruitment order) (141). Therefore, as more of the cutaneous mechanoreceptors were cooled due to the segmental cooling protocol, altering their sensitivity, this could have changed muscle behavior which might have made it more difficult to perform the stork stand by reducing effectiveness of postural corrections. Two, cooling of sensory afferents can reduce their conduction velocity (129). The greater the amount of the lower limb cooled (i.e. cooling entire limb versus up to knee) may have translated to greater impairments to afferent and efferent nerve conduction velocity to the foot to control COM. Three, an increase in muscle tone can occur with muscle cooling (95). During the stork stand, this increased muscle tone may have stiffened joints due to increased co-activation (115). For example, cooling the hip joint might have increased joint stiffness and made it more challenging to perform hip movement strategies to keep their balance.

Dynamic balance performance:

Previous research observed a 1% reduction in maximal excursion per degree Celsius drop in muscle temperature during a bipedal limit of stability test after a 60 min., 15°C CWI up to the popliteal fossa (121). A limit of stability test requires a participant to keep their feet stationary while actively shifting their COG as far as possible in a variety of directions and as such could be considered a dynamic stability task (121). Similar to this past study by Piedrahita, SEBT performance during this study was reduced after CWI. The anterior SEBT reach direction resulted in a relative drop in mean reach distance by 1.38, 2.48 and 4.73% for ankle, knee and hip CWI respectively compared to the control reach distance (figure 4.11A). The posterior SEBT reach direction resulted in a relative drop in mean reach distance by 0.74, 2.74 and 4.05% for ankle, knee and hip CWI respectively compared to the control reach distance (figure 4.11B). Significance was achieved for pairwise comparison between hip and the control and ankle conditions ($P<0.05$). Caution should be taken interpreting these results as previous research has indicated that a 6-8% change in normalized reach distance is needed between tests to be certain that measurement error is not the main influence on results (105). With this in mind it can be tentatively stated that hip immersion negatively impacted SEBT reach distance. It is even possible that there was impairment in reach distance from ankle and knee CWI as there was a drop in the mean scores compared to the control. Perhaps it was that the SEBT was not a sensitive enough field test to detect a significant change in reach distance due to cold exposure. This is a possibility as cooling down just the plantar aspect of the feet with ice was enough in one study to generate a cautious walk pattern (less ground reaction force and braking peak force) (34) and in essence influence dynamic balance.

Hypothetically if one ignores statistical significance and looks at the reduction in mean SEBT reach distances and then relates that to the limb volume exposed to the CWI as a weighted mean (see appendix A) a different pattern for reach distance versus environmental condition becomes manifest. The greatest magnitude dynamic balance performance drop comes when the relatively small volume of the foot is cooled (~11.7% drop in reach performance) compared to the shank (an additional ~4.6% drop in reach performance) and thigh (an additional ~3.1% drop in reach performance). This result would be congruent with an alternative hypothesis that cooling down the foot would bring about the most substantial drop in balance performance. This potential increased susceptibility to balance performance within the feet could be due to the increased density of superficial mechanoreceptors and the greater chance for restricting degrees of freedom (55). It might be with more participants or more sensitive dynamic balance tests that this hypothetical analysis could show significance.

However, from the current research, through reach distance and statistical analysis, we would have to accept the null hypothesis that cooling the feet alone would not cause the most significant impairment to dynamic balance and that it is only when the entire limb is cooled that balance performance suffers. This could be due to the same environmental somatosensory impairment as stated during the static balance test.

There is a linear relationship between kinesthetic performance and body temperature (129). This current experiment required CWI up to the hip to show a significant reduction in SEBT reach distance. This thermal relationship and result generates two hypotheses: One, an integrative hypothesis, that it is the cumulative effect of more lower extremity volume cooled that led to reduced balance performance with hip

CWI, or two, a segregated hypothesis, that the hip and surrounding musculature, when cooled creates an impaired reach unique to SEBT mechanics. Due to the integrated nature of the human body, the first hypothesis seems to intuitively bear more traction. For reasons similar to those given for the stork stand test performance (i.e. decreased nerve conduction velocity) and by looking at joint kinematics and muscle activation we can try to provide evidence for an integrative effect on dynamic balance performance from varying amounts of cold exposure.

Joint kinematics:

Previous research has determined that sagittal plane joint kinematic analysis of the SEBT through passive marker and camera use is a reliable and valid method to capture joint angle data for slow dynamic motor tasks (50). Within the context of this study, joint kinematics were used to determine if there were any changes in joint angle of the support leg at the ankle, knee and hip during the maximal reach of the SEBT throughout the 4 different environmental conditions. Although no significant changes in joint angle at maximum reach were detected there were still some potential patterns within the data.

Previous research on active ankle joint range of motion after CWI noted a significant drop in ankle dorsiflexion when participants were cooled in a 10°C whirlpool bath up to the fibular head (116). The current study showed no significant change in ankle dorsiflexion at maximal reach of the SEBT. It could be that there was a drop in ankle dorsiflexion although the challenge of placing the markers over four conditions and manually measuring the joint angles through MATLAB may have increased the chance for measurement error through decreased precision. For example, previous research, which proved the validity of 2-D kinematic analysis of the SEBT, did so over only 2 test sessions and achieved a standard error of 0.83° (50) at the ankle during maximal reach of the SEBT, not the 4 sessions which our study employed which achieved a larger standard error of 1.92°. Pursuing a different avenue of thought, SEBT reach distance is thought to be correlated to reach distance (32). Within this study through correlation of maximum reach distance and ankle dorsiflexion angle there was a moderate association between how far participants could reach and how much dorsiflexion was achieved (0.358 Posterior reach ,0.385 Anterior reach, $P<0.05$). This could lend evidence that the cold had no or a very minor effect on ankle dorsiflexion active range of motion within the closed kinematic chain SEBT movement. The previous study which showed impairment to ankle dorsiflexion ROM did so in an open kinetic chain exercise (116). It could be that the close chain, semi-squat exercise of the SEBT creates an effect which reduces the impact that cold has on ankle ROM. Since the SEBT is closed chain it is important to look at the knee joint as well to observe what is occurring and relate that to the overall SEBT mechanics.

No previous research has looked at changes in knee flexion during a balance task with cold immersion. The current study showed a non-significant decrease in mean knee joint flexion angle at maximum SEBT reach as participants had greater amounts of their lower extremities exposed to a CWI. The decrease was on a magnitude of 3-4° comparing knee flexion angle between the control to hip CWI conditions. There was no significance achieved due in part to the higher than expected variability of the data. The current study resulted in a standard error of 3.67° degrees at the knee over 4 sessions while the previous study looking at 2-D kinematics during the SEBT held a standard error of only 1.70° over 2 sessions (50). While there were no significant findings with knee angle in relation to the cold there was a moderately strong correlation with maximal posterior SEBT reach distance and knee joint angle (-.556, P<0.01). Although no significant changes in either knee or ankle joint angles were found as a result of cold exposure it is still possible that there were slight changes in joint angle, which in turn affected reach distance of the SEBT. It could be limitations due to measurement error with the 2-D kinematic analysis (i.e. standard error, frontal/transverse plane motion) which diminished any significant joint angle pattern from developing.

