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THE EFFECTS OF MANIPULATED SOMATOSENSORY INPUT ON SIMULATED FALLS DURING WALKING

by

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Honours Bachelor of Science, Human Kinetics & Neuroscience 2014

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ABSTRACT

Previous research has demonstrated that there is a distinct relationship between aging and instability. The somatosensory system plays a significant role in balance control in conjunction with vision and the vestibular system (Qiu et al., 2012). Evidence has shown that manipulation of the mechanoreceptors on the plantar surface of the foot has a direct effect on balance control. By manipulating these receptors with hypothermic anesthesia and vibration, researchers are capable of simulating the effect of sensory modification on healthy individuals, in order to understand the role that plantar-surface sensation has in adapting to perturbation during gait (Perry et al., 2001; Priplata et al., 2006).

This study included 14 healthy young adults (mean age 23.07 (±2.43)). Within this study, participants were asked to walk the length of an 8-meter platform at a comfortable speed. Participants were required to walk with reduced, enhanced and normal levels of somatosensory information of the plantar foot surface. During walking trials the participants travelled along a raised platform that had 4 sections in which removable foam squares were placed to provide either a stable or unstable situation when stepped upon. Located underneath three of these squares were three force plates (OR-6-2000 (AMTI, Waterdown, MA)). In order to prevent learning bias the location of the foam, as well as the direction of the perturbation was randomized. Participants were perturbed in either the anterior or lateral direction based upon the direction in which the removable foam squares within the platform were placed. Moreover, participants experienced three separate conditions (control, vibration, and cooled) on the plantar surface of the foot to manipulate the sensory information received. Electromyography (AMT-8 (Bortec, Calgary, Alberta)) was used to analyze magnitude and onset changes in muscle activity within the Gastrocnemius and

Tibialis Anterior of the right lower limb, and the Rectus Femoris, and Biceps Femoris muscles of the left lower limb. Three-dimensional motion analysis was also used to capture observable changes in gait (Optotrak, NDI, Waterloo, Ontario).

A main effect of condition was found for the third burst of muscle activity recorded within the Tibialis Anterior ($F_{(2,17)}$=2.75, $p<0.01$), with post-hoc analysis between the cooled and vibration conditions. A significant positive correlation was found between Rectus Femoris EMG amplitude and rate of loading ($r=0.94$,$p=0.05$). Within the anterior perturbations, a main effect for condition was observed for maximum COM velocity (($F_{(2,35)}$=3.71, $p=0.05$), minimum COP velocity ($F_{(2,35)}$=4.62, $p=0.03$), and for the maximum distance between COM and COP ($F_{(2,35)}$=4.37, $p=0.04$). A trend was also observed for the maximum distance the COM travelled within the lateral direction in the BOS ($F_{(9,35)}$=2.61, $p=0.06$). Within the lateral perturbations, a trending effect for condition was also observed for maximum COM velocity ($F_{(2,55)}$=3.07, $p=0.06$), the maximum distance between the COM and COP ($F_{(2,55)}$=2.98, $p=0.06$), and a main effect was observed for condition for the rate of loading ($F_{(2,55)}$=3.86, $p=0.03$).

This study provides evidence of a relationship between the plantar cutaneous mechanoreceptors and gait parameters regarding to balance control as observed by the significant effects on commonly used measurements of balance control (i.e. COP and COM velocity). A relationship between mechanoreceptors and EMG amplitude, as well as foot contact forces and EMG amplitude is also evident. These relationships may be used to further knowledge for balance control during adaptive gait, as well as provide further development of footwear and insoles to improve balance control.

ACKNOWLEDGMENTS

I would first like to thank my supervisor, Dr. Stephen Perry for his support throughout the duration of this project. Without his ongoing advice to assist in my completion of this project and facilitating a higher level of learning, this project would not have been possible. His support has allowed me to greatly expand on my own knowledge and pushed me to develop new skills, while expanding on old ones as well.

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GLOSSARY

Anterior-Posterior (AP)

- Refers to directions towards the front (anterior) and back (posterior) of the body(Hall, 2003).

Balance Control

- A broad phrase describing the dynamics of the human body to prevent falling (DA A. Winter, 1995)

Base of Support (BOS)

- The area in which the object is in contact with the ground, for humans it is generally perceived as the area within the feet as that is typically the only part of the body in contact with the ground (Shumway-Cook & Woollacott, 2002)

Biceps Femoris (BF)

- A posterior thigh muscle that spans from the ischial tuberosity, linea aspera, and lateral supracondylar line of the femur to the lateral side of the head of the fibula. The biceps femoris acts to flex the leg, extends the thigh, and laterally rotates the lower limb while the knee is flexed (Moore, Agur, & Dalley, 2011).

Centre of Mass (COM)

- The point that is the centre of an individual's total body mass (Shumway-Cook & Woollacott, 2002).

Centre of Pressure (COP)

- The representation of the application of the ground reaction forces into a single point on the ground (Shumway-Cook & Woollacott, 2002; M. H. Whittle, 2007).

Central Nervous System

- The human central nervous system consists of the human brain and spinal cord (Nieuwenhuys, Voogd, & Huijzen, 2008).

Cutaneous Mechanoreceptors

- Mechanoreceptors send information from the surface of the skin to the central nervous system. The cutaneous mechanoreceptors have been identified and classified based upon receptive field sizes and firing patterns (Johansson, 1978).

Double Stance

- A phase during the human gait cycle during which both feet are in contact with the ground (Rose & Gamble, 2006)

Electromyography (EMG)

- Measurement of the biomechanical signal associated with electrical signals created by muscles (Raez et al., 2006)

Fast Adapting Receptors

- Cutaneous mechanoreceptors that produce activity at the onset and removal of contact. Fast adapting receptors include Meissner and Pacinian Corpuscles (Johansson, 1978; Mcglone & Reilly, 2010).

Gastrocnemius (MG)

- A plantarflexor muscle within the posterior compartment of the leg that originates on the lateral aspect of the lateral condyle of the femur, and the popliteal surface of the femur, and attaches to the posterior surface of the calcaneus. The gastrocnemius plantar flexes the ankle while the knee is extended, raises the heel during walking, and flexes the leg at the knee joint (Moore et al., 2011).

Golgi Tendon Organ

- Sensory receptor that responds to passive and active stretching of muscle fibres, monitoring the level of muscle force (Enoka, 2001)

Hypothermic Anesthesia

- Method of cooling the plantar surface of the foot to observe alterations in balance control (Perry et al., 2000)

Kinematics

- Description of motion of the human body, for example velocity and acceleration (Hall, 2003; Hamill & Knutzen, 1995).

Kinetics

- Description of the forces that occur with human motion (Hall, 2003).

Medio-Lateral (ML)

- Refers towards the midline of the human body (medial) and away from the midline of the human body (lateral) (Hall, 2003).

Meissner's Corpuscles

- A fast adapting, type I mechanoreceptor that has relatively small receptive fields within the epidermis level of the skin (Johansson, 1978).

Merkel Cells

- A slow adapting, type I mechanoreceptor that has relatively small receptive fields within the epidermis level of the skin (Johansson, 1978).

Muscle Spindles

- Responsible for signaling changes in muscle length and contraction velocity to the CNS (Kistemaker et al., 2012)

Pacinian Corpuscles

- A fast adapting, type II mechanoreceptor that has large receptive fields within the dermal level of the skin (Johansson, 1978).

Rectus Femoris

- An anterior thigh muscle originating from the anterior inferior iliac spine and ilium, attaching to the quadriceps tendon at the base of the patella. The Rectus Femoris acts to extend the leg at the knee joint and steady the hip joint (Moore et al., 2011).

Ruffini Endings

- A slow adapting, type II mechanoreceptor that has large receptive fields within the dermal level of the skin (Johansson, 1978).

Single Stance

- A phase during the human gait cycle during which one foot is in contact with the ground (Rose & Gamble, 2006)

Slow Adapting Receptors

- Cutaneous mechanoreceptors that demonstrate a sustained firing pattern following activation/indentation of the skin. Slow adapting receptors include Merkel's discs and Ruffini Endings (Johansson, 1978; Mcglone & Reilly, 2010).

Tibialis Anterior (TA)

- A dorsiflexor muscle located within the anterior compartment of the leg, originating at the lateral condyle and lateral surface of the tibia and interosseous membrane and attaching at the medial cuneiform and base of the 1^{st} metatarsal (Moore et al., 2011).

CHAPTER 1
INTRODUCTION

Within the Canadian senior population, falls are consistently the leading cause of injury-related hospitalizations, with 20-30% of seniors experiencing at least one fall each year in Canada (Stinchcombe, Kuran, & Powell, 2014). On a global landscape, 28-35% of individuals 65 and older encounter a fall each year, with that percentage increasing to 32-42% after the age of 70 (WHO, 2007a). While falls typically result in both negative physical and mental health effects, within Canada, older adult falls have been estimated to have financial costs of approximately $2 billion annually (Stinchcombe et al., 2014). The World Health Organization’s 2007 report on fall prevention has linked aging and frailty as major contributing factors to the frequency of falls experienced (WHO, 2007b). Based upon the national and global reports on falls and older adults, it is evident that fall intervention and prevention programs are necessary.

Previous research has demonstrated that there is a distinct relationship between aging and postural instability. The somatosensory system plays a significant role in postural control in conjunction with vision and the vestibular system (Qiu et al., 2012). The somatosensory system includes information from muscles and the skin (mechanoreceptors specifically) that is sent to the central nervous system (CNS) to influence postural control and stability. The CNS uses this information in order to produce effective postural control strategies (Nurse & Nigg, 2001). It has been demonstrated that older adults have an increased likelihood of falling in comparison to young adults as a result of sensory and motor degradation that occurs due to aging (Menant, Steele, Menz, Munro, & Lord, 2009). Evidence has demonstrated that manipulation of the mechanoreceptors on the plantar surface of the foot has a direct effect on postural control. By manipulating these receptors with hypothermic anesthesia, researchers are capable of simulating the age-related effect of sensory degradation on young healthy individuals, in order to understand how the body adapts to changes in gait similar to what an older adult would experience (Eils et al., 2002; S. D. Perry et al., 2001).

Purpose

The overall goal of this study is to gain a better understanding of how healthy young adults adapt to a gait perturbation when cutaneous somatosensory information is manipulated. Previous research has focused on the effects of both reduced and enhanced sensory information, and postural control (Priplata et al., 2002). The purpose of this study is to expand the knowledge of postural control in humans, and the ability to adapt under different sensory conditions. Moreover, the goal of this study is to analyze the interactions between altered somatosensory conditions on individuals undergoing gait perturbations, as well as the effects that these conditions have on an individual's ability to react to unexpected perturbations.

1.1 Normal Gait, control of gait, importance of balance during gait

Gait Kinematics

Within the field of biomechanics, kinematics is typically used to analyze motion without regard to the forces involved (Rose & Gamble, 2006). The gait cycle is typically outlined based upon the timing of when the two main gait events (foot strike and foot lift) are completed (Rose & Gamble, 2006). Generally when referring to the gait cycle, the terminology used to describe these events are referred to as foot strike and foot lift because initial foot contact may not occur at the heel or contact may not end at the toe (Rose & Gamble, 2006). As such, the typical terms, heel strike and toe off, should be replaced with foot strike and foot lift in order to take into account gait events observed in pathological gait (Rose & Gamble, 2006).

There are four main events that occur during the gait cycle based upon the previous terminology: foot strike (FS), opposite foot-lift (OFL), opposite foot strike (OFS), and foot lift (FL) (Rose & Gamble, 2006). The two main phases of gait; swing and stance, can be determined based upon the occurrence of the previous four events as observed in *Figure 1.1* (Rose & Gamble, 2006). The gait cycle can also be broken down based upon the periods observed within the cycle. Stance phase can also be organized into four specific periods: loading (the initial period of double leg stance), midstance (single leg support until the body is positioned directly above the supporting leg), terminal stance (from the end of midstance until the end of single leg support), and finally unloading (the second period of double leg stance) (Shiavi, 1985). Swing phase can be more simply broken down into initial, middle, and terminal periods (Shiavi, 1985). The organization of the gait cycle is useful to not only understand what the body is doing during locomotion, but it can also be used as a framework to be paired with the phases of muscle activation that occur during gait.

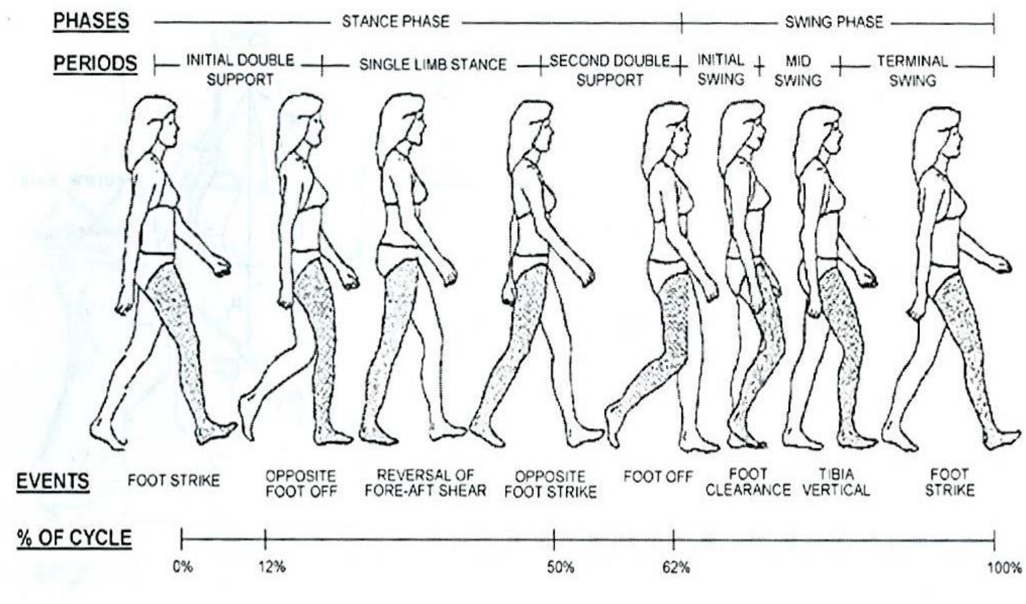


Figure 1.1: Phases within the normal gait cycle (J. Perry & Burnfield, 2010)

Two major kinematic measurements are the base of support and centre of mass. Within balance control and gait, it is determined that an individual is stable (or at equilibrium) if their centre of mass is contained within their base of support (Shumway-Cook & Woollacott, 2002). The base of support (BOS) is characterized as the area in which the object is in contact with the ground, for humans it is generally perceived as the area within the feet as that is typically the only part of the body in contact with the ground (Shumway-Cook & Woollacott, 2002). The centre of mass (COM) is termed as the point that is the centre of an individual's total body mass (Shumway-Cook & Woollacott, 2002). In both static and dynamic conditions, the COM is controlled by the body continually producing muscular forces to maintain the COM within the BOS (Shumway-Cook & Woollacott, 2002).

This maintenance of the COM within the BOS becomes challenged during locomotion. The reason for this difficulty is due to the fact that during locomotion, not only are the BOS and COM both in motion, but the size of the BOS is constantly changing (Patla, 2003). As motion occurs, the BOS size adapts to transference of weight between single and double support phases (Patla, 2003). Similarly, the BOS and COM are moving at two separate speeds (Patla, 2003).

Gait Kinetics

Although the kinematic components of gait are necessary to understand the changes in movement that occur under normal conditions, it is important to also take into consideration the forces applied to and generated by the human body during movement. Specific components of gait kinetics that are imperative to balance control are the centre of mass, centre of pressure, and base of support.

Although the COM is generally captured through kinematic analysis measures, it is important to note its close relationship with such kinetic measurements as the centre of pressure. The representation of the application of the ground reaction forces into a single point on the ground is referred to as the centre of pressure (COP) (Shumway-Cook & Woollacott, 2002; M. H. Whittle, 2007). Essentially, the COP works to relocate the COM within the base of support in order for the body to remain in equilibrium during standing and walking (Shumway-Cook & Woollacott, 2002). Should the COM fall outside of the BOS, then an individual's balance becomes threatened and a fall can occur (Rose & Gamble, 2006; Shumway-Cook & Woollacott, 2002). However, this movement of the COM inside and outside of the BOS is a necessary component for forward progression in walking.

The Somatosensory System

The somatosensory system includes information from muscles (spindles and golgi tendon organs) and the skin (mechanoreceptors specifically) that is sent to the central nervous system (CNS) to influence postural control and stability. The human central nervous system consists of the human brain and spinal cord (Nieuwenhuys et al., 2008). Information from the muscles and cutaneous mechanoreceptors in the lower limbs are sent to the CNS to provide information regarding rate of loading and pressure distribution throughout the plantar surface of the foot (Nurse & Nigg, 2001). The CNS uses this information in order to produce effective postural control strategies (Nurse & Nigg, 2001). Evidence from previous studies has demonstrated that reflexes from the cutaneous mechanoreceptors on the plantar surface of the foot aid in the body's ability to adapt to obstacles and perturbed gait (Nurse & Nigg, 2001). Furthermore, previous research has demonstrated that sensations from the feet play a large role in the control of dynamic postural responses (Perry, Santos, & Patla, 2001). Based upon this evidence, it has been further suggested that mechanoreceptors in the plantar surface of the foot contribute significantly to postural control in both dynamic and static conditions (Perry, Santos, & Palta, 2001).

1.2 Plantar Surface Cutaneous Mechanoreceptors

A major component of research on the somatosensory system's role in balance is the manipulation of skin receptors. Within the glabrous skin of the human hand and foot are receptors known as cutaneous mechanoreceptors. These mechanoreceptors send information from the surface of the skin to the central nervous system. The mechanoreceptors have been identified and classified based upon receptive field sizes and firing patterns (Johansson, 1978). It has been identified that Type I mechanoreceptors have relatively small receptive fields within the epidermis level of the hand however these boundaries are well defined (Johansson, 1978). These Type I receptors can be further divided into Fast Adapting (FA) and Slow Adapting (SA) receptors, with FAI receptors (Meissner Corpuscles) producing activity at the onset and removal of contact while SAI receptors (Merkel's discs) demonstrate a sustained firing pattern following activation/indentation of the skin (Johansson, 1978; Mcglone & Reilly, 2010). Type II mechanoreceptors demonstrate large, obscure boundaries of their receptive fields and are typically found deeper within the glabrous skin at the dermis level (Johansson, 1978; Mcglone & Reilly, 2010). The FAII receptors (Pacinian Corpuscles) demonstrate a firing pattern similar to that of the FAI Receptors, while the SAII (Ruffini Endings) have firing properties similar to that of the SAI receptors (Mcglone & Reilly, 2010). Johansson's 1978 study also determined that in the skin of the hand, both Type I receptors demonstrated a higher density within the fingertips of the hand, while in the palm the density of receptors was more dispersed (Johansson, 1978).

Kennedy and Inglis (2002) aimed to address the differences in the cutaneous mechanoreceptors of the glabrous skin in the hand and foot sole. The observed differences in the foot sole in comparison to the hand are largely a result of the tactile properties of the hand (specifically how the use of the human hand differs from the foot), resulting in a difference in the distribution of the receptors within the foot (Kennedy & Inglis, 2002). Furthermore, while previous research has determined that the distribution of mechanoreceptors in the hand tends to show a pattern (for instance, a high population of Type IA receptors within the fingers), the mechanoreceptors within the foot have been found to be randomly distributed throughout the plantar surface (Kennedy & Inglis, 2002). Kennedy and Inglis suggested that this random distribution of mechanoreceptors is largely due to the fact that the plantar surface of the foot is more involved with weight bearing and as such, the need for acuity found in the hand is not as necessary for the foot. It is important to note that the difference in mechanoreceptors between the hand and foot in humans does not end with receptor distribution. Kennedy and Inglis study found that cutaneous receptors within the foot demonstrated a higher level of activation thresholds than what has previously been found in the glabrous skin of the hand (Kennedy & Inglis, 2002). This difference in activation thresholds was found for all four classifications of mechanoreceptors. These findings are suggested to be as a result of the difference in the thickness of the skin between the hand and foot (Kennedy & Inglis, 2002).

The information from the plantar mechanoreceptors are sent to the CNS via afferent fibres (Nieuwenhuys et al., 2008). These afferent fibres are classified based upon their conduction velocity, from which two classification systems have emerged (Nieuwenhuys et al., 2008). The Erlanger-Gasser system classifies the fibres as one of the following: A (alpha through gamma), B, or C and is used primarily to categorize sensory nerves, while Lloyd's roman numeral classification is used for muscle nerves (Nieuwenhuys et al., 2008). A classification table for the mechanoreceptors mentioned within this section, along with their corresponding afferent fibres can be found in *Figure 1.2.*

Information received from the cutaneous mechanoreceptors within the skin (both upper and lower limbs) is sent through afferent connections to the dorsal column-medial lemniscus (Purves, Augustine, & Fitzpatrick, 2001; Abraira & Ginty, 2013). Upon entering the spinal cord, the afferent fibers branch into two main tracks: ascending and descending branches (Purves et al., 2001; Abraira & Ginty, 2013). The descending branches penetrate the dorsal horn of the spinal cord to synapse onto neurons located within an area termed "Rexed's laminae II-V" (Purves et al., 2001). However, the major branch created within the spinal cord ascends ipsilaterally through the dorsal columns of the spinal cord into the medulla, before terminating in the dorsal column nuclei (Purves et al., 2001; Abraira &

Ginty, 2013). From here, information from mechanoreceptors located within the lower limb is sent to fibres in the medial subdivision of the dorsal columns (Purves et al., 2001). Second order neurons relays this somatic sensory information to the somatic sensory portion of the thalamus for interpretation (Abraira & Ginty, 2013).

Encapsulated nerve endings

Type	Adaptation	Localization	Sensation	Type afferent	Calibre
Merkel discs	Slowly adapting	Glabrous skin: epidermis; hairy skin: aggregates	Touch	A-beta	7–12 ηm
Ruffini endings	Slowly adapting	Skin: dermis deep tissues, joints		A-beta (II)	7–12 ηm
Meissner corpuscles	Rapidly adapting	Skin: dermis lanceolate endings in hair follicles	Shape and texture	A-beta	7–12 ηm
Pacinian corpuscles	Rapidly adapting	Deep tissues	Vibration	A-beta/gamma II/(III)	3–12 ηm
Golgi tendon organs	Slowly adapting	Tendons	Position and movement	A-alpha (Ib)	12–22 ηm
Muscle spindles, annulospiral or primary endings	Slowly adapting	Striated muscles		A-alpha (Ia)	12–22 ηm
Muscle spindles, secondary endings	Slowly adapting			A-beta (II)	6–12 ηm

Figure 1.2: Peripheral receptors and their corresponding afferent fibres (Nieuwenhuys et al., 2008)

The activation of muscles within the human body occurs in concurrence with activation of plantar surface cutaneous mechanoreceptors, as both muscles and mechanoreceptors provide significant information to the overall somatosensory system. The relationship between muscles and the cutaneous mechanoreceptors within the foot has been demonstrated by several studies.

Similar the typical afferents involved in sending information from the cutaneous mechanoreceptors mentioned above, group III and IV afferents originating from the muscles send information to the CNS that is also of importance for the relaying of information.

Previous research has demonstrated that these afferent groups have several different functions in regards to the information sent to the CNS, one such function has observed a strong involvement in the reduction of central motor output via information received by these afferents at the spinal and supraspinal levels (Laurin et al., 2015).

In 2005, researchers observed that manipulation of the cutaneous mechanoreceptors within the glaborous skin of the foot resulted in modulation of muscle activity within the lower limb (Fallon, Bent, McNulty, & Macefield, 2005). Similarly, a 2013 study observed that activation of the cutaneous mechanoreceptors on the dorsum surface of the foot resulted in reflexive activity recorded in the muscles of the upper limbs. As such, the modulation of muscle activity as a result of mechanoreceptor activation suggest that muscular activity and the cutaneous mechanoreceptors are closely related (Bent & Lowrey, 2013).

1.3 Muscular Components

The muscles within the human body play a large role in human gait. The muscles within the human body are primarily responsible for movements at the joints that allow for gait to occur (M. W. Whittle, 2007). However, it is also important to understand the physiology of the muscles in order to better understand their role within the balance control system.

The muscles within the lower limb follow a phasic activation during gait in accordance with the phase of gait that an individual is in (Rose & Gamble, 2006). While locomotion typically involves whole body muscle activation (trunk, upper, and lower extremities), for the purpose of this review the focus will be primarily on the muscles within the lower extremities (Rose & Gamble, 2006; Shiavi, 1985). Moreover, the muscles involved in gait can be broken down into major groups such as: ankle dorsiflexors, ankle plantarflexors, quadriceps, and hamstrings (Shiavi, 1985). While there are muscles within the feet and hip joint that play a role within locomotion, they will not be focused on within this review.

The Tibialis Anterior (TA) is one of the major muscles that acts as an ankle dorsiflexor during motion (Shiavi, 1985). The TA has several roles as a dorsiflexor, including producing rapid dorsiflexion to allow for the foot to clear the floor during the transition from the stance to swing phase (Shiavi, 1985). Similarly, concentric contraction of this muscle observed during the latter portion of the loading period of gait has been observed to contribute to stabilization of the ankle (Shiavi, 1985). As the TA acts as an ankle inverter as well as a dorsiflexor, it also contributes to transferring weight onto the lateral aspect of the foot after heel strike (Shiavi, 1985). The Gastrocnemius and Soleus muscles are both major contributors to ankle plantarflexion during motion (Shiavi, 1985). The ankle plantarflexors are primarily observed to be active throughout the stance phase of locomotion (Shiavi, 1985). Gastrocnemius specifically has been observed to perform eccentric contractions that contribute to the deceleration of the tibia prior to heel strike (Shiavi, 1985). An overview of the muscle activations of the plantar- and dorsiflexion groups can be viewed below in *Figure 1.2* (Shiavi, 1985).

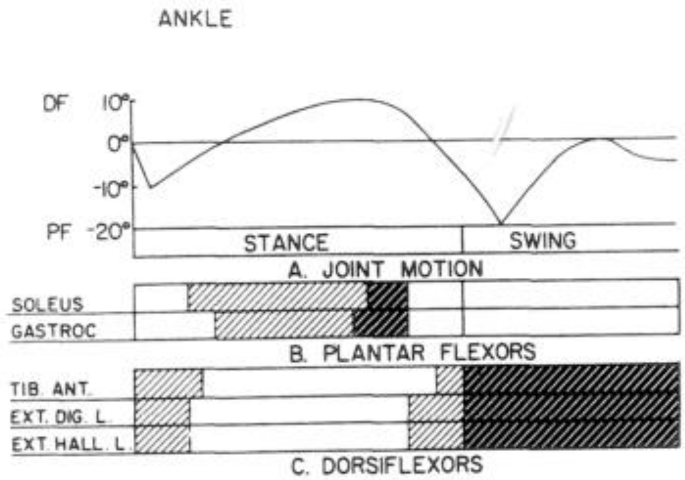


Figure 1.3: Muscle activation about the ankle joint (Shiavi, 1985).

Along with the plantar- and dorsiflexor muscle groups, the Quadriceps and Hamstrings play equally large roles in regards to gait. The quadriceps muscle group has been observed to be consistently active during the swing-stance transition of gait, with two major observable activation periods (Shiavi, 1985). The first activation phase can be observed during the loading period of gait which is thought to assist with knee stability and load bearing, and is perceived to cease activity as knee extension begins to occur (Shiavi, 1985). The second major phase of muscle activation of the quadriceps group occurs during the loading stage of the opposite lower limb (Shiavi, 1985). It has been suggested that this secondary activation occurs in order increase stabilization of the knee as well as to prepare for acceleration of the limb at the commencement of the swing phase (Shiavi, 1985). The major muscles within this group that contribute to the movements previously described are the Rectus Femoris and Vastus Lateralis muscles (Shiavi, 1985).

The final contributing groups of muscles within the lower extremity are the hamstring muscles. While all major heads of hamstrings are active during the swing to stance transition within gait, the Biceps Femoris is the most commonly recorded (Shiavi, 1985).

Activity of the hamstrings has also been observed during the midstance period, and has been shown to contribute to deceleration of the lower extremity during the late swing phase via eccentric contraction (Shiavi, 1985). The hamstring muscles have also been observed to concentrically contract at heel strike, resulting in subsequent extension at the hip during both the loading and midstance periods (Shiavi, 1985). A secondary phase of activation has also been reported as an eccentric contraction during hip flexion, aiding in flexion of the knee and leg clearance of the floor (Shiavi, 1985). An overall view of muscle activation of the major muscles mentioned during the gait cycle can be observed in *Figure 1.3* (Shiavi, 1985).

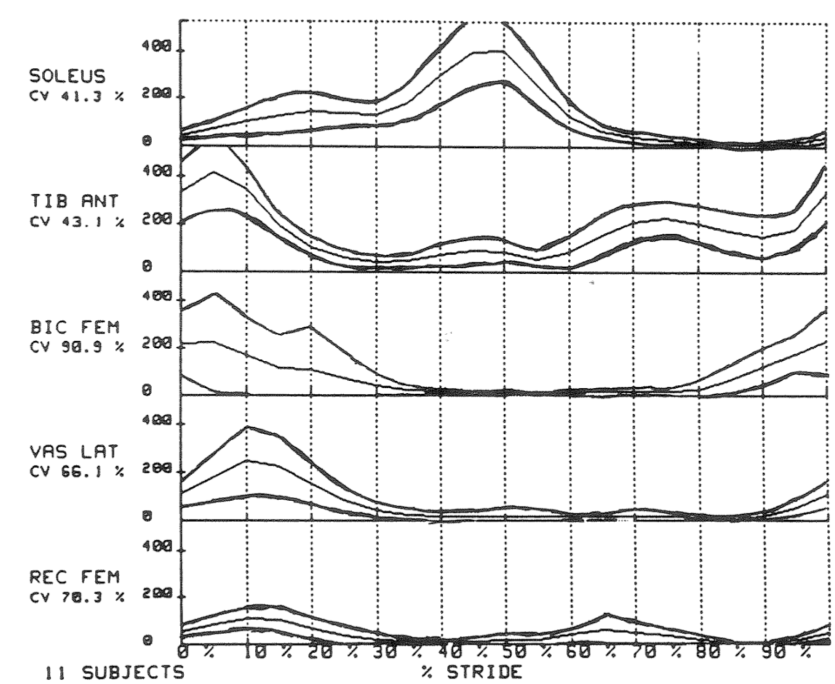


Figure 1.4: Muscle activation of major muscles during locomotion (Shiavi, 1985).

Overall, it is of importance to understand how normal gait functions within a healthy population to compare against populations that have adapted different strategies as a result of sensory and/or motor degradation. The typical segments of the swing and stance phases of gait in coordination with the muscle activity associated with those phases allows researchers to observe where and how gait deviates from normal activity in populations at a higher risk of falling through daily activities, such as older adults.

1.4 Perturbed gait and the influence of aging and sensory information

From prior evidence it has been accepted that balance control in humans is a result of the visual, vestibular, and somatosensory systems working together to create the aforementioned properties of gait (Eils et al., 2002). The extent to which each sensory system aids in balance control is based upon a variety of influences. Age, specifically, plays a significant role in what sensory systems are available to influence postural control (Laughton et al., 2003). Older adults have been shown to have an increased likelihood of falling in comparison to young adults as a result of sensory and motor degradation that occurs from aging (Menant et al., 2009; Qiu et al., 2012).