If there is an effect of cold exposure on joint kinematics it would make sense that during the ‘squat-like’, closed kinematic chain motion of the SEBT that if cold restricts the ROM at one joint it would influence the ROM at other joints (140). In the case of the current study a slight decrease in knee flexion angle was observed across environmental conditions. However, one would expect to see a decrease in ankle dorsiflexion as well. There may have been a very small decrease in ankle dorsiflexion angle across conditions but the change was too small to be considered. Therefore, if only a change in knee angle with CWI occurred it could be that the cold impaired joint mobility and coordination of joint ambulation. For example, if during maximal reach of the SEBT ankle dorsiflexion was unchanged but knee flexion angle was reduced this might have moved an individual’s centre of gravity further forward making a fall or reach error more likely.

Generally speaking, joint stiffness and coordination can be altered by the cold. Joint stiffness can increase with cold exposure due to increased synovial fluid viscosity (121), while joint coordination can be challenged from reduced joint position sense due to impaired glaborous superficial mechanoreceptors (34, 94, 138), or alterations in the thixotropic properties of skeletal muscle (23, 136). It is difficult to pin down the exact mechanistic cause of the possible reduced knee joint angle at maximum SEBT reach. Perhaps employing electrogoniometers to more precisely measure joint angle would have helped to find more statistical significance and determine if the ankle dorsiflexion angle at maximum SEBT reach changed with cold exposure.

Muscle activation:

Previous research has observed the averaged, normalized RMS value of the leg muscles during the SEBT (32). Similar to this current study, Earl and Hertel found that the vastus lateralis, as well as the vastus medialis, regardless of reach direction, were the most active muscles during a 1-second window analyzing the averaged, normalized RMS around the maximal reach of the SEBT. For instance, the present study during anterior and posterior reach of the SEBT generated a vastus lateralis RMS of between 80-120% MVC and a biceps femoris RMS of approximately 40-60% MVC. Earl and Hertel found a vastus lateralis RMS of between 90-110% MVC and a biceps femoris RMS of roughly of 20-40% MVC (32). The present study RMS values might be slightly higher due to the smaller 250 ms data window and particularly for the biceps femoris as the MVC for this muscle was recorded in a mechanically compromised position (60° knee flexion). Earl and Hertel’s study also parallels the findings in this study regarding the reach direction and specific muscle activation patterns. Both this study and theirs show a significant increase in biceps femoris and tibialis anterior activity ($P<0.05$) when reaching posteriorly in relation to the forward reaching task. During the posterior SEBT participants reached higher degrees of knee flexion and ankle dorsiflexion (squatted down further). It is possible with a ‘deeper’ squat that biceps femoris activity increased to counter anterior shear of the tibia (37) or resist knee internal rotation (10) while the tibialis anterior increased to help stabilize the ankle (127) or manage COP (45).

Only one muscle group showed any change approaching statistical significance with respect to activation with cold exposure. The lateral gastrocnemius muscle activity during the anterior reach of the SEBT dropped as the participant was cooled up to the knee and hip (P=.059). Due to the bi-articular design of the gastrocnemius it is possible that if participants were not squatting down as far when cooled that the gastrocnemius activity would be reduced (127). This would also provide evidence to show that there was indeed a change in knee joint angle at maximum SEBT reach from the CWI. The reason why RMS and cold exposure significance was not detected could be due to the variability of the RMS values obtained throughout the course of the study. Lateral gastrocnemius activity had a much lower variability between participants and trials compared to the other 3 muscles analyzed which allowed for a stronger statistical pattern to develop. It could also be that the physiological changes from the cold and SEBT mechanics were not significant enough to elicit a response that could be detected by the sensitivity of the recording instruments.

Muscle co-activation:

Through use of the CI equation, listed in the methods section and appendix A, a statistical analysis was performed on the RMS data set of the agonist / antagonist relationship between the thigh muscles (vastus lateralis and biceps femoris) and shank muscles (tibialis anterior and lateral gastrocnemius) (see appendix E) during a 250 ms data window around the maximal reach of the SEBT. During the maximal reach of the SEBT, the vastus lateralis and tibialis anterior acted as agonists while biceps femoris and lateral gastrocnemius acted as antagonists based on the relative averaged and normalized RMS. There was no statistically significant change in co-activation as a result of the cooling protocol. This lack of significance is most likely due to the high degree of variability in the averaged RMS value that was obtained. Variability was due to intrinsic factors such changes in how participants reached from one trial to the next (i.e. more / less hip flexion) and how well and consistently they performed the normalization MVC. Variability was also due to extrinsic factors related to skin preparation and EMG sensor location between trials although great care was taken to minimize these extrinsic factors. When one looks at the CI values, despite the lack of significance, there does appear to be a general increase in co-activation of the vastus lateralis and biceps femoris as the limb is cooled regardless of if the thigh was cooled directly or it was only the foot with a lower tissue temperature from ankle CWI. For example during the anterior SEBT the control thigh CI was 66.9 versus a thigh CI of 74.0 after the limb had been exposed with CWI up to the ankle, knee of hip. This pattern of increased co-activation of agonists and antagonists due to cold exposure has been documented previously (7, 111, 113, 123).

Within this study, the possible increased co-activation within the thigh from the CWI could be due to a drop in the average RMS of the vastus lateralis and a modest increase in biceps femoris activity when compared to the control (see figure 4.16A-B). The decrease in vastus lateralis RMS could be due to both the direct physiological affect of the cold influencing motor unit recruitment (141) or indirectly due to a reduced reach distance which was a result of the participants not squatting down as far as they did when under the control condition. The modest increase in biceps femoris activity, even when not cooled directly, could be a result of reflexive mechanisms (crossed extensor reflex) as a means to protect the limb from injury when cooling reduces proprioceptive ability (92). It would have been advantageous to measure EMG activity in the reaching limb to see if patterns changed to reinforce the possibility that a crossed extensor reflex resulted from the cold exposure. As mentioned, ultimately it might be down to the squat mechanics, specifically the joint angle at maximum reach which dictated the hamstrings RMS activity. During the control condition, when the participant average knee joint angle at maximum SEBT reach was the most flexed, resulted in a reduced hamstrings RMS activity compared to the CWI conditions. This might be due to the hamstrings being in more of a mechanically compromised state (shortened length) then during less knee flexion in maximal SEBT reaches (55). It would have been possibly more advantageous to select a specific joint angle during excursion to compare RMS values instead of the maximal reach. This might have filtered out the variability in squat mechanics as a factor for RMS and CI differences across conditions. Although there is evidence pointing for increased CI with cold exposure, based on statistical analysis there was no change and therefore the hypothesis that cold exposure would not increase CI is accepted.