A major indication of falling in older adults is an increase in postural sway (Laughton et al., 2003). This observed increase in postural sway has been further confirmed by the significant increases in muscle activation found in older adults in comparison to young adults (Laughton et al., 2003). This observation was further confirmed in a 2012 study by Qui et al., in which older adults showed greater postural sway than younger adults, particularly within a barefoot setting. As slip-related falls have been demonstrated to account for 25% of falls, it is of importance to analyze perturbed gait in both young and older adults in order to better understand the mechanisms used to regain balance for further fall prevention (Yang, Bhatt, & Pai, 2009). Furthermore, sudden termination of gait has also been demonstrated to be challenging for older adults and, as such, compromises an older adult’s stability (Menant et al., 2009). Menant et el.’s 2009 study observed that older adults displayed a delay in muscle activation as well as a delayed reaction time when asked to terminate gait unexpectedly on a range of surfaces. Furthermore, the older adults took a longer time to return to stability (as measured by postural sway, and COP displacement/velocity) resulting in a slower response then their young adult comparisons (Menant et al., 2009).

The visual, vestibular, and somatosensory systems each play a large role in facilitating balance control in both static and dynamic conditions in order to both maintain and recover balance control from such perturbations. The loss of visual information, whether it is from occluded vision or a decline as a result of aging, has been demonstrated to change the typical gait patterns previously addressed (Hallemans et al., 2009). Previous research has observed that a reduction or loss of vision can result in changes in gait speed, as well as COM motion (Perry et al., 2001). Perry et al.'s 2001 study also observed that vision, in conjunction with components of the somatosensory system (reduced and control plantar sensation), is important in regards to foot placement. With aging, a loss of visual field, acuity, and contrast can occur, resulting in an inability to perform the aforementioned feats of the visual system correctly (Shumway-Cook & Woollacott, 2002).

Similarly, the vestibular and somatosensory systems experience reductions in functions as a result of aging (Shumway-Cook & Woollacott, 2002). As the vestibular system works as an absolute reference system in which the visual and somatosensory systems can be compared against, a decline in function as a result of aging can develop a disturbance in postural adjustments due to balance threats (Shumway-Cook & Woollacott, 2002). Dizziness as a result of vestibular dysfunction can also result in instability in older adults (Shumway-Cook & Woollacott, 2002). Similar to the vestibular and visual systems, the somatosensory system has been demonstrated to have a reduced tactile sensitivity as a result of aging (Shumway-Cook & Woollacott, 2000). Moreover, as mentioned previously, onset of muscle activity within older adults has also been observed to slow down as a result of aging (a symptom that is common within the multiple sclerosis and peripheral neuropathy populations as well) (Shumway-Cook & Woollacott, 2000).

1.5 Manipulation of Plantar Surface Cutaneous Mechanoreceptors

The contributions of skin have been analyzed in many different respects. Removing and enhancing the somatosensory information to study the effects upon gait are the most common methods adopted. In order to analyze the effects of balance deficits as a result of loss of somatosensory information similar to what is observed in older adults, researchers focus on healthy young and older adult populations primarily, in order to understand the mechanics of what is causing the decrease in balance control, without any external influences. In order to do this with a young adult population, a technique called hypothermic anesthesia is used to observe simulated effects of decreased somatosensory information (Perry et al., 2000). Hypothermic anesthesia is typically achieved through cooling of the foot via ice water for approximately 15-20 minutes (Perry et al., 2000). This method of manipulation of somatosensory information has been used frequently by researchers aiming to expand the understanding of the skin's role in both static and dynamic conditions. The effects of cooling the plantar surface of the foot to observe alterations in balance control is still relatively new and researchers are continuing to understand the role that reduced somatosensory information plays on balance in both young and older adult populations (Magnusson, 1990).

It is of importance to note that there are several methods with which temporarily removing somatosensory information from the skin can be accomplished. Several studies have also utilized intradermic anesthetic solution primarily containing lidocaine in order to remove sensation from the foot (Hohne, Ali, Stark, & Bruggemann, 2012; Meyer, Oddsson, & De Luca, 2004). While this method of removal is as effective as hypothermic anesthesia in terms of loss of sensitivity, it does require the use of a registered anesthesiologist as well as multiple injection sites that must be kept clean after the solution has been injected (Meyer et al., 2004). Topical anesthetic creams are also available to simulate a loss of sensation. While topical anesthetics are not as invasive as intradermic anesthetics, the time period for the topical anesthetics to achieve a loss of sensation is significantly greater than that of the other two methods listed above (Howe et al., 2015). Overall, the use of hypothermic anesthesia is a more commonly used technique within research environments.

Vibration stimulation can be used to enhance somatosensory input. While the use of vibration as a method of sensory enhancement has only begun to be used recently (Priplata et al., 2002, 2006), there has been a steady increase in evidence demonstrating the role that vibration plays in perception and sensitivity. Both slow and fast adapting mechanoreceptors within the hand and feet respond to certain frequencies of vibration (Kennedy & Inglis, 2002; Vallbo & Johansson, 1984; Vedel, 1989). In accordance with this information vibration to the plantar surface of the foot has been shown to change the firing properties of the slow and fast adapting mechanoreceptors, generating a response to the vibration stimulus (Vedel, 1989). This response has been observed to result in an increase in balance control within several different populations. Therefore, while hypothermic anesthesia has been shown to simulate the effects found in populations at greater risk of falling, vibration has been observed to increase balance control in populations at a greater risk of falling (Priplata et al., 2006).

Previous literature regarding the use of vibration/electric foot sole stimulation has demonstrated its uses to manipulate sensory information. A 2014 study completed by Zehr et al., demonstrated that non-noxious cutaneous stimulation at discrete site on the plantar surface of the foot elicited reflexive responses throughout the gait cycle. The researchers of this study suggested that the afferent feedback from the cutaneous stimulation served to both restore balance as well as promote ankle stabilization (Zehr et al., 2014). A 2015 study performed by Strzalkowski et al. demonstrated that the mechanical properties of the skin (thickness, stiffness, etc.) did not have an influence on perceived vibration thresholds when presented with a vibratory stimulus on the plantar surface of the foot (Strzalkowski et al., 2015). Therefore, the use of mechanical/electrical stimulation on the foot sole has been more recently explored, and suggestive of improving balance control.

Plantar-surface Cutaneous Mechanoreceptors and Static Postural Control

The centre of pressure (COP) plays a significant role in both static and dynamic balance control conditions. When the plantar-surface cutaneous mechanoreceptors are manipulated, an individual's balance control is also manipulated as a direct consequence. Within static balance conditions specifically, the COP has been demonstrated to be significantly affected. Within a reduced somatosensory condition such as hypothermic anesthesia, the primary effect on COP found has been an increase in velocity while performing a static balance task such as standing (Billot, Handrigan, Simoneau, Corbeil, & Teasdale, 2013). Aforementioned, as the COP's main role within balance control is to maintain the centre of mass within the base of support (Shumway-Cook & Woollacott, 2000). As such, the observed significant increase in velocity suggests that the participants within these previous studies are demonstrating behaviours that would indicate they are at a higher risk of falling then what would be observed without manipulation (Billot et al., 2013; Meyer et al., 2004).

A specific study of interest is the 2004 study by Meyer, Oddsson, & DeLuca in which they determined that when the forefoot was anesthetized and participants were in unipedal stance, the greatest effects on balance control were found, and while in bipedal stance there were no significant effects on balance when vision could be incorporated. The results of this study further elaborate on the relationship between vision and the somatosensory system in regards to balance control. Another example demonstrating the relationship between sensory manipulation and balance control is the more recently published study Billot et al., also aimed to address the effects of cooling plantar mechanoreceptors on quiet standing (static) postural control. This study also demonstrated that cooling of the plantar cutaneous mechanoreceptors resulted in a significant effect on balance control while standing as well as adaptations in muscle activity as a result of these manipulations (Billot et al., 2013).

From the previous evidence demonstrating a response to vibration, further research has been conducted to evaluate the effect that vibration has on not only the specific mechanoreceptors, but on postural control overall. As previously stated, the use of vibration has direct effects on an individual's balance control, through mechanoreceptor responses to vibration. Further research has demonstrated that in conjunction with this knowledge, vibration has been observed to increase the ability of tactile sensation when the vibration applied is at or near threshold levels (Richardson, Imhoff, Grigg, & Collins, 1998). This was confirmed in Richardson et al.'s 1998 study demonstrating an increase in tactile sensation perception in healthy young adults. A further demonstration of balance control being enhanced through vibration stimulation was published by Priplata et al. in 2002. Within this study, the researchers observed that during quiet standing, balance control condition (such as COP range) were significantly improved in both healthy young and older adults with the introduction of vibration stimulation (Priplata et al., 2002). The phenomenon presented by these studies is referred to as "negative masking" in which a weak stimulus is able to be enhanced through the presence of another signal (Priplata et al., 2002; Richardson et al., 1998). As such, balance control in static conditions can be both reduced and enhanced through the use of hypothermic anesthesia and vibration, respectively.

Plantar-surface Cutaneous Mechanoreceptors and Dynamic Balance Control

Although the relationship between somatosensory system and static balance control is important, humans are rarely stationary. As such, the relationship between the plantar mechanoreceptors and balance control during gait is essential to understand as it is the primary time in which falling or loss of balance can occur. Similar to static balance control, dynamic tasks such as gait are also influenced through hypothermic anesthesia and vibration. There are multiple dynamic situations in which these sensory manipulations can be experienced, such as walking, stepping, gait termination and obstacle avoidance. As previously mentioned, these scenarios are all found to be difficult for older adults to do in daily life.

Several studies have addressed the observed changes during gait when there is reduced sensation from the mechanoreceptors. The cutaneous mechanoreceptors have been found to provide information regarding weight distribution and the limits of base of support (Perry et al., 2001). Based upon this evidence, previous research has observed that a common measure of gait adaptations to reduced sensation is a change in the distribution of pressure, COP velocity, and initial loading (Nurse & Nigg, 2001). Correspondingly, a change in the roll over pattern was identified in Eils et al.'s study, in a more cautious heel contact and foot lift that was observed as a result of the reduced sensation from the plantar mechanoreceptors.

Similar to walking, gait termination plays a large role in dynamic balance during gait, as humans are rarely ever within a constant static postural condition. Perry, Santos, & Patla carried out a study in 2001, examining the role of plantar mechanoreceptors during gait termination in which they observed that when participants were asked to terminate gait with reduced sensation, there was an increase in the rate of loading and subsequent COM velocity. Thus suggesting, that the reduced sensation of the mechanoreceptors resulted in an inability to slow down correctly (Perry et al., 2001). While adaptations to gait as a result of reduced sensation has been well documented, there is still a need for research on gait when vibration is applied directly to the mechanoreceptors. However, the literature on vibration and gait for various populations (for example older adults and individuals with cerebral palsy) has demonstrated that the use of vibration has elicited changes in gait that are in correspondence with improved mobility and confidence while walking (such as faster speed and larger step lengths) (Dickin, Faust, Wang, & Frame, 2013; Lam, Lau, Chung, & Pang, 2012).

1.4 Relevance of proposed research

Balance control is important in everyday life, particularly for older adults and other populations who are at a greater risk of falling. In Canada, between 20-30% of older adults fall each year, with falls continuing to be the leading cause of injury-related hospitalizations in Canada (Canada, 2014). Moreover, the majority of injuries resulting from falls are broken or fractured bones (Canada, 2014). As such, the prevention of falls is of importance for balance control research. This proposed research aims to expand the knowledge of balance control in humans, and the ability to adapt under different sensory conditions. Similarly, there has been evidence showing the relationship between enhanced sensory information and balance control, however the majority of these studies have focused on static conditions. As such, this proposed study also aims to expand this area of research.

Research Objectives and Hypotheses

The proposed study will aim to address the following research questions:

1) Does reducing somatosensory input from the cutaneous mechanoreceptors affect an individual's ability to adapt to perturbed gait?
2) Does enhancing somatosensory input from the cutaneous mechanoreceptors affect an individual's ability to adapt to perturbed gait?
3) How is muscle activity affected when the information being sent to the central nervous system from the plantar surface of the foot is altered?
4) Is there a correlation between EMG amplitude of specific muscles within lower limb and loading during walking?

It is hypothesized that, based upon previous evidence, a decreased level of balance control will be observed during the reduced sensory trials. A decrease in balance control will be assessed based upon changes observed within the COM and COP. Similarly, the enhanced sensory trials will demonstrate an increased level of balance control based upon the same variables. Furthermore, it is hypothesized that muscle activity in the lower limb (specifically within the dorsi- and plantar flexors, as well as the hamstring and quadriceps muscle groups) will be increased during reduced sensory trials in an effort to compensate for the decrease in information from the plantar cutaneous mechanoreceptors. Moreover, it is also hypothesized that the muscle activity of the lower limb will demonstrate a correlation with the loading patterns of the foot while walking under all three conditions.

CHAPTER 2

METHODOLOGY

Participants

For this study, fourteen participants (4 males, 10 females) aged 18-29 (mean 23.07 years (± 2.43)), refer to *Tables 2.1,2.2, and 2.3* were recruited and participated in this study. The participants within this study were screened prior to participation in order to ensure that none of these individuals had any known neuromuscular disorders or balance deficits that could occur as a result of aging. Reasons for exclusion from this study are recent surgery, paralysis, balance disorders, etc. An example of the screening questionnaire can be found within Appendix A. The experimental protocol was explained and participants gave their written, informed consent to participate in this study. The Wilfrid Laurier University Research Ethics board reviewed and approved the methods of this study. A copy of the Informed Consent statement as approved by the Research Ethics board can be found within Appendix B.

Table 2.1: General Participant Information

Participant	Gender	Age	Height (cm)	Weight (kg)
1	F	23	170	57
2	F	24	177	70
3	F	23	161	59
4	F	21	172	59
5	M	23	150	52
6	M	24	183	85
7	F	29	175	68
8	M	23	160	72.5
9	F	24	170	63.5
10	F	23	168	55
11	F	19	155	45
12	F	19	160	42
13	M	24	180	86
14	F	24	180	75
MEANS		**23.5**	**168.5**	**63.5**

Table 2.2: Participant Monofilament Sensitivity Information

Participant	RGT	R5thMT	R1stMT	RHeel	LGT	L5thMT	L1stMT	LHeel
1	2.83	3.44	3.22	3.22	3.22	2.44	3.22	3.61
2	3.22	3.22	3.84	3.84	3.84	3.61	3.84	3.84
3	3.22	3.84	3.84	3.84	3.61	3.84	4.17	4.17
4	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.84
5	3.22	3.84	3.61	3.22	3.22	3.22	3.22	3.22
6	3.84	3.22	3.22	4.56	4.08	3.61	4.08	4.56
7	3.61	2.83	3.61	3.11	3.61	3.22	3.84	3.84
8	3.61	3.84	4.08	3.84	3.22	3.84	3.61	4.08
9	3.22	3.22	3.84	3.22	3.22	3.22	3.22	3.22
10	3.61	3.22	3.22	3.61	3.22	3.22	3.22	3.22
11	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22
12	3.22	2.83	3.22	3.22	3.22	3.22	2.83	3.22
13	3.22	3.22	3.61	3.22	3.61	3.22	3.61	4.08
14	3.22	3.22	3.22	4.08	3.22	3.84	3.22	4.08
MEANS	**3.32**	**3.31**	**3.49**	**3.53**	**3.41**	**3.35**	**3.46**	**3.72**

Table 2.3: Participant Vibration Sensitivity Threshold Information

Participant	**Vibration Threshold (mV)**	**Participant**	**Vibration Threshold (mV)**
1	N/A	8	0.82
2	0.74	9	0.88
3	1.22	10	1.02
4	0.82	11	1.08
5	0.78	12	0.98
6	0.78	13	0.96
7	1.1	14	0.76

Experimental Equipment

Kinematic motion analysis was used to analyze observable changes in gait through 3D motion capture by the Optotrak system (Northern Digital Inc, Waterloo, Ontario). For kinematic data collection, a total of 12 markers were used (Left/Right 5th Metatarsals, Left/Right Malleoli, Left/Right Tibial Plateaus, Left/Right ASIS, Left/Right Acromion Process, Forehead, Zyphoid Process), as observed in *Figure 2.1*. Data collection included motion of the centre of mass and the base of support. The centre of mass was calculated from the twelve marker setup above by creating a seven segment model from the markers (head, upper trunk and arms, lower trunk, left thigh, right thigh, left shank, and right shank).Electromyography (AMT-8 (Bortec, Calgary, Alberta)) was recorded to analyze the magnitude of muscle activation, as well as to determine onset timing of the muscles collected. Data were collected from a total of four muscles (Right Medial Gastrocnemius, Right Tibialis Anterior, Left Rectus Femoris, Left Biceps Femoris), the organization of which can be viewed in *Figure 2.2*. The organization of the muscles recorded was chosen in order to assess not only the foot being perturbed, but the trail limb as it attempts to stabilize during the perturbation. Finally, force plates (OR-6-2000 (Advanced Mechanical Technology Inc, Waterdown, MA)) were used to assess changes in centre of pressure displacement and velocity, as well as rate of loading. A schematic of the force plate/platform setup can be found in *Figure 2.3* within the Methodology section. Both electromyography and force plate data were collected at 500 Hz for 10 seconds, while the 3D motion data was collected at 100 Hz for 10 seconds.