To conclude, all 3 null hypotheses based on the statistical evidence had to be accepted. Observational evidence seems to show a linear decrease in SEBT performance as more volume of the lower extremities is cooled by a 12°C water immersion. However, these drops in performance are relatively small and it is only hip CWI that causes significant impairment. Isokinetic strength at 45°/s was not impaired with cooling and so it is plausible that muscular strength required to perform the SEBT was not reduced to a level which affected reach distance. Electromyographic activity supports the linear and angular kinematic data that show little effect of cold exposure on dynamic balance performance. It is most likely that the cold does have an impact on dynamic balance performance through impairment of a variety of NMS sub-units, but more sensitive tests or more participants are required to prove that dynamic balance performance is significantly impaired.

Application to boardsports:

In relation to athletics and boardsports in particular, the results of this study demonstrate one item of importance. Maintaining adequate levels of warmth within the lower extremities and specifically distal regions can be key to balance performance. Many boardsport enthusiasts may neglect the warmth maintained within their feet by either not wearing appropriate / adequate insulation in regards to skiing and snowboarding or in the case of kiteboarding go without wetsuit booties or opt for a ¾ length wetsuit in water temperatures which rapidly conduct/convect heat away from the body. This act could put the boardsports athlete at increased risk for injury or at least reduce their performance and enjoyment of their respective disciplines. For example, it has recently been observed that lower ambient temperatures result in an increase occurrence of knee injuries in female alpine skiers (125) and that even as skiers remain active their intra-articular temperature can drop (8).

Future Directions:

Previous research had mentioned that there was a need to look at the effect that cold temperature has on more challenging dynamic balance tasks (95). The SEBT was one such field test that lent itself well to see what kind of relationships exist between thermal stress and the NMS during taxing dynamic balance motor tasks. However, only 2 of a possible 8 reach directions were used in this study due to reliance on the sagittal plane for joint kinematics and also due to the time constraints within the study (rewarming). Future studies could look at lateral reach directions to see if impairment is incurred from cold exposure.

This study dealt with constant thermal stress for its CWI and so when participants were exposed up to the ankle this resulted in a significantly warmer dorsal foot temperature during the SEBT and SS then when the lower limb was cooled up to the knee or hip (~22°C with ankle CWI versus ~20°C with knee and hip CWI). This could have skewed the results with an effect of decreasing the impact that cooling the foot alone had on balance performance. Future studies could elect to use a constant thermal strain model for its CWI where a slightly colder temperature for the ankle CWI could be used.

A revisit of isokinetic muscular strength and CWI could be undertaken in future studies. A focus on eccentric muscle contractions as well as utilizing a closed kinetic chain leg press could be beneficial in drawing closer comparisons between the SEBT, SS and isokinetic strength.

Developing a more mechanistically-centred approach may help to shed light onto the exact pattern of integration that exists between the subunits of the NMS. Including Hoffman reflexes of the lower extremity as well as monofilaments to gauge the superficial mechanoreceptor sensitivity could help to determine how impaired these organs become when cooled and how this could influence challenging balance and strength tasks.

Limitations:

Although the nature of the experimental design lends itself well in applying balance performance to the big picture it is weaker at isolating specific mechanisms to weight NMS subunit susceptibility to cold and impact on kinesthetic performance. Although scientifically it is important to break components (ie. joint ergoreceptors) down to try and establish the exact relationship it is ultimately the entire machine, in the case of this research the NMS, which works in synergy to create the end product (balance, force).

Participants were recruited from the general population who were recreationally active (3 days per week, +30 minutes per session). This resulted in a large variance in fitness levels, in that some individuals were more resistance trained and others more aerobically trained. This may have impacted some of the results, specifically the muscle activation patterns.

Although kept to a minimum, the cooling protocol at times resulted in parts of the posterior aspect of the thigh to be submerged during the CWI. This could have been avoided with participants maintaining different postures during the various CWI depths. However, the researchers in this study thought it important to maintain as similar a posture between immersion depths to rule out any thixotropic joint position effects due to differing joint angles during the CWI.

Muscle temperature was limited to single time points and to the periphery of the vastus lateralis and lateral gastrocnemius. This made it difficult to discern how cooled the deeper portions of the muscle became after the CWI and what muscle temperature was like at the exact time the balance and strength tasks took place

Glossary	
Agonist	role played by a muscle acting to cause a movement
Antagonist	role played by a muscle acting to slow or stop a movement
Balance	the ability of an individual to assume and maintain a stable position, specifically referring to maintaining one's centre of mass within one's base of support
Concentric	action that occurs when a muscle overcomes a load and shortens
Eccentric	action that occurs when a muscle lengthens during a contraction as a result of insufficient tension development or to help control a movement
Exteroception	body sense pertaining to stimuli and associated receptors which originate and detect respectively from sources outside of the body
Extrafusal muscle	muscle which contains the majority of proteins which actively generate contraction
Ground Reaction Force	the force exerted by the ground on a body in contact with it
Glabrous skin	hairless skin
Interoception	stimuli and detectors associated with internal processes related to organ function
Intrafusal muscle	muscle which runs in parallel to its extrafusal counterpart that contains muscle spindles to allow for monitoring muscle length
Isokinetic	referring to dynamic muscle activity in which a joint moves through a range of motion at a constant velocity
Isometric	referring to muscle activity in which force is generated without a change in joint angle
Kinematic	referring to motion
Kinetic	referring to force
Kinesthesia	awareness of the position and movement of the parts of the body by means of sensory organs (inclusive of proprioception, exteroception and to a lesser extent interoception)

Glossary (Cont’d)	
Lever class	▪ 1st – a lever in which the fulcrum is between the effort force and the resistance ▪ 2nd- a lever in which the resistance force acts between the fulcrum and the effort force ▪ 3rd- a lever in which the effort force acts between the fulcrum and the line of action of the resistance force
Mechanoreceptor	receptor that responds to mechanical stimulation (ex. Stretch or pressure)
Non-Glabrous skin	hairy skin
Prime mover	(see agonist)
Proprioception	body sense pertaining to stimuli originating from within the body related to spatial position and muscular activity and/or the sensory receptors that they activate
Root Mean Square	the square root of the mean of all the squared values of EMG activity within a given window of data
Somatic Sense (Somatosensory)	Referring to senses of the body (proprioception, exteroception, interoception, nociception, thermoreception)
Stability	resistance to losing one’s equilibrium
Stabilizer	a muscle that contracts with no significant movement to maintain a posture or fixate a joint
Synergist	- a muscle which performs or helps perform the same set of joint motion as the agonist
Thermoreceptor	temperature sensitive receptor
Thixotropy	stiffness during joint motion attributed to crossbridge attachment and altered muscle spindle sensitivity from previous contractions
Torque	the product of the magnitude of a force and the perpendicular distance from the line of action of the force to the axis of motion