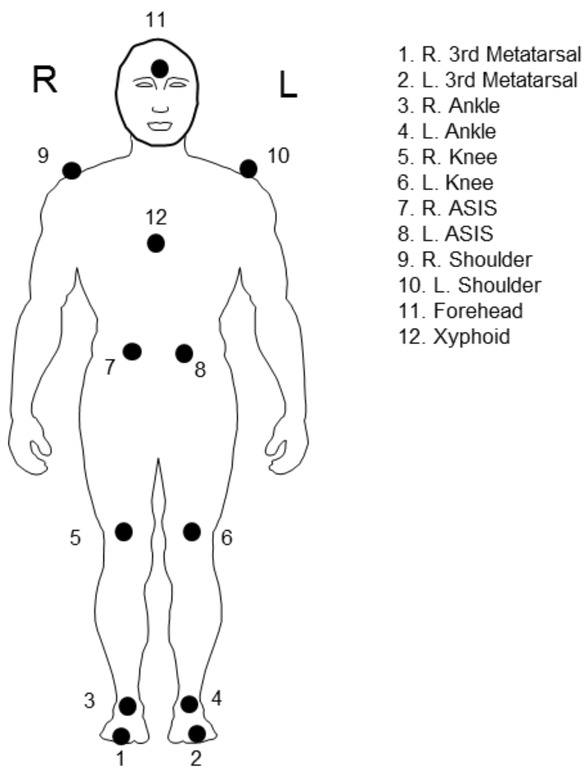


Figure 2.1: Kinematic 3D Analysis marker positioning

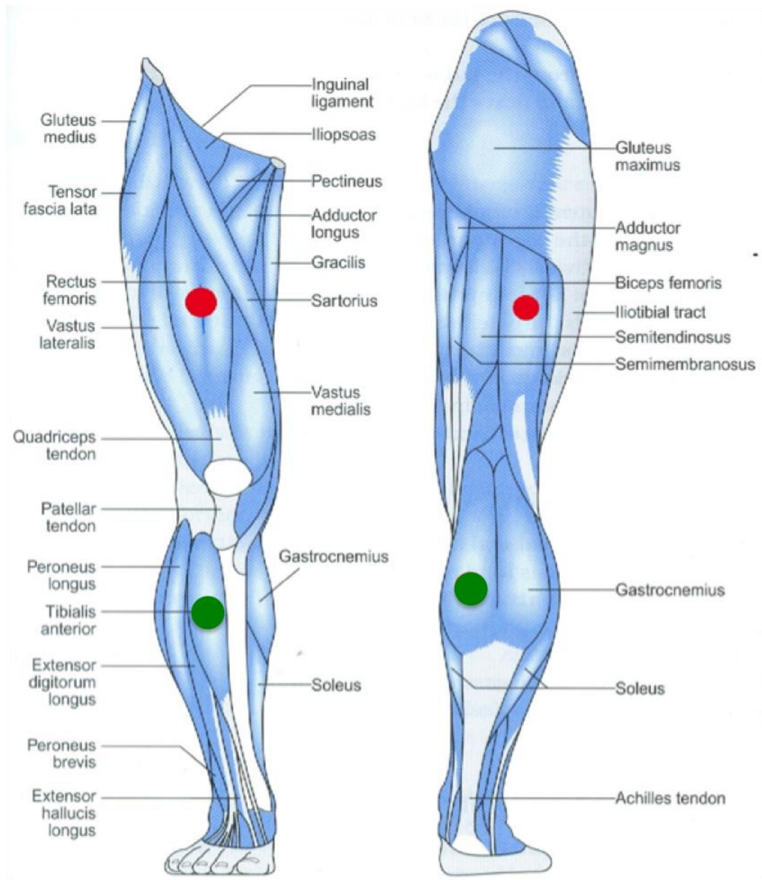


Figure 2.2: Electrode placements for electromyography recordings, indicating the different recordings for each leg (red for left leg, green for right leg) (M. W. Whittle, 2007)

Experimental Protocol

Within this study, participants were asked to walk the length of an 8-meter platform at a comfortable speed. Participants were required to walk with reduced, enhanced and normal levels of somatosensory information of the plantar foot surface. Prior to walking across the platform, the participants underwent baseline sensitivity tests on the soles of the feet using Semmes-Weinstein monofilaments (Northwest Medical, USA). Each participant was found to be within a normal sensory range as defined by the monofilament test. In regards to the Touch Test Sensory Evaluator Chart provided along with the Semmes-Weinstein monofilaments, a normal plantar threshold range was determined to be between 1.65 and 3.61 for the evaluator size. Measurements greater than 4.31 suggested a diminished touch. The specific sites of testing for the monofilaments can be viewed in *Figure 2.3.* The participants were seated with the customized vibration device within a pair of converse shoes, with the vibration device located at the 1st metatarsal and the heel. An example of the vibration device can be observed in *Figure 2.2.* The device was taped down onto the insoles within the converse shoes used for this study and vibrated at a frequency of 100Hz. In order to ensure that the vibration devices operated correctly, they were placed within modified washers in order to distribute pressure across the insole. Initial testing determined the perceived threshold of vibration for each participant in order to calculate the white noise level for the enhanced level of somatosensory information (determined to be at 90% of perceived threshold). The white noise level for the vibration device refers to the fact that while the vibration is centered around 100 Hz as the primary base, the signal is fed into the device and is then combined with a variety of noise signals to create a white noise with other frequencies.

Participants were instructed to wear the converse shoes in which the vibration device was attached. With both shoes on, participants were asked to sit down while the vibration device was turned on. The amplitude of vibration began at 0 mV and was slowly increased for all four sites (1st metatarsal and heel for both feet). As the amplitude increased, participants were instructed to inform the researcher when they were able to perceive the vibration occurring on their skin within the shoe. An oscilloscope was used to visually inspect the amplitude at which the participants were able to sense the vibration. This measurement was noted on the oscilloscope as the participants' perceived threshold. From this information, the 90% subthreshold level was calculated and the vibration amplitude was adjusted to this level with visual confirmation via the oscilloscope. After the threshold at been determined, participants were then set up with EMG and kinematic markers. The vibration device was on for the duration of the markers set up and was the first condition recorded for the trials. For a more detailed description of the Semmes-Weinstein monofilaments and Vibratory device protocols, please refer to Appendix C: Protocols.

For the reduced sensation, the participants underwent an ice bath on the plantar surface of the foot (so as not to affect the ankle joint and muscles of interest in the lower limb). This ice bath was completed within 15-20 minutes until a desired foot temperature had been reached. After returning to the platform for the reduced sensation trials, the participants returned to the ice bath every 5-6 trials for another 2-5 minutes in order to ensure that the plantar surface of the foot remained at a lower temperature. The participants performed both the vibration and control trials prior to the reduced condition as they were unable to distinguish between them, with the reduced trials last in order to ensure no lasting effects of the reduced condition influenced either the vibration or control conditions.

Figure 2.3: Identified sites of the plantar surface of the foot for sensory testing and vibration application

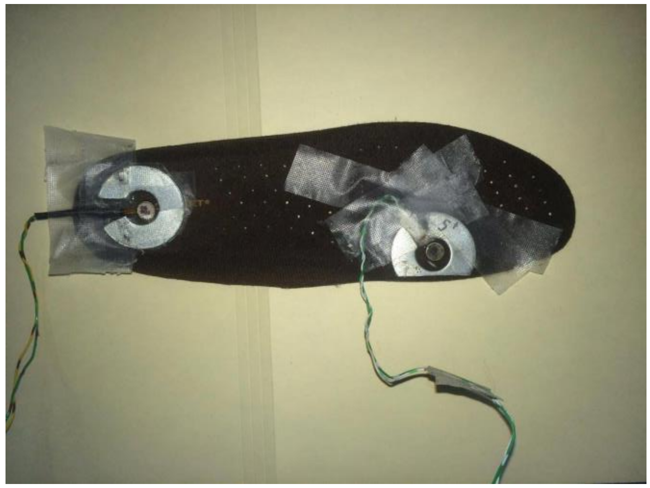


Figure 2.4: Example of vibration device within insoles prior to being inserted into converse shoes for participants.

During the trials the participants travelled along a raised platform that had 4 square sections where there had exchangeable hard or foam supports that provided either a stable or unstable situation when stepped upon. Located underneath three of these squares were three force plates (OR-6-2000 (AMTI, Waterdown, MA)). When stepped upon during an unstable situation, the platform sections tilted in either the anterior/downwards direction (opposite direction of movement across the platform) or the lateral/downwards direction (*Figure 2.3*). In order to prevent learning bias, the location of the foam support as well as the direction of the perturbation was randomized. The three force plates placed underneath were utilized to allow for force measurements to be collected. The specific force outcomes of interest for this study were centre of pressure velocity and rate of loading. Approximately fifty trials were conducted that included each of the three conditions, with a total of 20 of these trials being recorded and analyzed. This allowed for the analysis of approximately seven trials recorded for each condition, per participant. The three conditions of the study were enhanced (subthreshold vibration), control, and reduced (hypothermic anesthesia). Within each of these conditions, the participants were exposed to both anterior and lateral direction perturbations while walking across the platform. Anterior and lateral perturbations occurred separately, therefore the for each trial participants were exposed to one sensory condition and experienced one direction of perturbation. Prior to the recorded trials, participants were asked to walk across the runway 3-4 times for each condition in order to ensure that walking patterns of each participant allowed the right foot to strike the first force plate correctly each time. The participants were asked to change which foot they started with in order to prevent bias, however the trials recorded/analyzed were specifically for the right foot striking the first force plate. The schematic of the platform with the force plates' positions outlined can be observed in *Figure 2.4*.

a)  b) 

Figure 2.5: a) Stable condition schematic b) Unstable condition schematic

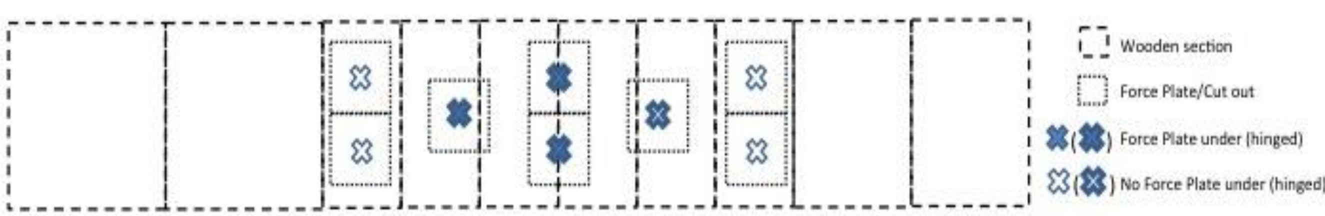


Figure 2.6: Aerial view of walkway platform with accompanying legend

The primary muscles of interest for this study were the Tibialis Anterior (TA), Medial Gastrocnemius (MG), Rectus Femoris (RF), as well as the Biceps Femoris (BF). The TA and MG were recorded from the right lower extremity (limb that contact the perturbed section), while the RF and BF were recorded from the left (trailing limb). For the electromyography recordings, two electrodes were placed on all of the muscles, with grounding electrodes placed upon the patella of the right lower extremity (*refer to Figure 2.2*). In order to lower impedance of the electrodes, participants' skin was prepared with Nu Prep gel (BioMedical, Clinton Township, MI) to remove oils and loose skin to improve signal. Furthermore, the muscle bellies of each individual muscle were determined via palpation in order for the prevention of any physiological cross talk between neighbouring muscles.

The kinematic data was captured with the Optotrak 3D analysis system and infrared markers. While the primary balance control measurements were recorded by the force plate system, the kinematic data served to confirm findings through the force plate technology. Similar to the electromyography electrodes, the infrared optotrak markers were placed primarily on the lower limb. However, both limbs were used for collecting kinematic data, along with the participants' trunks (via the xyphoid process, forehead, and left/right acromion processes) in order for a seven segment model of centre of mass to be calculated. The marker placement on each participant can be observed above in *Figure 2.1*.

The outcome measures for this study (COP velocity, rate of loading, muscle onset/magnitude) were decided upon as they are closely related with balance control within the individual. For example, the COP has commonly been derived from force plate measures to assess kinematic body sway as it allows for a pinpoint location of where the vertical force against the supporting surface is located (Jancová, 2008). Similarly, the location of the COP under the foot can aid in understanding primary muscle groups activated during that time period (Jancová, 2008). The force plate and kinematic technology allowed for a combined view of kinetic and kinematic balance control during gait as it relates to the manipulated sensory information from the foot. Similarly, the use of electromyography to analyze muscle activity provided evidence regarding the muscular response to both the sensory and platform perturbations. Due to the nature of this study in which perturbations were elicited to result in a quick reaction, the variables mentioned above were determined to be the best fit for assessing balance control. This is primarily due to the fact that the variables chosen for this study were discrete variables that related back to the specific analysis window chosen for this study. An example of the trajectory plots used to determine the difference between the COM-COP observed during data analysis for this study can be observed in *Figure 2.7.*

Data Analysis

Three-dimensional kinematic data were converted from raw format file types into DAT files in order to interpolate any missing data points. In order to fix any missing data points from the markers used for testing, the converted DAT files were run through the program Optofix (customized Visual Basic software). Optofix allowed for missing points in data to be interpolated (a cubic spline was used in which a minimum of four points on either side of the gap had to be available for interpolation to occur) in order to correctly analyze the centre of mass for each trial collected. Once the converted files were "fixed", they were then run through a centre of mass analysis program that calculated and graphed the centre of mass for each trial based upon the 12-marker model setup (Winter, 1990).

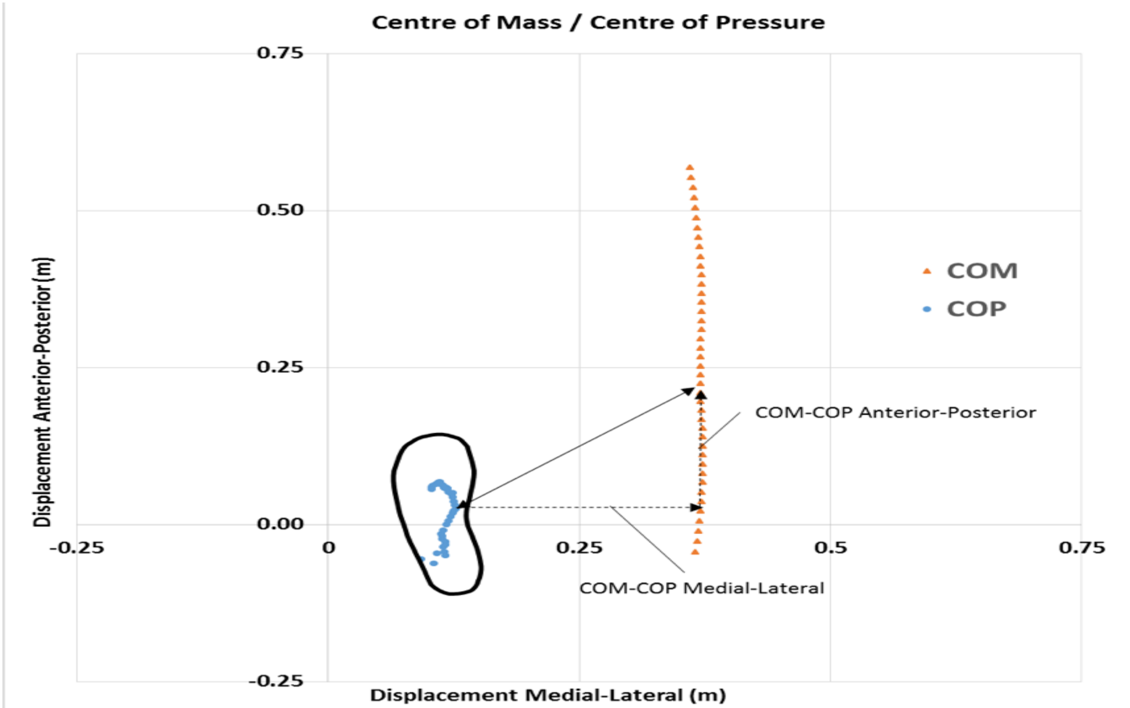


Figure 2.7: A transverse plane view of a typical walking trial depicting the determination of the Centre of Mass-Centre of Pressure (COM-COP) difference at a specific discrete point in time. COM and COP are only displayed during the single stance phase of the foot contacting the ground.

Similarly, EMG and force data were converted from raw data to text files to be read by the custom analysis programs used. All kinetic and force data were normalized to body weight, with analysis focusing on the right single stance phase on the first force plate. Loading rates were calculated from force plate data in Newtons and expressed as a function of time to determine the rate of loading (N/s). The EMG data was run through a custom analysis program that full wave rectified and filtered the data using a second order low-pass butterworth filter at 40Hz. This filter was chosen in order to eliminate high levels of noise within the EMG signal. Bursts of muscle activity were established when their magnitude exceeded threshold of four standard deviations. Bursts of EMG magnitude that met this requirement within the analysis window were analyzed for this study. The analysis window chosen for this study was the right single stance phase, occurring during the perturbations elicited within this study.

Due to technical errors, some trials did not produce clear enough signals to analyze EMG, kinematic, or kinetic data. Therefore, data analysis was limited to trials in which a clear signal for the variables of interest was available. For the collected electromyography data, a reduced number of participants' data (n=6) was used for analysis due to technical problems during data collection. The kinetic and kinematic data analysis used data collected from all participants (n=14).

Statistical Analysis

The three conditions within this study were analyzed in comparison with one another. For consistency across results the control condition is labelled as condition 1, the cooled condition as condition 2, and the vibration condition as condition 3. Analysis of electromyography data performed focused primarily on EMG amplitude, as well as muscle activity onset in relation to the first force plate within the walkway being triggered. The primary variables focused upon for analysis from the kinetic and kinematic data captured were: the maximum and minimum Centre of Mass velocity (within both the anterior-posterior, and medial-lateral directions), maximum and minimum Centre of Pressure velocity (within both the anterior-posterior, and medial-lateral directions), the maximum distance between the COM and COP, the maximum distance travelled by the COM within the BOS (within both the anterior-posterior, and medial-lateral directions) and the Rate of Loading.

Statistical Analysis was conducted using SAS software version 9.2. Eight one-way analysis of variance (ANOVA) tests were conducted in order to examine the main effect of condition on muscle onset time, and magnitude during each condition all with an a priori significance level of $p<0.05$. Scheffe’s post-hoc was used to examine differences between conditions. Similarly, an additional five one-way ANOVA tests were conducted to examine the main effect of condition on COM velocity, COP velocity, the COM-COP relationship, the COM-BOS relationship, and the rate of loading of the right foot. Similar to the electromyography analysis, Sheffe’s post-hoc was chosen to analyze differences between conditions. Within the one-way ANOVAS performed for this study, the ANOVA model used variability between participants in the calculation within the Type 3 error in order to test the differences in main effect. As such, the main effect analyzed was the condition but the model allowed for observations to be made for any variability between participants as well. Finally, Pearson’s correlations were performed between the EMG amplitude recorded for TA and RF, and the rate of loading.

CHAPTER 3
RESULTS

Muscle Activity Onset and Magnitude

The muscle activity analyzed was organized based upon bursts of muscle activity during the right foot strike and subsequent left step. From this analysis window, muscle activity demonstrated three separate periods of increased EMG amplitude. A trending effect of condition for the first burst of EMG amplitude within the Tibialis Anterior ($F_{(2,34)}$=3.16, p=0.06) was observed, *Figure 3.1*. Furthermore, variability between participants was observed ($F_{(7,34)}$=2.53, p=0.04). The interaction observed between participant and condition could have resulted in the lack of a significant effect for condition. A main effect of condition was found for the third burst of muscle activity measured within the Tibialis Anterior $F_{(2,17)}$=2.75. $p<0.01$. Scheffe’s post-hoc analysis demonstrated a significant difference between the cooled and vibration conditions.

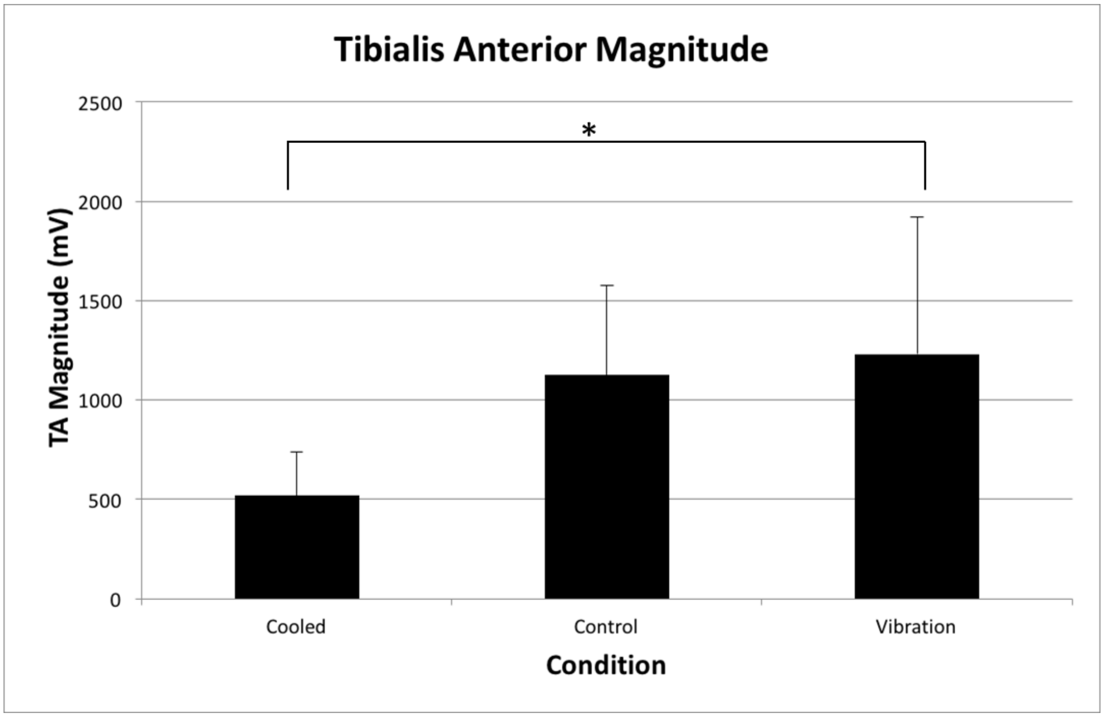


Figure 3.1: A main effect of condition was found for the EMG amplitude of the third TA burst recorded.

Interestingly, while no other significant differences between conditions were observed for EMG amplitude within the other muscles recorded, it was found that there was an effect of participants several muscle bursts recorded. Both the first burst (mean=2570 mV, SD=443) for Tibialis Anterior and the third burst recorded for Biceps Femoris (mean=2329 mV, SD=144) demonstrated significant variability between participants. These results suggest that while no significant differences occurred between conditions, the participants within this study responded to the conditions differently. This variability in participant response was also observed for the onset timing of the first burst of Gastrocnemius (mean=-32.3ms, SD=23.4),as well as the second burst recorded for Rectus Femoris, (mean=48.9ms ,SD=15.6)

Muscle Activity Magnitude and Rate of Loading

The magnitude of muscle activity (mV) within the Tibialis Anterior and the Rectus Femoris muscles were further analyzed in relationship to the rate of loading patterns collected from each participant. Correlations were defined to be very strong within the ±0.9-1.00 range, strong within the ±0.7-0.9 range, moderate within the ±0.5-0.7 range, low within the ±0.3-0.5 range, and negligible within the ±0.0-0.3 range (Mukaka, 2012).

Some correlations were observed in the lateral perturbation direction for the Tibialis Anterior activity and the rate of loading with a low, negative correlation observed for the cooled condition (r=-0.44). Within the anterior direction, a positive correlation in the control condition was observed (r=0.77), and a moderate, positive correlation for the cooled condition (r=0.61). For the Rectus Femoris activity and rate of loading during lateral perturbations, no correlation was found for the control condition (r=-0.12), and a significant, positive correlation was observed for the cooled condition (r=0.94, p=0.05). Within the anterior direction, a trending negative correlation was observed for the control condition (r=-0.91, p=0.08), a low, positive correlation was observed for the cooled condition (r=0.47), and a moderate, positive correlation was observed for the vibration condition (r=0.62). A summary of Pearson's correlations for EMG amplitude and rate of loading can be found in *Table 3.1*.

Table 3.1: Summary of Pearson's Correlation for EMG amplitude (mV) and Rate of Loading (kN/s).

Condition	Lateral Perturbation		Anterior Perturbation	
	r	p-value	r	p-value
	Correlation Between Rate of Loading and Tibialis Anterior			
Cooled	-0.44	0.44	0.61	0.57
Control	-0.20	0.69	0.77	0.43
Vibration	-0.03	0.93	0	0.99
	Correlation Between Rate of Loading and Rectus Femoris			
Cooled	0.94	0.05	0.47	0.68
Control	-0.12	0.80	0.91	0.08
Vibration	-0.16	0.57	0.62	0.57

The kinematic and kinetic data were analyzed together in order to observe possible relationships between the COM and COP. Kinematic and kinetic data were analyzed in two groups, falls in the lateral direction and falls in the anterior direction, as these were the two possibilities throughout the study. The decision to analyze the data based upon the direction of the perturbation was chosen as previous research has suggested that the direction of perturbation plays a role in the individual's response.

Anterior Perturbations - Centre of Mass and Centre of Pressure

Within the anterior direction for perturbations, no significant results were observed for any of the variables analyzed. However, similar to the electromyography findings, several variables demonstrated significant effects of participants. The maximum COM velocity measured within the anterior-posterior direction, the minimum COP velocity measured within the anterior-posterior direction, the measurement of the maximum distance between the COM and COP in the anterior-posterior direction, and the measurement of how close the COM reached the lateral border of the BOS, all demonstrated an effect of participants.

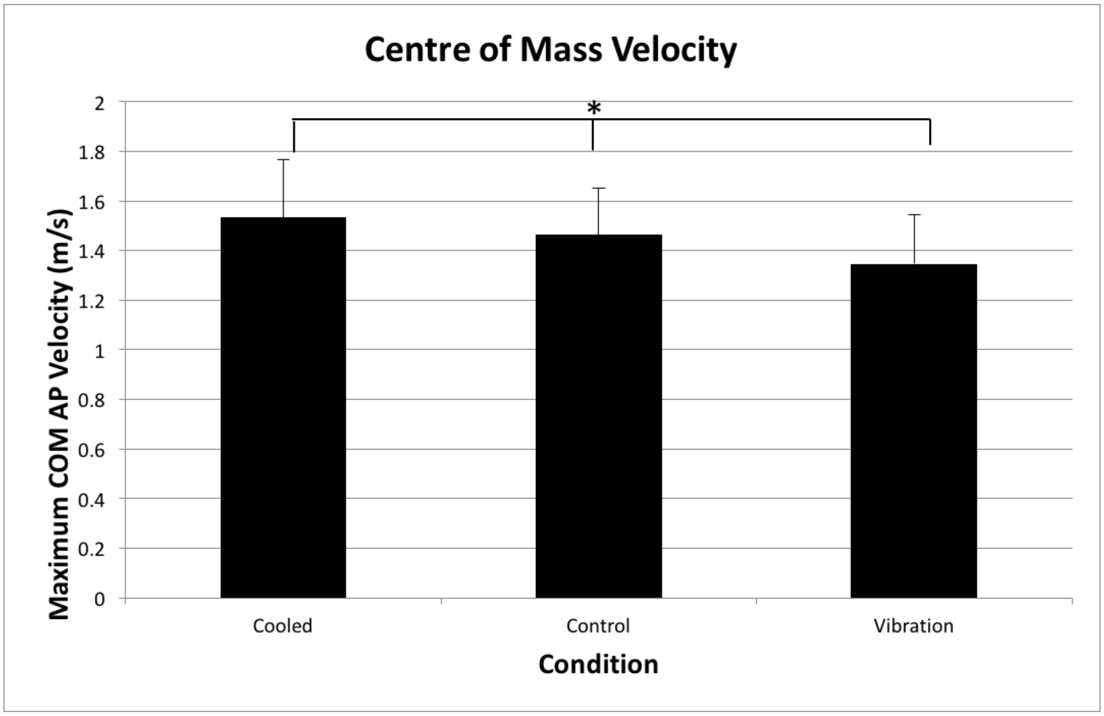


Figure 3.2: Condition means across participants for Maximum COM Velocity in the Anterior-Posterior direction (m/s).

The comparisons created by the one-way ANOVA, separated by conditions for the Centre of Mass velocity measured within the anterior-posterior direction can be observed above in *Figure 3.2*, ($F_{(2,35)}$=3.71, p=0.05). In conjunction with a significant result observed for the effect of condition on the COM velocity, a trending variability between participants was also observed ($F_{(9,35)}$=2.72, p=0.06). Post hoc analysis demonstrated significant differences between all three conditions tested.

Similarly, the one-way ANOVA separated by conditions for the minimum Centre of Pressure Velocity resulted in a main effect for condition ($F_{(2,35)}$=4.62, p=0.03), as depicted in *Figure 3.3.* Similarly, significant variability between participants was observed ($F_{(9,35)}$=3.93, p=0.01). Post-hoc analysis demonstrated the main effect for condition occurring between the cooled and vibration conditions, as well as the control and cooled conditions.

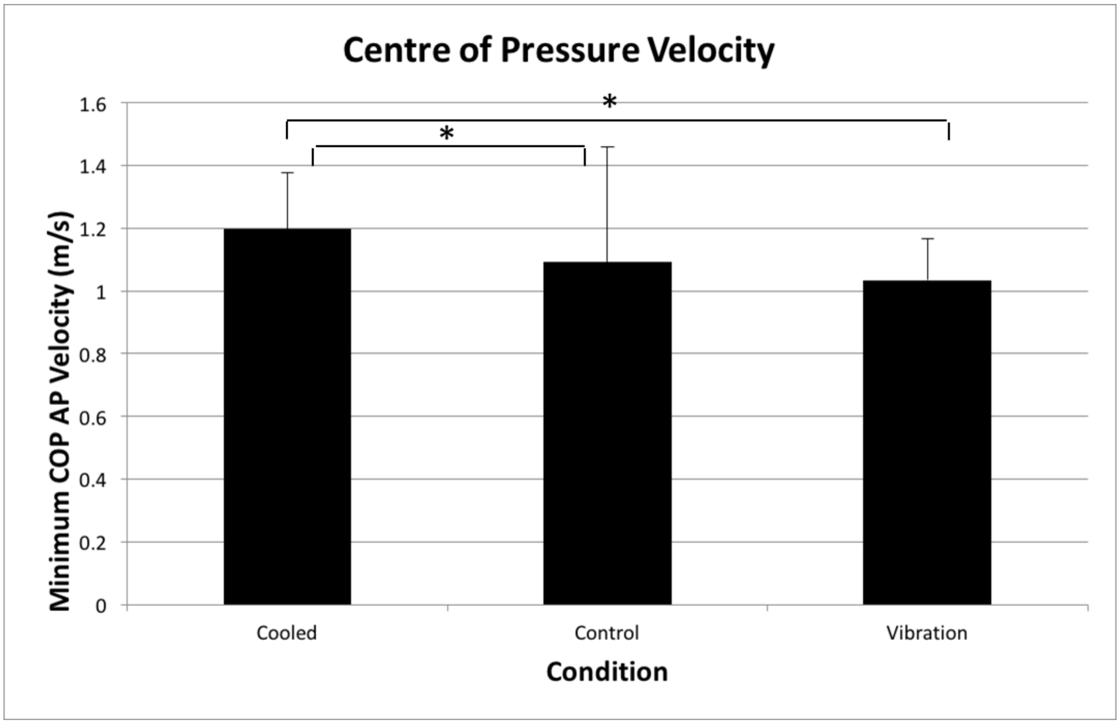


Figure 3.3: Condition means across participants for Minimum COP Velocity in the Anterior-Posterior direction (m/s).