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Appendices

Appendix A: equations

$$RMS = \sqrt{\frac{1}{T}\sum_{t=1}^{T} EMG^{2}\,(t_i).}$$

Equation 1: root mean square amplitude (RMS) (78)

$$\dot{S} = \dot{M} \pm \dot{W}_k \pm \dot{R} \pm \dot{C} \pm \dot{K} - \dot{E}\ (W \cdot m^{-2})$$

Equation 2: Heat balance (76)

$$R = \frac{Temperature\ gradient}{Heat\ flow}\frac{°C}{W \cdot m^{-2}}$$

Equation 3: Thermal resistance (76)

$$CI = \left[\frac{Less\ active\ EMG_{RMS}}{More\ active\ EMG_{RMS}} \times (Less\ active\ EMG_{RMS} + More\ active\ EMG_{RMS})\right]$$

Equation 4: Co-activation index (68)

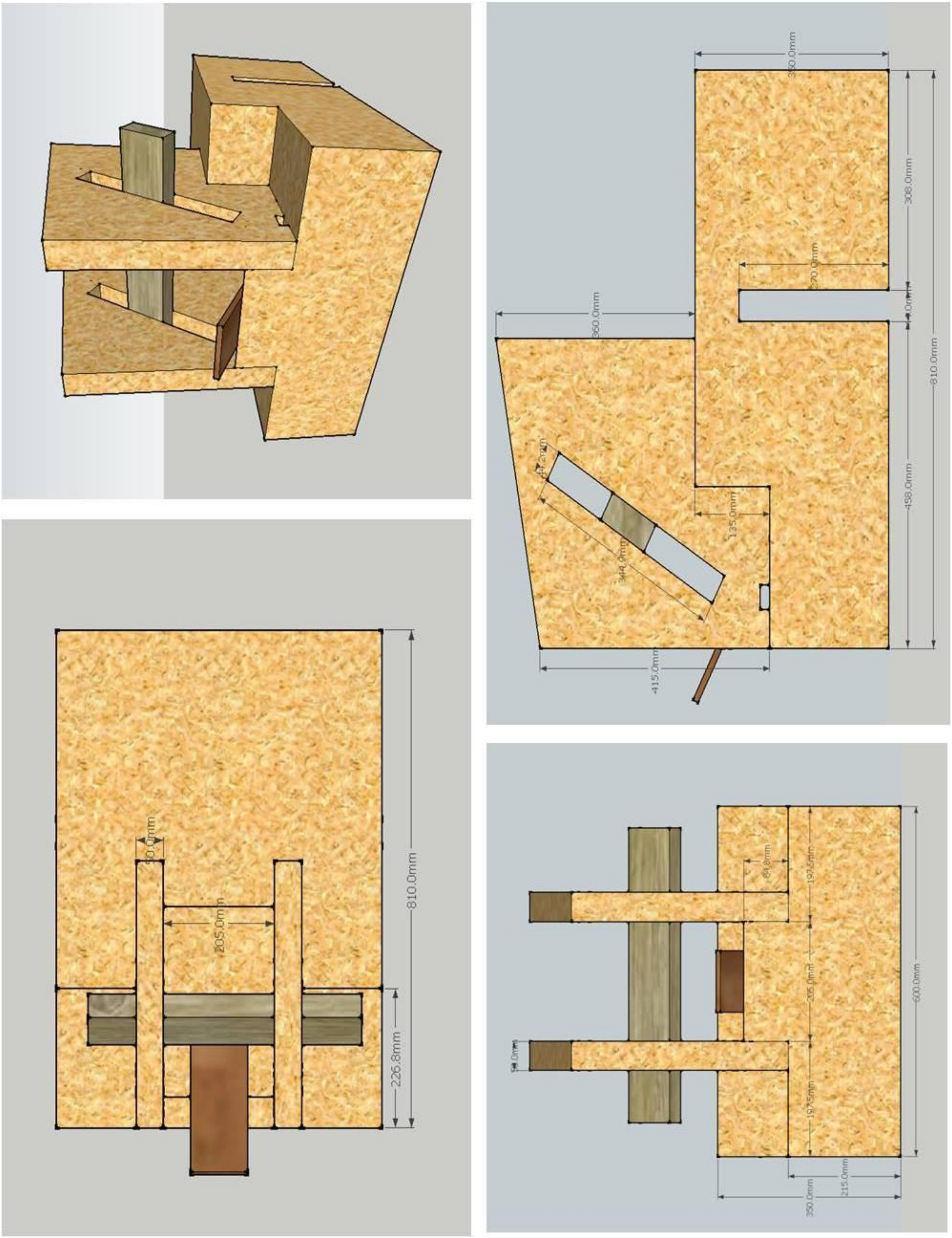
$$\overline{T}_{sk} = 0.3\ t_{chest} + 0.3\ t_{arm} + 0.2\ t_{thigh} + 0.2\ t_{leg}$$

Equation 5: 4-site Ramanathan mean skin temperature (124)

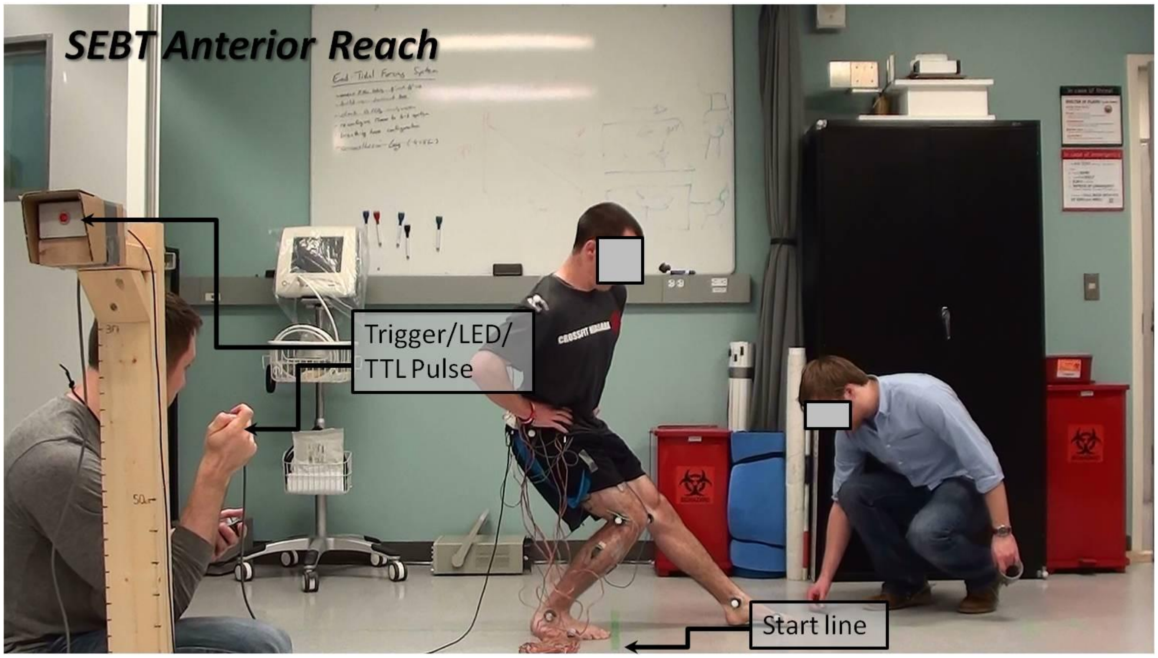
$$\frac{Precent\ change\ in\ normalized\ reach\ distance}{Percent\ volume\ of\ lower\ extremity\ cooled}\ \frac{\%}{\%}\ \textbf{(i.e. control to ankle CWI = }\frac{\mathbf{1.06}}{\mathbf{9.04}} = \mathbf{11.73\%)}$$