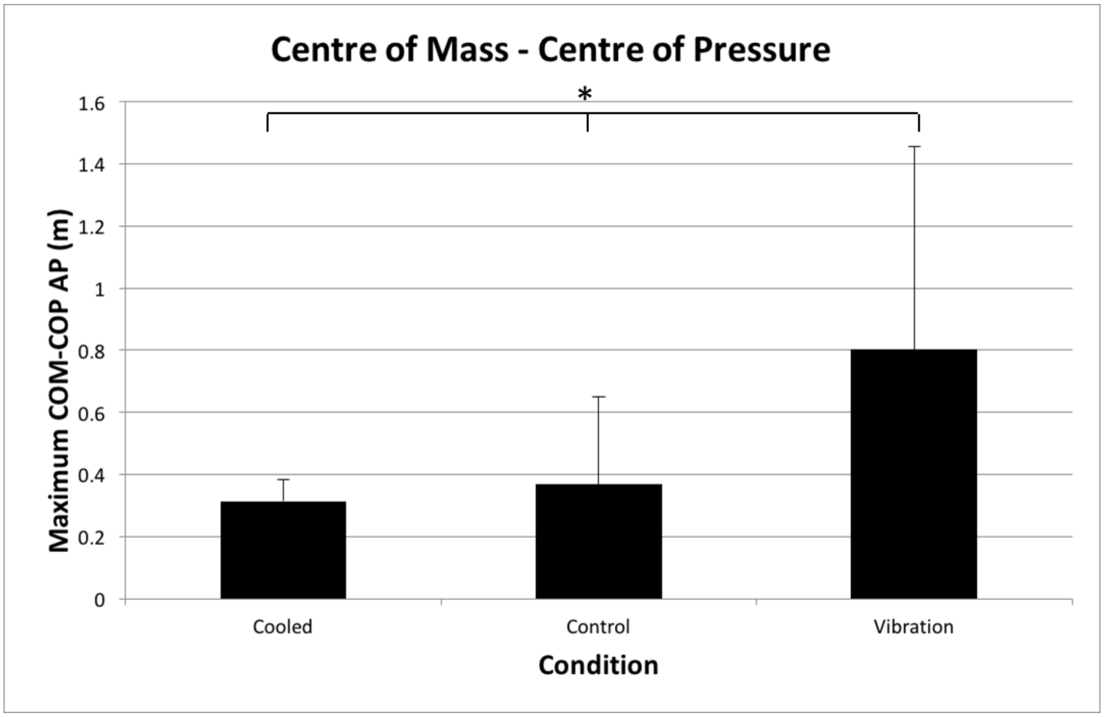


Figure 3.4: Condition means across participants for Maximum COM-COP in the Anterior-Posterior direction (m).

The maximum distance between the COM and COP within the anterior-posterior direction as seen in *Figure 3.4,* also displayed a main effect for condition ($F_{(2,35)}$=4.37, p=0.04), with post-hoc analysis demonstrating significant differences between all three conditions. Similarly, trending variability between participants was observed ($F_{(9,35)}$=2.61, p=0.06).

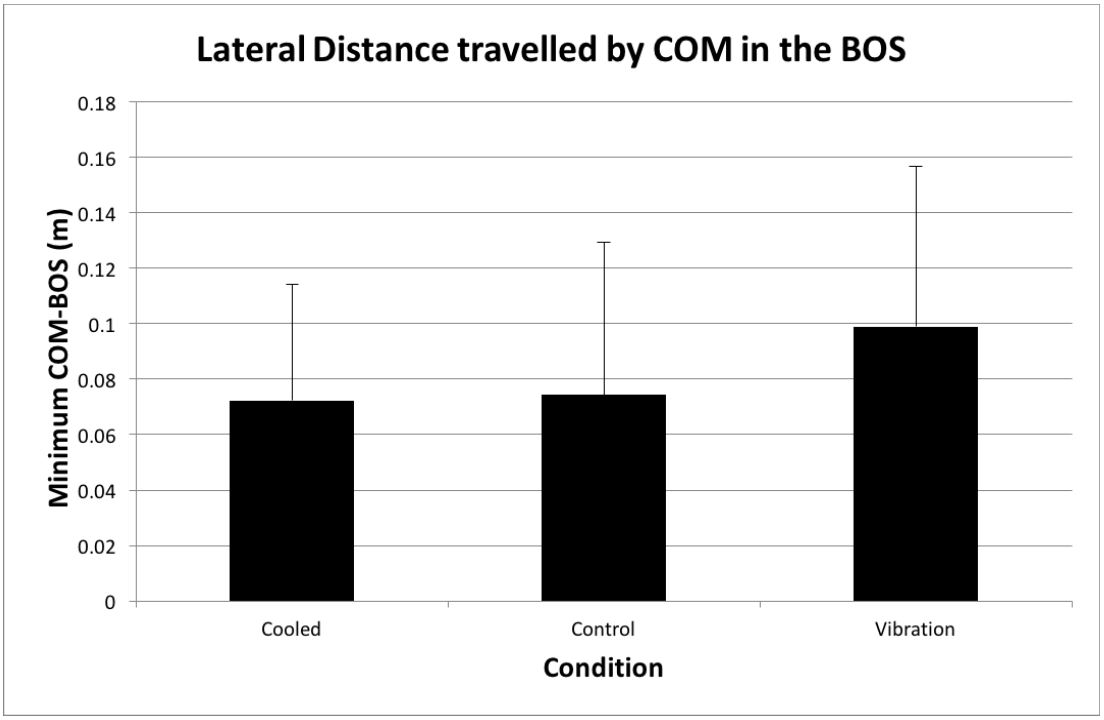


Figure 3.5: Condition means across participants for Minimum COM-BOS in the Medial-Lateral direction (m).

The final variable within the anterior perturbations that demonstrated a main effect of condition is the distance the COM reached within the BOS in the lateral direction ($F_{(2,35)}$=5.37, p=0.02). Significant variability between participants was also observed ($F_{(9,35)}$=5.86, p=0.004). The BOS-COM relationship can be observed above in *Figure 3.5*.

Lateral Perturbation - Centre of Mass and Centre of Pressure

Within the lateral direction perturbations, the maximum COM velocity within the anterior-posterior direction displayed a trend for condition ($F_{(2,55)}$=3.07, p=0.06), with post-hoc analysis demonstrating significance between control and vibration conditions, as well as between the cooled and vibration conditions. The main effect for condition within the COM AP Velocity can be observed in *Figure 3.6*.

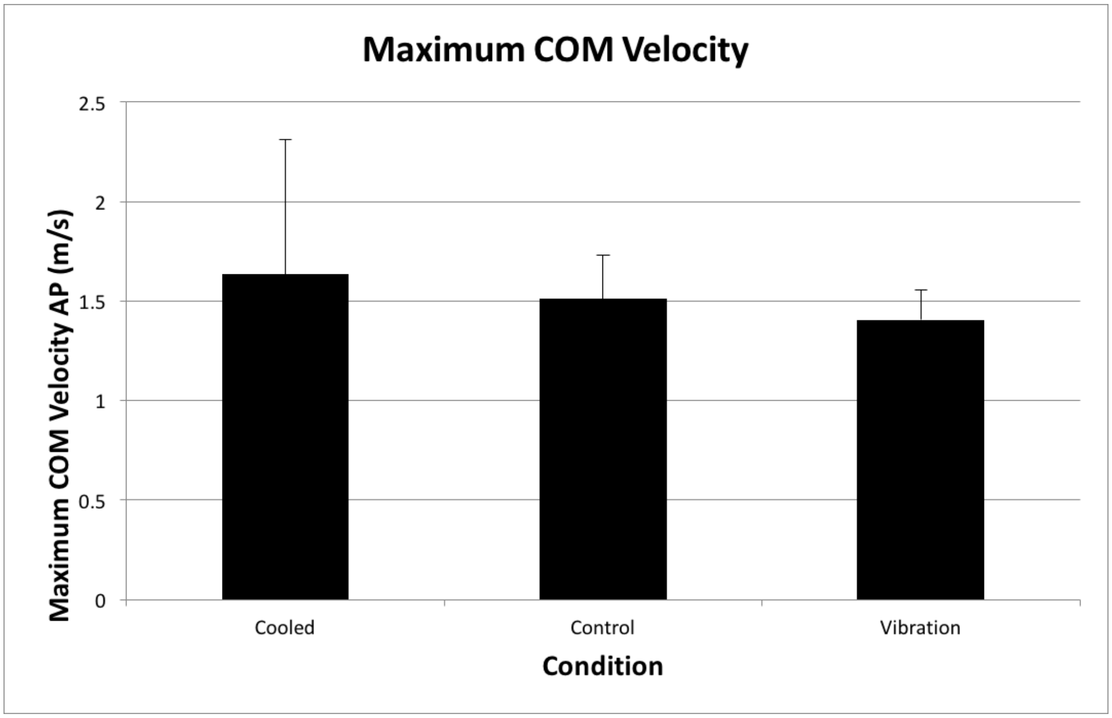


Figure 3.6: Maximum COM Velocity within the Anterior-Posterior Direction (m/s).

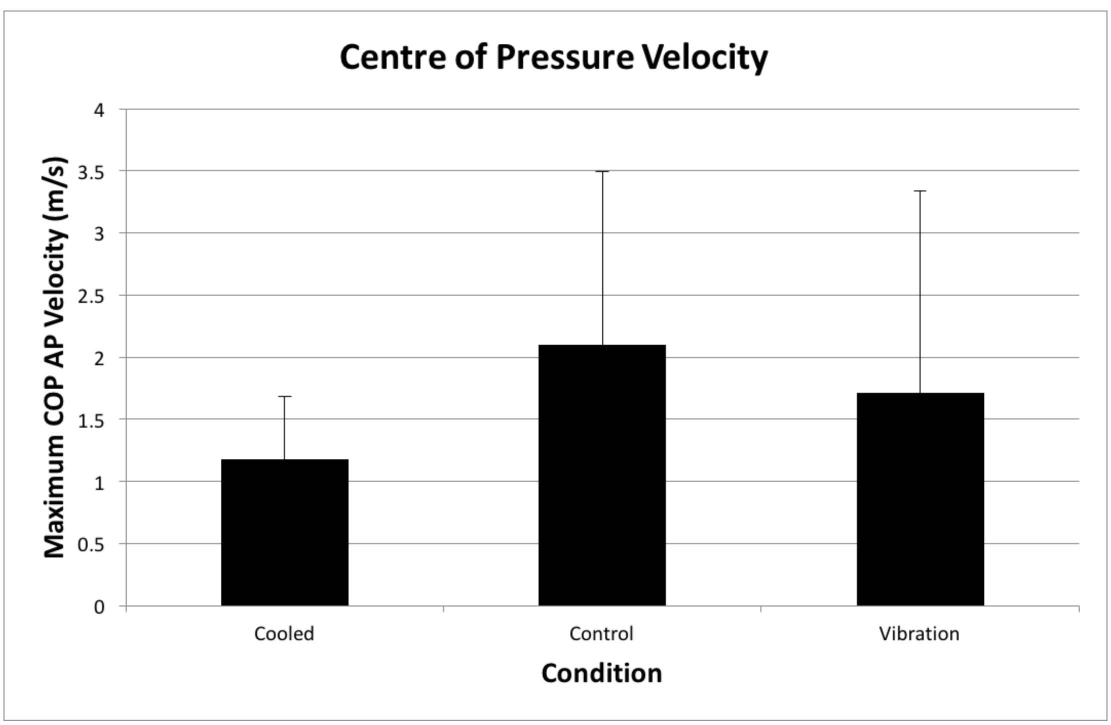


Figure 3.7: Condition means across participants for Maximum COP Velocity in the Anterior-Posterior direction (m/s).

In *Figure 3.7*, while a main effect for condition was not observed, a significant interaction between participant and condition was observed ($F_{(15,55)}$=2.93, p=0.008) . Within *Figure 3.8*, a trending effect of condition can be observed for the maximum distance between the COM and COP within the medial-lateral direction ($F_{(2,55)}$=2.98, p=0.06). Significant variability between participants was also observed ($F_{(15,55)}$=2.12, p=0.04).

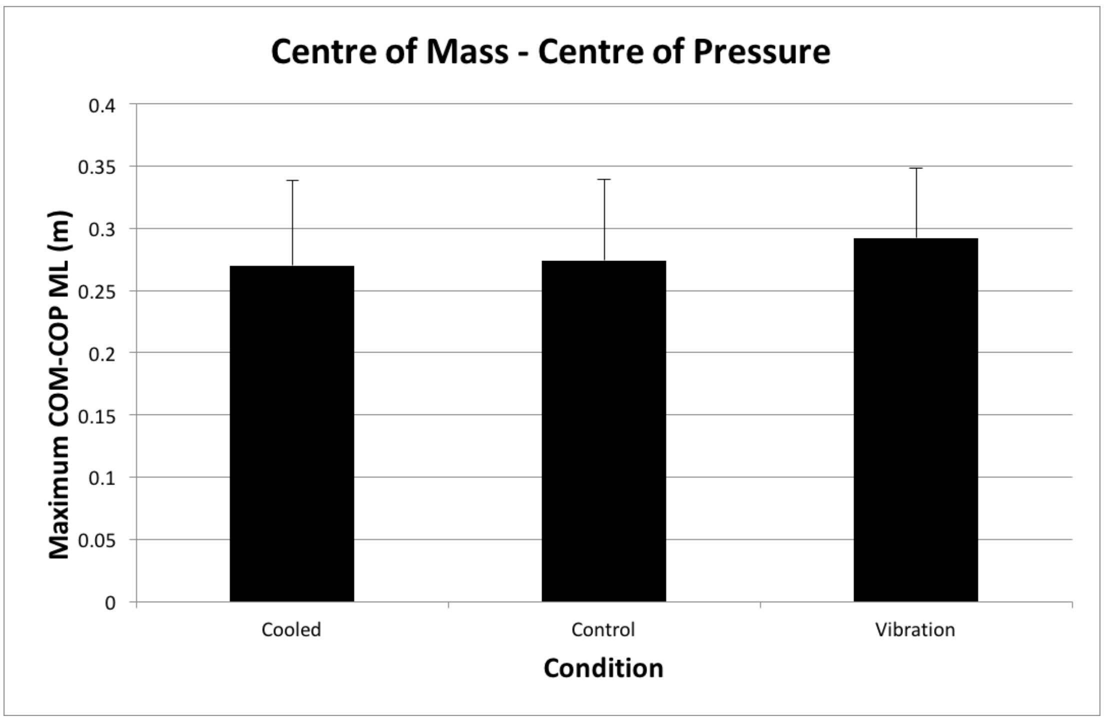


Figure 3.8: Maximum COM-COP in the Medial-Lateral direction (m) across conditions.

The final variable within the lateral perturbations that exhibited a main effect for condition was the Rate of Loading (kN/s). The Rate of Loading demonstrated a main effect for both condition ($F_{(2,55)}$=3.86, p=0.03), as well as a significant variability between participants ($F_{(15,55)}$=3.13, p=0.005). However, post-hoc analysis did not demonstrate significant differences between conditions, which could have occurred as a result of the variability between participants.