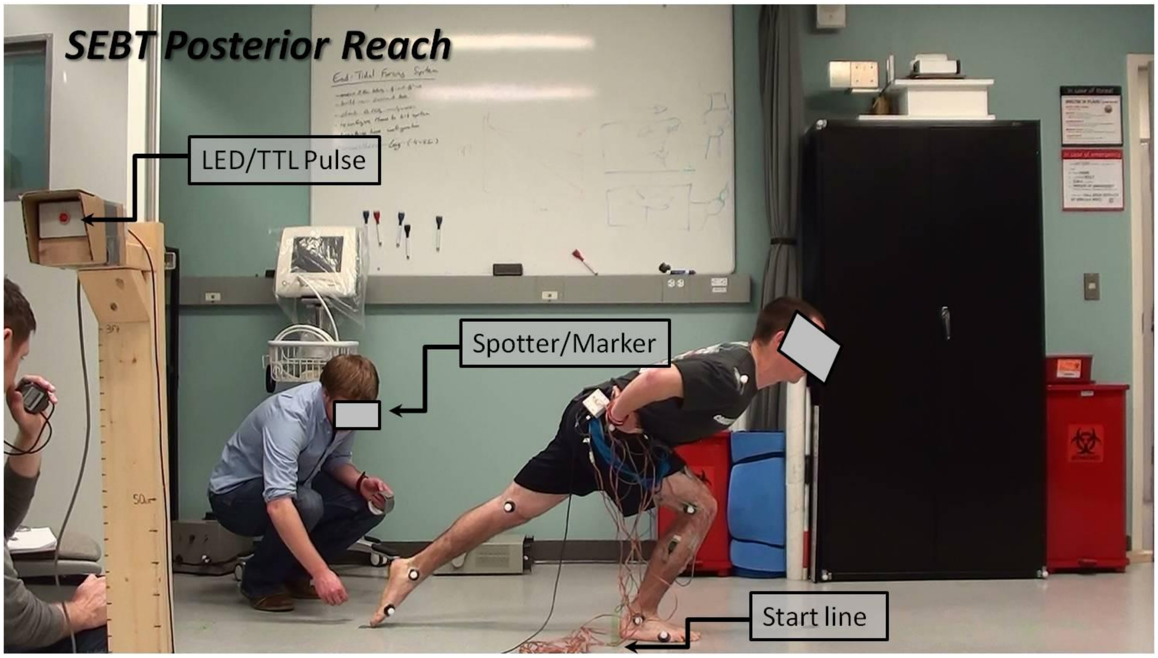
Equation 6: Weighted mean percentage for volumetric analysis of SEBT

Appendix B: Orthographic projection of MVC device



Appendix C: SEBT Pictures





Appendix D: Muscle and nerve supply of the lower extremities

Muscle and associated nerve supply of the hip

Action	**Muscle**	**Attachement**	**Innervation**
Flexion	Iliopsoas	*Proximal:* T12-L5 transverse processes, iliac crest, and sacrum *Distal:* Lesser trochanter	Femoral nerve
	Rectus femoris	*Proximal:* AIIS and anterosuperior acetabulum *Distal:* Superior patella	Femoral nerve (L2-L4)
	Tensor fascia latae	*Proximal:* ASIS and iliac crest *Distal:* Iliotibial tract	Superior gluteal nerve (L4,L5)
	Sartorius	*Proximal:* ASIS *Distal:* Anteromedial tibial plateau	Femoral nerve (L2, L3)
Extension	Gluteus maximus	*Proximal:* Outer cortex of ilium, posterior sacrum and coccyx *Distal:* Posterior iliotibial tract and gluteal tuberosity	Inferior gluteal nerve (L5, S1, S2)
	Biceps femoris	*Proximal:* Ischial tuberosity *Distal:* Fibular head and posterolateral tibial plateau	Tibial branch of sciatic nerve (L5, S1, S2)
	Semimembranosus	*Proximal:* Ischial tuberosity *Distal:* Posteromedial tibial plateau	Tibial branch of sciatic nerve (L5, S1, S2)
	Semitendinosus	*Proximal:* Ischial tuberosity *Distal:* Anteromedial tibial plateau	Tibial branch of sciatic nerve (L5, S1, S2)
Abduction	Gluteus medius	*Proximal:* Anterior gluteal line *Distal:* Lateral surface of greater trochanter	Superior gluteal nerve (L4, L5)
	Gluteus minimus	*Proximal:* Outer cortex of ilium *Distal:* Anterior surface of greater trochanter	Superior gluteal nerve (L5, S1)
	Tensor fascia latae	See above	See above
Adduction	Adductor magnus	*Proximal:* Inferior pubic ramus, ischial tuberosity *Distal:* Gluteal tuberosity and adductor tubercle of medial femur	Obturator nerve (L2, L3)
	Adductor longus	*Proximal:* Body of pubis *Distal:* Midle third of linea aspera	Obturator nerve (L2-L4)

	Adductor brevis	*Proximal:* Inferior ramus and body of pubis *Distal:* Proximal linea aspera and pectineal line	Obturator nerve (L2_-L4)
Internal rotation	Gluteus medius	See above	See Above
	Gluteus minimus	See above	See Above
External rotation	Obturator internus	*Proximal:* Inner surface of obturator membrane *Distal:* Medial greater trochanter	Nerve to obturator internus (L5, S1)
	Obterator externus	*Proximal:* Outer surface of obturator membrane, pubic ramus, and ischium *Distal:* Trochanteric fossa	Obturator nerve (L3, L4)
	Superior gemellus	*Proximal:* Ischial spine *Distal:* Posterior greater trochanter	Nerve to obturator internus (L5, S1)
	Inferior gemellus	*Proximal:* Ischial tuberosity *Distal:* Posterior greater trochanter	Nerve to quadrates femoris
	Piriformis	*Proximal:* Anterior surface of sacrum and sacrotuberous ligament *Distal:* Posterosuperior greater trochanter	Ventral rami of S1 and S2
	Quadratus femoris	*Proximal:* Lateral boarder of ischial tuberosity *Distal:* Quadrate tubercle	Nerve to quadratus femoris

Muscles of the thigh and associated nerve supply that act on the knee

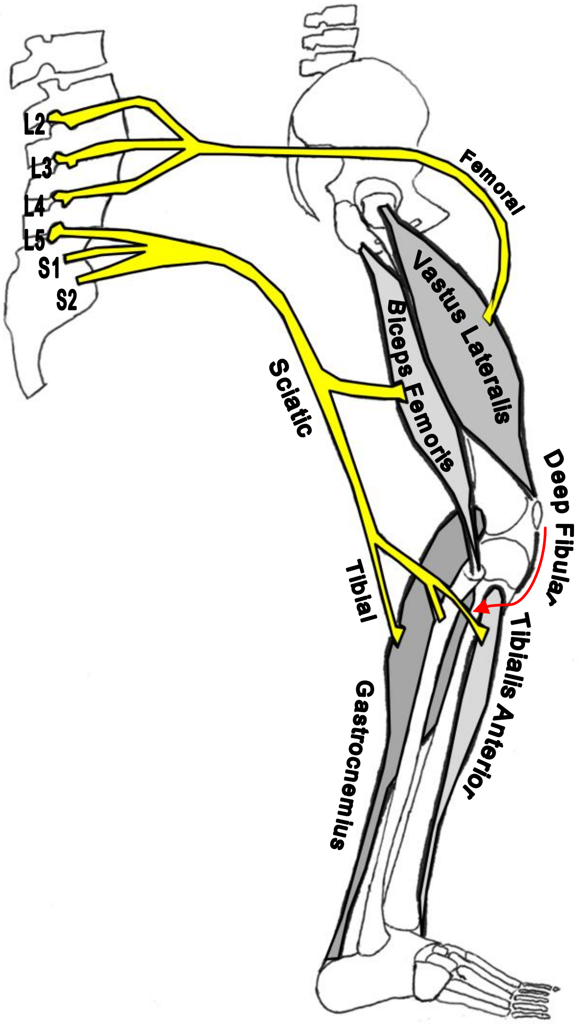
Action	Muscle	Attachment	Innervations
Knee extension	Rectus femoris	*Proximal:* Anterior inferior iliac spine and ilium superior to acetabulum *Distal:* Tibial tuberosity	Femoral nerve (L2, L3, L4)
	Vastus lateralis	*Proximal:* Greater trochanter and lateral lip of linea aspera *Distal:* same as R.F.	Femoral nerve (L2, L3, L4)
	Vastus medialis	*Proximal:* Intertrochanteric line and medial lip of linea aspera of femur *Distal:* same as R.F.	Femoral nerve (L2, L3, L4)
	Vastus intermedius	*Proximal:* Anterior and lateral surfaces of shaft of femur *Distal:* same as R.F.	Femoral nerve (L2, L3, L4)
Knee flexion	Semitendinosus	*Proximal:* Ischial tuberosity *Distal:* Medial surface of superior part of tibia	Tibial division of Sciatic nerve (L5, S1, S2)
	Semimembranosus	*Proximal:* Ischial tuberosity *Distal:* Posterior part of medial condyle of tibia	Tibial division of Sciatic nerve (L5, S1, S2)
	Biceps femoris (long and short heads)	*Proximal: Long:* Ischial tuberosity *Proximal: Short:* Linea aspera and lateral supracondylar line of femur *Distal:* Lateral side of head of fibula	Long head: Tibial division of Sciatic nerve (L5, S1, S2) Short head: Common fibular division of sciatic nerve (L5, S1, S2)

Muscles of the shank and associated nerve supply that act on the ankle and foot

Action	Muscle	Attachement	Innervation
Dorsiflexion	Tibialis anterior	*Proximal:* Lateral condyle and superior half of lateral surface of tibia and interosseous membrane *Distal:* Medial and inferior surfaces of medial cuneiform and base of 1st metatarsal	Deep fibular nerve (L4, L5)
	Extensor hallicus longus	*Proximal:* Middle part of anterior surface of fibula and interosseous membrane *Distal:* Dorsal aspect of base of distal phalanx of great toe	Deep fibular nerve (L5, S1)

	Extensor digitorum longus	*Proximal:* Lateral condyle of tibia and superior three fourths of anterior surface of interosseous membrane *Distal:* Middle and distal phalanges of lateral four digits	Deep fibular nerve (L5, S1)
	Fibularis tertius	*Proximal:* Inferior third of anterior surface of fibula and interosseous membrane *Distal:* Dorsum of base of 5th metatarsal	Deep fibular nerve (L5, S1)
Plantarflexion	Fibularis longus	*Proximal:* Head and superior two thirds of lateral surface of fibula *Distal:* Base of 1st metatarsal and medial cuneiform	Superficial fibular nerve (L5, S1, S2)
	Fibularis brevis	*Proximal:* Inferior two thirds of lateral surface of fibula *Distal:* Dorsal surface of tuberosity of base of 5th metatarsal	Superficial fibular nerve (L5, S1, S2)
	Gastrocnemius	*Proximal: Lateral:* lateral aspect of lateral condyle of femus, *Medial:* popliteal surface of femur, superior to medial condyle *Distal:* Posterior surface of calcaneus via calcaneal tendon	Tibial nerve (S1, S2)
	Soleus	*Proximal:* Posterior aspect of head of fibula, superior quarter of posterior surface of fibula, soleal line and medial border of tibia *Distal:* Posterior surface of calcaneus via calcaneal tendon	Tibial nerve (S1, S2)
	Flexor hallucis longus	*Proximal:* Inferior two thirds of posterior surface of fibula and inferior part of interosseous membrane *Distal:* Base of distal phalanx of great toe	Tibial nerve (S2, S3)
	Flexor digitorum longus	*Proximal:* Medial part of posterior surfaceof tibia inferior to soleal line and by a broad tendon to fibula *Distal:* Bases of distal phalanges of lateral four digits	Tibial nerve (S2, S3)
	Tibialis posterior	*Proximal:* Interosseous membrane, posterior surface of tibia inferior to soleal line, and posterior surface of fibula *Distal:* Primarily to tuberosity of naviular, also to cuneiforms, cuboid and bases of 2nd-4th metatarsals	Tibial nerve (L4, L5)

Appendix E: Trial specific muscles for surface EMG



Appendix F: Informed Consent

Informed Consent: EEL-069

Project Title: The effect of a segmental localized lower limb cooling protocol on muscular strength and balance (EEL-069)

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INVITATION

You are invited to participate in a study that involves research. The purpose of this study is to examine the relationship of lower limb muscle temperature on muscular strength and balance. The human body and its temperature state is dynamic and constantly interacts with the external environment. When temperature within the human body shifts from a thermoneutral state (28-35 degrees Celsius for skin and muscle temperature) a change in performance is often incurred. For example, with localized cold exposure, blood vessels constrict, muscles stiffen and nerves transmit messages more slowly within the affected tissue. This altered performance can have practical consequences. For instance, with more individuals partaking in recreational activities (e.g. skiing, water boardsports) that require participants have a high level of muscular performance in strength and balance while placing them at risk for decreased localized skin and muscle temperature. It is therefore important to try and better understand the impact that this temperature dependant relationship may have on both sport performance and personal safety.