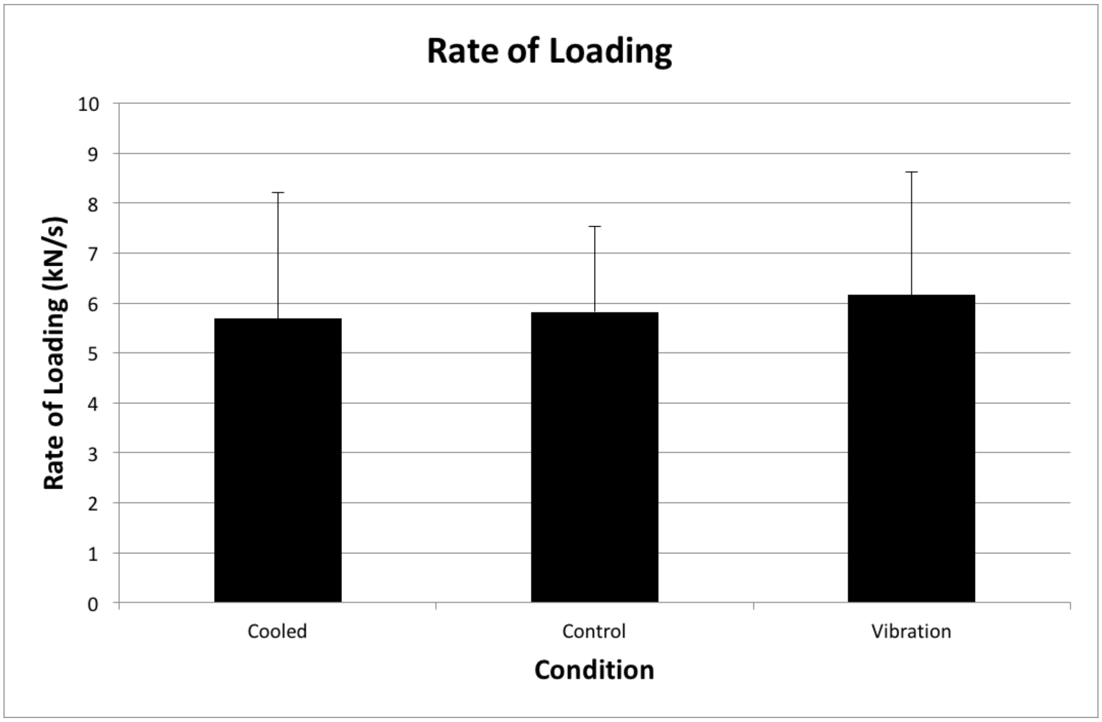


Figure 3.9: Rate of Loading means across conditions.

CHAPTER 4
DISCUSSION

This study had three main objectives. To examine the relationship between cutaneous mechanoreceptors within the plantar surface of the foot and an individual's ability to adapt to perturbed gait. To examine the interaction between muscle activity and the manipulation of the aforementioned mechanoreceptors, and finally to observe possible relationships between muscle activity and foot contact forces during somatosensory manipulation. This study aimed to address all three of these objectives and hypothesized that balance control parameters would be affected as a result of the manipulation of mechanoreceptors (specifically an increase in the dependent variables being measured in response to a decrease in plantar surface information). Muscle activity would also be increased primarily by a reduction in plantar somatosensory information, and an interaction between loading patterns and muscle activity would also be observed.

Muscle Activity Amplitude and Timing

Results from the EMG amplitude and onset timing analysis across all three conditions outlined several interesting relationships. In contrast to one of the main hypotheses of this study where we predicted an increase in muscle activity during the reduced sensation conditions, the Tibialis Anterior instead demonstrated a significant reduction of EMG amplitude for the reduced sensation recorded. It was hypothesized that an increase in muscle activity would have been observed as the lack of plantar information to the central nervous system could have resulted in an increase in information from golgi tendon organs or muscle spindles within the muscles. The reasoning for this hypothesis was that the cooling procedure performed was based upon a previous study's methodology in which the skin was in contact with ice for a duration long enough to reduce the temperature without affecting the muscles of the foot (S. D. Perry et al., 2000). As the golgi tendon organs and muscle spindles are responsible for providing changes in muscle tension, contraction velocity, and length, any changes in muscle activity would likely occur as a result of this relationship (Enoka, 2001; Kistemaker et al., 2012). However, previous research has also observed a significant decrease in Tibialis Anterior magnitude in response to decreased somatosensory information from the plantar cutaneous mechanoreceptors (Nurse & Nigg, 2001; Eils et al., 2002; Eils et al., 2004).

In contrast, previous research has also observed an increase in EMG amplitude of the Tibialis Anterior when exposed to downward slope walking (Lay et al., 2007). While the perturbations were classified as anterior and lateral, the slope of every perturbation was downwards. Similarly, Höhne et al.'s 2007 study, demonstrated significant increases in Tibialis Anterior magnitude throughout the stance phase of walking following cooling of the plantar cutaneous mechanoreceptors.

The resulting decrease in EMG amplitude of the Tibialis Anterior is likely due to the fact that when experiencing a decrease in cutaneous plantar sensation, participants have a tendency to display a cautious walking style (Eils et al., 2004). Specifically, Eils et al., demonstrated that a decrease in EMG amplitude occurred as a direct result of decreased foot contact with the ground as well as push off (Eils et al., 2002, 2004). While this study did not demonstrate significant reductions within the rate of loading for either directions of perturbations, it is still possible that a decrease in EMG amplitude observed could be a result of cautious walking. This result is likely to have occurred within this study as the vibration and control trials occurred at the beginning of each testing session, with the cooled trials occurring last. The reasoning for this being that although the perturbations were randomized every trial, the first half of data collection allowed for participants to become aware of the experience of the perturbations. The cooling procedures of this study are similar in nature to Eils et al.'s 2004 study, as well as Nurse & Nigg's 2001 study in which ice was used as the method of choice to induce hypothermic anesthesia. In comparison, Höhne et al.'s 2007 study utilized injected anesthetic solution. As such, this difference in methodology could be a factor in why a significant decrease in TA activity similar to Eils et al.'s 2004 study and Nurse & Nigg's 2001 study was observed, in contrast to results recorded by Höhne et al. in 2007.

As the methodology for the cooling procedure has stated, the icing was provided for a specific time period to ensure that golgi tendon organs and muscle spindles were not affected by the ice. The time period of 15 minutes, with subsequent re-cooling after approximately 2-5 minutes was chosen based upon Perry et a.'s 2000 study methodology. Therefore, the resulting changes in muscle activation can be concluded to be a result of manipulated sensory information from the plantar surface of the foot. Moreover, the decrease in EMG amplitude confirms that a relationship between information from the cutaneous mechanoreceptors and muscles within the lower limb plays a significant role in balance control, however the relationship differed from that which was hypothesized.

Anterior Perturbations influence on Centre of Mass and Centre of Pressure

Within the anterior perturbations, the cooled condition demonstrated a significantly larger velocity for the COP in the posterior direction. Meyer et al.'s 2004 study investigated the effects of forefoot and whole foot anesthesia on balance parameters. The study observed that under both the whole foot and forefoot conditions, reduced plantar sensation via hypothermic anesthesia resulted in an increase in COP Velocity in all directions (Meyer et al., 2004). As the perturbation occurred within the anterior direction in the current study, the increase in velocity observed within the posterior direction could be a result of a postural response to maintain balance. Due to the lack of information being provided to the central nervous system in regards to balance status, it is difficult for individuals to sense that they are being perturbed. As such, if the ability to sense balance is compromised, a longer reaction time to slow down both the COM and COP velocity occurs. As suggested by the hypothesis of this study, the significant increase in velocity observed for the cooled condition can be concluded to have occurred as a result of loss of plantar sensation resulting in a greater response to the perturbation occurring.

Within the results of this study, the maximum difference between the COM and COP in the anterior-posterior and medial-lateral directions, indicates the most unstable position during the stance phase of the right foot while undergoing the perturbations. A significant increase in this difference between COM and COP was observed for the vibration condition in comparison to the other conditions measured. However, the timing is unknown for how long the participants held this position, which could suggest that the difference observed could be due to a larger response of the body because of the vibration stimulus present. Therefore, it is possible that the vibration stimulus served to enhance the body’s ability to respond to the perturbation. Similarly, the maximum lateral distance that the COM reached within the BOS suggested that the COM travelled significantly farther in the lateral direction during the vibration condition. This reaction could also have occurred as a result of the vibration creating a large response to balance control, however without the timing it is difficult to discern.

While Priplata et al.'s 2002 study demonstrated that subthreshold vibration decreased postural sway during static conditions, a dynamic condition such as walking or an unexpected perturbation in conjunction with subthreshold vibration has not been investigated. As such, it is difficult to discern if this observed increase in the distance between the COM and COP is a result of the increased plantar sensation information. Further research is needed to explore this relationship further.

Lateral Perturbations influence on Centre of Mass and Centre of Pressure

The results of this study demonstrated trends for the maximum and minimum COM velocity. As the results are trending it is difficult to distinguish which conditions are trending towards being different from one another. However, analogous with the anterior perturbations, it is possible that an increase in COM velocity within the iced condition in comparison to the other two conditions measured would be demonstrated. This possible result is suggested based upon the increase in COM velocity within the cooled the condition observed within the results section.

In contrast to the anterior perturbations, while not significant, a decrease in COP velocity (in the anterior-posterior direction) within the cooled condition was observed in comparison to the control and vibration conditions. Potential reasoning for these results could be due to the fact that the significant effect of participants (groups of participants responding differently within the different conditions) resulted in no significance for the ANOVA performed for condition.

In conjunction with the anterior perturbations, the maximum difference between the COM and COP in the anterior-posterior directions demonstrated significant differences between conditions. As this significance was observed between the vibration and control conditions only for the lateral perturbation, in comparison to the significance observed between all three conditions within the anterior perturbations, it is possible that the effect of the participants responding differently across conditions has resulted in a limited amount significance observed within the post-hoc analysis.

Loading Patterns and Muscle Activity

Results indicated a significant correlation between the first burst of EMG amplitude within the Rectus Femoris and the Rate of Loading for the cooled condition of the lateral perturbations ($r=0.94$, $p=0.05$). Similarly, a trending correlation between the secondary burst of activity for the Rectus Femoris muscle was observed for the control conditions during the anterior perturbations ($r=0.91$, $p=0.08$). These strong, positive correlations suggest that as the EMG magnitude increase, as did the rate of loading. The significant results of these correlations conclude that the third hypothesis of this study was correct.

Previous research has demonstrated that there are significant increases in muscle activity during specific phases of the gait cycle during downslope walking (Lay et al., 2007). Lay et al.'s 2007 study determined that an increase in Rectus Femoris activity occurred as a result of the increase in knee extensor moment occurring at the end of stance phase. Similarly, the Tibialis Anterior demonstrates an increase in activity during the transition from heel strike to single stance phase (Lay et al., 2007). From this information, due to the unexpected perturbations used in this study, these muscle were chosen to see if activity would be affected in conjunction with loading patterns by the change in conditions as well. As previously mentioned, the afferent groups located within the muscles of the human body have previously been demonstrated to have a significant role in manipulating motor output at the spinal and supra-spinal levels (Laurin et al., 2015). As such, these afferent relationships could be the main reasoning behind the relationships observed within this study between muscle activity and rate of loading. Therefore, from these results, it can be concluded that the changes observed in loading patterns of the foot have a relationship with the activity of muscles within the lower limb.

Final Conclusions

It is of importance to establish the significance of the comparisons between the cooled and vibration conditions used within this study. For the cooled condition, the results of this study are in agreement with previous research suggesting that the cooling has a disadvantageous effect on an individual's ability to perform tasks such as gait and perturbation reactions in comparison to how they would respond under control conditions. As for the vibration condition, while significant results within this study are limited, they are suggestive of a relationship in the opposite nature of the cooled condition used within this study. Specific examples of this relationship can be viewed in the results section of this study, such as the COM and COP velocities measured. Therefore, the use of these conditions suggest that an individual's ability to adapt to perturbed gait is affected by the use of different sensory conditions as made evident by the cooled and vibration conditions used within this study.

CHAPTER 5
CONCLUSION

Concluding Statement

During reduced sensation walking, a number of relationships emerged that could extend the information of cutaneous mechanoreceptors' role in human gait. Main effects observed for COM and COP velocity suggest that the reduction in sensation plays a significant role in an individual's ability to adapt to a perturbed environment. As these effects were observed for both the anterior and lateral perturbations, it can indicate that the direction of the perturbation does not affect an individual's ability to adapt to gait, but rather the lack of sensation can disrupt this ability. Relationships observed for the vibration condition were both similar and different from normal sensation, suggesting that subthreshold vibration could be important in regards to improving balance control in regards to minimizing postural sway observed through the COP, as well as the speed of COM and COP while walking.

The relationships between muscle activity and plantar sensation were also apparent by the main effect for condition observed within the Tibialis Anterior. As the major significance observed for this result occurred within the reduced sensation condition, it is a good example of the relationship between the information sent to the central nervous system by the plantar cutaneous mechanoreceptors proves to be of great importance to alter muscle activity for an increase in stability. The lower magnitude observed for the cooled condition suggests that the feedback of instability is not being received in time for an appropriate muscle reaction.

Finally, the correlations observed between muscle activity and the foot contact forces suggest that a relationship exists between the output of force and muscle activity. However, this relationship should be investigated further to better understand the mechanics of the connection between the two, as well as the possible implications for human gait.

Limitations

Although the number of participants recruited for this study fell within the desired range for this study, a larger number of participants might have provided a better understanding of the role that plantar sensation has during unexpected perturbations. Similarly, an increase in participants could have allowed for trending results to have demonstrated significance.

For the significance found between participants for EMG amplitude and onset timing, COM velocity, COP Velocity, the COM-COP relationship, the BOS-COM relationship, and the Rate of Loading, possibilities for this result could be simply due to the variability across participants' walking styles. While no significance for single stance duration was observed, the speed at which participants chose to walk at varied. Participants were asked to maintain the same speed of walking throughout the duration of the study, however it was observed that the walking speed of some participants was faster than others, regardless of the condition of the study. Another possibility for these results could be due to the fact that although the mean age of participants was 24, one participant (age 29) was older than some of the other participants by 10 years. Although all participants did not have any conditions that could affect balance control and all classified as a young adult, this large range in ages could account for some of the significant differences found between participants for some of the variables analyzed.

Another potential limitation of this study was that although the perturbations and the directions in which the perturbations occurred were randomized, once the first perturbation occurred, participants became aware of the sensation of the perturbation and most likely were prepared to trip during every walking trial after the fact. Furthermore, while participants were screened for any visual or vestibular system abnormalities, these sensory systems were not fully controlled. Participants were instructed to walk across the platform looking straight ahead and were blinded from the change in perturbation location/direction however, vision was not tracked. Similarly, the vestibular system was not controlled for as it was beyond the scope of this study, however as the young adults who participated within the study were screened prior to their participation, it is unlikely that this was a factor.

Further Implications

As the results of this study suggest, a significant relationship between the cutaneous mechanoreceptors of the plantar surface of the foot and balance control exists. Additional analysis into the role that subthreshold vibration has on changes in gait parameters is necessary to provide information that could assist with further development of orthotics and insoles to assist with gait. Further research analyzing the effects of subthreshold vibration during walking with older adults is suggested. As older adults are the primary age group in which falls occur, the possibility of improving balance control within this group should be explored. As the platform used within this study was able to be used in conjunction with a harness, it is possible that platforms similar to the one used in this study could be used within clinical settings. It would be of benefit to examine such perturbations and vibration within a clinical environment as older adults are not the only group that is at a higher risk of falling. By performing adaptation tasks such as the one in this study with the use of vibration, it is possible that vibration could be used more frequently in fall prevention settings. Future studies would also benefit from the control or manipulation of the other sensory systems involved with gait, the visual and vestibular systems, in order to evaluate if subthreshold vibration has a greater or smaller role when these other systems are at risk.

Finally, future research would benefit from perturbations within all directions. For the purposes of this study, the perturbations were limited to the anterior and lateral directions. Possible perturbations within the posterior and medial directions could expand the knowledge of an individual's ability to adapt to gait under manipulated sensory conditions.