WHAT'S INVOLVED

There will be a total of **five** sessions. The first session will assess your body composition (skinfold thickness, lower Limb length, height, weight) and provide familiarization for you with the cooling protocol and test battery. The following **four** sessions (1. Thermoneutral, 2. Ankle inclusive water immersion, 3. Knee inclusive water immersion, 4. Hip inclusive water immersion) will be used to discover the effect of varying proportions of lower body surface area exposure to cold on test battery performance. These sessions will each take place at the same time of day to avoid diurnal variations in core temperature and other physiological performance measures. These trials will be administered in a randomized order with at least 72 hours in between each. Prior to each session, you will be asked to refrain from alcohol and/or heavy exercise for 24 hours prior to the trial and caffeine on the day of the trial. In all five sessions, you will change into your own t-shirt and shorts. Appropriate change rooms will be provided for you to change into the required clothing.

Anthropometric Measurements and Familiarization Session

In the first session, you will have your height, weight, lower limb length and the amount of body fat in your body measured. Body fat testing will be performed using skinfold calipers, which might cause a slight pinching sensation, and will be taken by someone of the same sex in a private room. You will also be familiarized with the cooling tank, and the array of sensors that you will be instrumented with during the following four experimental trials. We will also take you through the isokinetic strength test and balance field tests (Star Excursion Balance Test, Stork Stand Test) in order that you have a thorough understanding of what will be expected of you during the experiment. The total session will take about 1.5 h.

Experimental Sessions

During the second through to fifth sessions, you will have your internal temperature measured using a tethered core temperature probe. You will be asked to insert this probe up to 15cm past the anal sphincter just prior to the experimental trial after you arrive at the lab. You will be asked to report to the laboratory at your predetermined time for each of the experimental sessions. These sessions will be spaced with a minimal time span of 72 hours to minimize any acclimation response.

Upon arrival at the laboratory, you will change into t-shirt and shorts, and insert core temperature probe. You will then be instrumented with a heart rate monitor strap across the chest for telemetric recording of heart rate. Skin temperature sensors will be taped onto the body surface at the following sites: chest, upper arm, thigh, calf, and foot, which will be used to calculate a mean skin temperature. Muscle activity will be recorded at 4 sites on the dominant leg and 2 sites on the non-dominant leg with the placement of active electromyographic (EMG) electrodes over the major muscle pairings of both upper legs (quadriceps/hamstrings) and dominant limb only lower leg (tibialis anterior/gastrocnemius). In order to ensure a clear signal from your muscles to the recording equipment we will need to shave and clean with alcohol the area under the electrodes. This process might leave your affected skin a bit red/sensitive but will disappear within 24h. Muscle temperature will also be recorded during the trials. Muscle temperature will be measured using a small sterile muscle temperature probe (needle) on 2 occasions throughout each trial: after 1st cooling protocol/before isokinetic test both on your non-dominant lower limb in the vastus lateralis (thigh) and lateral head of gastrocnemius (calf), and after 2nd cooling protocol/before the balance tests in your dominant limb. The muscle temperature probe will be inserted into the thigh and calf muscle at a depth of 3 mm in addition to the the overlaying subcutaneous tissue (fat/skin) (5-12 mm in depth) and will be removed immediately once a stable temperature measurement has been recorded (~5 seconds). A technician of the same sex will be available to assist with the dressing and instrumentation.

Cooling procedure

The experimental protocol will adhere to the following operating procedures: Once instrumented you will be guided to the cooling tank where you will climb into a plastic, water-proof immersion suit to the waist before lowering yourself into the seated position within the tank. This suit is to prevent the sensors and yourself from becoming wet thereby cutting down on the time needed to conduct the experiment (towelling off skin). The tank will be filled with water at 12˚C which is a common temperature used for athletes who use cold water baths during recovery from sporting events. Depending on the experimental condition for that day the tank might be filled with no water (thermoneutral), or up to your ankle, knee or hip. You will remain in the seated cooling tank for 20 minutes for the muscle to reach desired experimental temperature. Once 20 minutes has elapsed you will be helped out of the tank and immersion suit and wheeled in a transport chair to the isokinetic dynamometer lab.

Test Battery

Isokinetic dynamometry testing

You will be secured into the Biodex 3 Isokinetic dynamometer with waist and chest straps and an additional lower leg strap during ankle plantarflexion and dorsiflexion to minimize unwanted muscle substitution. You will be encouraged to contract as forcefully as possible (maximal voluntary contraction or MVC) concentrically at 45˚/s 3 times in both sagittal directions about the knee (extension and flexion) to normalize the EMG data. You will then perform 3 knee extension and flexion eccentric contractions at a speed of 45˚/s. You will be allowed 3 warm-up repetitions before the testing begins to prepare yourself for the maximal contractions.

Balance testing

After the isokinetic testing you will be wheeled back into the Environmental Ergonomics Lab for balance testing. Just prior to balance testing you will enter the cooling tank to bring limb temperature back down to a uniform level. This second exposure will last only 10 minutes. You will then exit the tank again and will be instructed to perform an MVC on your dominant leg for normalization of EMG data. You will then perform both the Star Excursion Balance Test and Stork Stand Test on your dominant leg.

The Star Excursion Balance Test is a multidirectional test of *dynamic* postural control which involves balancing on one leg while reaching maximally with the other leg in up to 8 directions, although only 2 directions will be employed for this research (anterior and posterior). The stork stand test challenges *static* postural control with an individual standing up on the ball of their foot for as long as possible while maintaining balance.

Electrical Stimulation

You will lie face down on a padded bench. You will allow a nerve in your leg to be electrically stimulated up to 300 times during any given session. This does not require the insertion of any needles. The electrode for stimulating the nerve will be taped to the skin surface and will deliver very brief electrical impulses through the skin. Changes in muscle electrical activity will be monitored by placing electrodes over an associated muscle on the lower extremities.

After completing the electrical stimulation you will be de-instrumented and the trial will be concluded.

The time commitment for each experimental session will be approximately 1.5 hours. Total time commitment for the study is ~7.5 hours.

POTENTIAL BENEFITS AND RISKS

Participants will receive no direct benefits from their involvement in this study. However, possible benefits of participation include your receiving a body composition assessment that will help you to understand your fitness/health level. The experimental testing will help you become aware of your body’s coping ability in cold temperatures.

There may be risks associated with participation. The test battery can be considered to be similar to what you might voluntarily perform in everyday life (e.g. strength training). There is a chance that you will incur delayed onset muscle soreness, however this soreness should disappear within 48-72 hours. There will be at least two investigators trained in First Aid and CPR present for each experiment. The investigators will contact you later in the day following each session to check on your health status.

The balance tests will challenge your equilibrium and therefore there is a slight chance of falling however you are in control during the testing and can use any means possible to regain your balance. Additionally, padding will be used around the perimeter of the balance platform and a researcher will be close by to maximize your safety. Spotters will be present to assist you in the event that you do fall in doing so they may need to physically contact you to help keep you upright.

RECTAL PROBE

When performed in a healthcare setting, insertion of the rectal probe is a controlled act as set out in the Regulated Health Professions Act. While this act does not extend to research outside of a healthcare setting, you should be aware of the following potential risks:

Insertion of the rectal probe can stimulate the vagus nerve which can cause slowing of the heart rate which may lead to fainting. This is more likely to happen if you have a low resting heart rate.

Perforation of the bowel can lead to peritonitis, a serious infection of the abdominal cavity.

You should not participate in this research if you are pregnant, are under the influence of alcohol or other sedating substances (tranquilizers, sleeping pills, street drugs) or have any history of fainting or heart disease.

Insertion of the flexible rectal probe may cause slight discomfort. You will be given instruction about how to prepare the probe, and will self-insert the probe in a private room. You will be provided with water-based lubricant if necessary, and will secure the probe with a soft gauze “sumo sling” harness which will keep it in place during exercise. There is a slight but real risk of perforation of the bowel from the insertion of the rectal probe, though the investigators are unaware of this ever occurring in a research setting. There is also a chance that surface temperature sensors or tape use with these sensors may cause some skin irritation.

MUSCLE TEMPERATURE PROBE

Placement of a muscle temperature probe (needle) into the muscle can be somewhat uncomfortable and is similar to the sensation from a flu vaccine needle. Like any foreign body, the needle probe poses a risk for infection. Signs and symptoms of infection include pain, redness, swelling and puss around the insertion site of the muscle temperature probe. If an infection is suspected, you should clean the affected area and contact your physician. The needle thermistors to be used in this investigation will be thoroughly sterilized prior to use. Although very unlikely, placement of muscle temperature probes (needles) may cause inadvertent neurological injury, such as paresthesia (the temporary sensation of tingling prickling or numbness). Following the experimental session, the investigator will test for neurological damage by examining the strength of local muscle groups. If any damage is suspected, you will be asked to consult your physician. Paresthesia due to nerve trauma from a needle rarely results in a long term loss of sensation. Sensation will usually return after 2 months as the nerves regenerate.

EVOKED STIMULATION

On rare occasion, a participant is unable to tolerate electrical stimulation of the nerve. This stimulation may be painful as the nervous system may perceive it, however brief, as noxious. As a result there is a potential for fainting. However with your body already in a prone position the chance of injury will be very minimal. There is also a small risk that the electrical stimulation may cause burns although this risk will be controlled with the brief length and low intensity of the stimulation as well as the quality of electrode contact with the skin and limited reuse of electrodes as per manufacturer's instructions.

CONDITIONS FOR EXPERIMENTAL TERMINATION

Experimental sessions will be terminated if:

1. Core temperature increases beyond 39.5^{o}C.

2. Core temperature drops below 35.0˚C.

3. Dizziness or nausea precludes further experimentation.

4. You decide, for any reason, to end the experiment.

5. The investigators determine that the subject is unable/unfit to continue.

REASONS TO NOT PARTICIPATE

You should not participate in this research if you are pregnant, are under the influence of alcohol or other sedating substances (tranquilizers, sleeping pills, street drugs) or have any history of fainting or heart disease. If you have any cardiac conditions then you should not participate. Nor should you participate with any history of digestive issues such as bowel or prostate problems (colitis, irritable bowel syndrome, prostate problems, haemorrhoids, diarrhea). You should also avoid participating if you have neuromuscular (epilepsy, multiple sclerosis, cerebral palsy) or skeletal (inflammatory or degenerative arthritis). If you have any balance related issues (inner ear infection, vertigo) then you should not participate.

CONFIDENTIALITY

Access to this data will be restricted to Dr. Cheung and the principal student investigator, Mr. Roger Montgomery. Your participation will remain confidential. The data collected from this investigation will be kept secured on the premises of the Department of Physical Education and Kinesiology (PEKN) at Brock University in Dr. Cheung's office or laboratory, and will not be accessed by anyone other than the listed investigators. The data (paper and electronic) will be destroyed five years after the publication of the results of the study.

Investigators will require disclosure of your name and contact information (phone, email), and therefore your participation is not anonymous during the conduct of the research. All participants will have their names removed from any data. The master list matching participants to data will be kept by Dr. Cheung, and will be destroyed following the publication of data.

All information you provide is considered confidential; your name will not be included or, in any other way, associated with the data collected in the study. Furthermore, because our interest is in the average responses of the entire group of participants, you will not be identified individually in any way in written reports of this research.

VOLUNTARY PARTICIPATION

Participation in this study is voluntary. If you wish, you may decline to answer any questions or participate in any component of the study. Further, you may decide to withdraw from this study at any time and may do so without any penalty or loss of benefits to which you are entitled. Participation, non-participation, or withdrawal from the study will not affect your standing at Brock University.

PUBLICATION OF RESULTS

Results of this study may be published in professional journals and presented at conferences, but your personal information and participation will remain confidential. Approximately one month after we finish testing all participants, we will provide you with a summary of your own results and also the overall group results. Feedback about this study will be available from Dr. Stephen Cheung (stephen.cheung@brocku.ca, 905-688-5550x5662).

CONTACT INFORMATION AND ETHICS CLEARANCE

If you have any questions about this study or require further information, please contact the Principal Investigator or the Faculty Supervisor (where applicable) using the contact information provided above. This study has been reviewed and received ethics clearance through the Research Ethics Board at Brock University (11-030). If you have any comments or concerns about your rights as a research participant, please contact the Research Ethics Office at (905) 688-5550 Ext. 3035, reb@brocku.ca.

CONSENT FORM

I agree to participate in this study described above. I have made this decision based on the information I have read in the Information-Consent Letter. I have had the opportunity to receive any additional details I wanted about the study and understand that I may ask questions in the future. I understand that I may withdraw this consent at any time. My participation, non-participation, or withdrawal from the study will not affect my standing at Brock University.

Name: ____________________________

Signature: ________________________________ Date: ____________________________

Thank you for your assistance in this project. Please keep a copy of this form for your records.