Appendix A:

SCREENING QUESTIONNAIRE

VOLUNTEER EXCLUSION CRITERIA **Date: (MM/DD/YYYY): _____, _____, _____**

Name: _____

Address:_____

_____

City, Prov:_____ Postal Code _____

Tel #: (_____)-_____ Best time to call: _____

Age: _____yrs. Height: _____cm Weight _____kg Shoe Size _____
Gender: M☐ F☐

Please check (√) if applies

	Y/N	little or none	mod	a great deal
How much does the condition interfere with your activities?				
Do you have any conditions that limit the use of your arms or legs?	Select	☐	☐	☐

Describe:

Do you have or have you ever had: Please check if applies

a)	paralysis	☐
b)	epilepsy	☐
c)	cerebral palsy	☐
d)	multiple sclerosis	☐
e)	Parkinson's disease	☐
f)	stroke	☐
g)	any other neurological disorder ______	
h)	diabetes	☐
i)	problem with your vision that isn't corrected by glasses	☐
j)	cataract surgery	☐
k)	a balance or coordination problem	☐
l)	an inner ear disorder	☐
m)	hearing problems	☐
n)	constant ringing in your ears	☐
o)	ear surgery	☐

Have you ever had any serious problems with your memory? Select

Have you had a concussion within the last three months? Select

Do you have or ever had recurrent ear infections? Select

Have you ever had frostbite in the lower extremities? Select

Do you have or have you ever had :

How much does the condition interfere with your activities?

		Y/N	little or none	mod	a great deal
a)	problems with your heart or lungs	Select	☐	☐	☐
b)	high blood pressure	Select	☐	☐	☐
c)	blood circulation problems (generally)	Select	☐	☐	☐
	(specifically lower extremities)	Select	☐	☐	☐

d)	cancer	Select	☐	☐	☐
e)	arthritis	Select	☐	☐	☐
f)	rheumatism	Select	☐	☐	☐
g)	back problems	Select	☐	☐	☐
h)	a joint disorder	Select	☐	☐	☐
i)	a muscle disorder	Select	☐	☐	☐
j)	a bone disorder	Select	☐	☐	☐
k)	spina bifida	Select	☐	☐	☐

Have you ever severely injured or had surgery on your

a)	head	Select	☐	☐	☐
b)	neck	Select	☐	☐	☐
c)	back	Select	☐	☐	☐
d)	pelvis	Select	☐	☐	☐
e)	ankle, knee, or hip joints?	Select	☐	☐	☐

	Y/N	How much does the condition interfere with your activities? little or none	mod	a great deal
Have you ever broken any bones?	Select	☐	☐	☐
Which ones? : _____				
Have you had any recent (specify)				
a) illnesses	Select	☐	☐	☐
b) injuries	Select	☐	☐	☐
c) operations	Select	☐	☐	☐
Do you have difficulties performing any daily activities?	Select	☐	☐	☐

Which activities?: _____

Are you currently taking any medications (prescription or over-the-counter), or other drugs?

Medication	Ailment	Frequency of use

Appendix B:

WILFRID LAURIER UNIVERSITY

INFORMED CONSENT STATEMENT

The Effects of Altered Plantar Somatosensory Input on Simulated Falls During Walking

Sarah Mitchell-Ewart, Master's Student, WLU

Dr. Stephen Perry, Professor, WLU, 519-884-0710 ext. 4215

You are invited to participate in a research study. The purpose of this study is to investigate the role of the somatosensory system on postural control during gait. Researchers are affiliated with Wilfrid Laurier University.

INFORMATION

A total of twenty participants will be recruited for this study. Participants will be asked to complete a series of walking trials across the length of an 8 meter walkway under two of three possible somatosensory conditions. The three experimental conditions are a reduction of somatosensory information through cooling of the foot via ice, sub-threshold vibration (determined to be at 90% of the participant's perceptual threshold) through a customized vibration device within an insole, and no manipulation (control trials).

Prior to the walking task, each participant will undergo baseline sensitivity tests. These sensitivity tests will take place on base of the first and fifth toes of both feet as well as the heel of each foot. After these sensory tests, participants will be assigned to one of the two manipulated sensory conditions (reduced or enhanced). For the reduced condition, the plantar surface of the foot will be submerged in icy water for approximately 15-20 minutes, with possible re-cooling every 5-10 minutes to ensure that the foot remains cooled. For the vibration condition, participants will be fitted to an insole to walk with, in which the sub-threshold vibration will be provided.

For the walking task of this study, participants will be required to walk across the length of an 8 meter platform for approximately 40 trials (20 trials for the sensory condition, 20 trials for the control condition). The platform will be elevated 4 inches above the ground. While performing these walking trials, participants will be exposed to gait perturbation, in which they may lose their balance. However, the harness provided will prevent any falls from occurring. Overall, the total time commitment for this research study will be approximately one hour to one and a half hours.

Through the duration of the walking tasks, muscle activity will also be recorded in conjunction with the vibration stimulation and cooling of the foot. The method of muscle activity measurement used for this study will be electromyography. The electromyography measurements will be recorded from the surface of the skin via electrodes.

RISKS

Each participant will be exposed to technology that they would not normally encounter in daily life. The optotrak and electromyography materials will result in a number of cables being attached to the participants' clothing and skin. However, the optotrak and electromyography sensors will not apply any electrical stimulation to the participant and cables will be managed to prevent them from being in the way of the participant as much as possible. Therefore, this should not be perceived as a risk. Furthermore, the vibration device will not apply electrical stimulation or pressure to the participant during its use. Therefore this should also not be perceived as a risk. Similarly, participants will be exposed to ice water on the plantar surface of the foot however, the participants will not be exposed to below freezing temperatures and as such, this should not be perceived as a risk. Finally, the participants will be exposed to possible gait perturbations in this study that they would not normally encounter in daily life. However, the participants will be connected to a harness to prevent falls and, as such, this should not be perceived as a risk.

BENEFITS

This study will be used to assist in the understanding of the role that vibration stimulation plays in enhancing the input of information from the somatosensory system. This research will also aim to expand the current knowledge of the relationship between reduced somatosensory information and balance control. There has been previous evidence suggesting that vibration stimulation can act to improve balance control, particularly in populations at risk of falling. As such, the hope for this research is the possibility of expanding research looking to enhance balance control through the somatosensory system. The possible results of this study could allow for further research to examine the role of vibration therapy in populations at risk of falling as a result of decreased somatosensory information. Furthermore, the use of ice in reducing somatosensory information has been used by previous research. The aim of this study is to expand the knowledge of this relationship by use of a more challenging task than normal gait.

COMPENSATION

For participating in this study you will receive$10.00 per hour. If you withdraw from the study prior to its completion, you will receive compensation for the time volunteered.

CONFIDENTIALITY

Participants will be assigned a participant number with which data will be collected under. Individual data will not be released, data will be presented as group means. Participant data will be organized by files with their assigned numbers and kept in a locked file cabinet within the laboratory. After data has been collected and analyzed, only group results will be published.

CONTACT

If you have questions at any time about the study or the procedures, (or you experience adverse effects as a result of participating in this study,*) you may contact the researcher, Sarah Mitchell-Ewart, at biomch@wlu.ca, and 519-884-0710 ext. 2370. This project has been reviewed and approved by the University Research Ethics Board (which receives funding from the Research Support Fund). If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact Dr. Robert Basso, Chair, University Research Ethics Board, Wilfrid Laurier University, (519) 884-0710 x4994 or rbasso@wlu.ca

PARTICIPATION

Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study, your data will be removed from the study, and the principal investigator and supervisor will have it destroyed. You have the right to omit any question(s)/procedure(s) you choose.

FEEDBACK AND PUBLICATION

The results of this study will be written as a final paper for directed study course for select faculty and students of Wilfrid Laurier University. If you are interested in a written summary of the results at the conclusion of this study, please provide your email below. A written summary of the results of this study will be forwarded to the email provided in September of 2015. The email provided will be kept confidential.

CONSENT

I have read and understand the above information. I have received a copy of this form. I agree to participate in this study.

Participant's signature_________________________________ Date _______________

Investigator's signature__________________________________ Date _______________

Appendix C:

Sensory Thresholds Protocol

Use Semmes Weinstein Monofilaments to provide a non invasive evaluation of cutaneous sensation levels in the feet. Good for diagnoses including nerve compression syndromes, peripheral neuropathy, thermal injuries and postoperative nerve repair.

The lab has a 20 piece Foot kit, to focus on 6 locations on the plantar surface of the foot including:

- Great toe
- 1st Metatarsal head
- 5th Metatarsal head
- Heel
- Medial Arch
- Lateral Arch

Figure 1: Locations for monofilament application

Arches	Right	Left
Medial Arch Filament Size:		
Lateral Arch Filament Size:		

Touch Thresholds	Right	Left
Great Toe:		
1st MT Head:		
5th MT Head:		
Heel:		

Testing Protocol

1. Rest the participant's foot on a stable surface, with them seated. The surrounding area should be quiet to enable complete concentration on sensory perception.
2. Explain the testing procedure fully to the participant and instruct the participant to respond when the stimulus is felt with "okay" or "yes".
3. Direct participant to look away or close their eyes during testing.
4. If any calluses are present, also test the sensitivity of the callus with the monofilaments as well, mark where the calluses are on the foot tracing in red.
5. When applying the filament, press the filament at a 90^{o} angle against the skin until it bows and then remove. For monofilaments from 1.65 to 4.08 apply the stimulus in the same location up to three times to elicit a response. A single response indicates a

positive response for that location. Cycle through the locations in a random pattern each time to avoid a learning pattern

6. Before the application of the first filament, demonstrate the filament with the largest filament, while doing this apply marker on the tip to the filament to mark the bottom of both the left and right feet in order to have consistent filament placement. **DO NOT PRESS WITH THIS FILAMENT FULLY!**
7. The filament to start with on the feet is filament 2.83mm if the filament starts to bend, straighten the filament between your fingers **gently** after each cycle through the points.
8. If the participants responds yes to the stimulus in all sites, the cutaneous sensation is 'normal' and the test is complete. If the patient does not respond to the stimulus, choose the next largest monofilament and repeat.
9. Refer to the below table (Table 1 – touch test sensory evaluator chart) for thresholds
10. For more in detail documentation refer to North Coast Medical Inc. Instructions and Tables

Table 1 – Touch Test ™ Sensory Evaluator Chart

Product Number	Evaluator Size	Target Force *	Plantar Thresholds
NC12775-01	1.65	0.008	Normal
NC12275-02	2.36	0.02	
NC12275-03	2.44	0.04	
NC12275-04	2.83	0.07	
NC12275-06	3.61	0.4	
NC12275-10	4.31	2	Diminished Light touch
NC12275-11	4.56	4	Diminished Protective Sensation
NC12275-14	5.07	10	Loss of protective sensation
NC12275-20	6.65	300	Deep pressure sensation only

* Individually calibrated to within a 5%SD

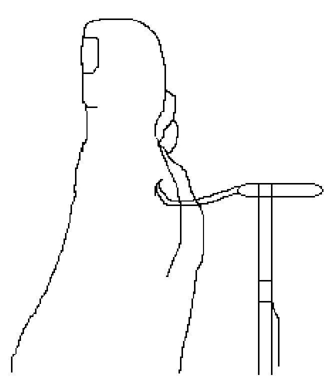


Figure 1: Monofilament application

Vibratory Thresholds Protocol

Log on to BIOMCH_096 in SR-119 and click "**vibration sensation**" shortcut icon. Follow provided black book or file entitled "**Vibration Device Setup**" on desktop to run vibration sensation software.

1. Trace participant's RIGHT bare foot on a sheet of white LEGAL paper.
2. Mark heads of 1st and 5th metatarsals (MTH) on foot tracing.
3. Mark heel and end of 2nd toe on foot tracing.
4. Draw line from 1st to 5th MTH marking. Indicate location of 1st MTH at 10% of the distance along the 1st-5th MTH line from the medial border of the foot. Indicate location of 5th MTH by moving 10% of the distance of the 1st-5th MTH line from the lateral border of each foot.
5. Draw line from heel to 2nd toe marking. Indicate location of heel at 10 % of the distance of the line from heel to the 2nd toe.
6. Outline the great toe on this sheet of paper.
7. Cut out a hole the size of the vibration-indentor in the centre of a piece of acetate.
8. Place a piece of acetate over the white paper.
9. Align indentor hole with the Great Toe marking on white paper below, and trace foot-print in RED marker on acetate.
10. Repeat foot tracing for each of 1st MTH, 5th MTH & heel markings using a different colour marker.
11. Ensure gains (POWER and VARIABLE) are turned down to zero (0) dB.
12. Turn power on both the Power Amplifier and Accelerometer amplifier.
13. On the computer, open the vibration threshold testing program. The parameters in the program are set so the trial sequence is 3 Hz, 25 Hz, 100 Hz, and 250 Hz. Four trials occur at each frequency, one for each foot placement (great toe, 1st MTH, 5th MTH, heel). Click the "START" button to begin each trial.
14. Have participant seated with their foot resting comfortably at the height of the indentor platform.
15. Instruct the participant to place their foot within the RED tracing, so the great toe is located over the indentor.
16. Instruct participant to press button twice as soon as a vibration is felt. The initial vibration frequency should not be difficult to feel. If no vibration is felt do not press the button.
17. Give participant earphones.
18. Press START on collection computer
19. Instruct participant to move their foot to test the next tracing (eg: 1st MTH) and relax. Remind the participant to press the button twice as soon as they feel the indentor vibrate.
20. Press START on the collection computer. Repeat #18 & #19 for each of the test locations and frequencies

Appendix D:

The Effects of Altered Plantar Somatosensory Input on Simulated Falls During Walking

Primary Investigators: Sarah Mitchell-Ewart & Dr. Stephen D. Perry

Subject Number: ________

Ht: ___' ___" Wt: _________N Gender ______

Converse Shoe Size: _____

Dated: (mm/dd/yyyy): ____/____/____

<u>Optotrak</u>:

Sample rate: *100 Hz* Trial Length: *10 sec*

Marker Strength: *70%*

RMS Registration______ (< 0.5) Alignment______ (<0.20)

<u>Force Plate & EMG</u>:

Sample rate: 500 *Hz* Trial Length: *10 sec*

# of Trials: *50*

Quick Protocol Checklist

1. Computer programs running include:

    a. ☐ NDI

    b. ☐ Biodaq (force plates with FZ showing for two force plates)
        i. Remember to save after each trial

2. ☐ Obtain Informed consent.

3. ☐ Explain protocol. Ask if there are any questions.

4. ☐ Obtain participant's weight and height.

5. ☐ Perform monofilament testing to establish sensitivity level.

6. ☐ Landmark for EMG

    a. ☐ Prep skin an adhere electrodes
        i. EMG1: Right tibialis anterior (TA)
        ii. EMG2: Right medialis gastrocnemius (MG)

7. ☐ Marker set up

    a. ☐ Set up markers (12)
        i. Marker 1: Toe
        ii. Marker 2: Ankle
        iii. Marker 3: Knee
        iv. Marker 4: Hip
        v. Marker 5: Shoulder

8. ☐ Check for EMG signals via MVC at each muscle and establish GAIN

9. ☐ Ensure all markers are visible by Optotrak

10. ☐ **Sensation:**

    a. Enhanced: Insert insole with vibration device

        i. Calculate vibration threshold for submaximal vibration (90%)

    b. Reduced: Cool foot for 15-20 minutes

11. Adjust starting position to ensure that subject hits two of the four cutouts, with force plates (walk across 5 sec, wait, turn around, repeat). Collect data for walking trials towards optotrak cameras.
12. When necessary, recool foot (~ every 2 minutes for 5 minutes)
13. ☐ Finish collection and clean up. Thank subject!

1.0 Foot Sensitivity

FOOT SENSATION

Touch Thresholds	Right	Left
Great Toe:		
1st MT Head:		
5th MT Head:		
Heel:		

2.0 Vibratory Threshold

	Frequency
Threshold Level	
Submaximal Level	
Supramaximal Level	

3.0 EMG Collection Information

	Tibialis Anterior (TA)	**Medialis Gastrocnemius (GA)**	**Rectus Femoris (RF)**	**Biceps Femoris (BF)**
MVC 1				
MVC 2				
MVC 3				
Average				

Electrode #	**Muscle**	**Gain**	
1	Tibialis anterior (TA) – Right		
2	Medialis gastrocnemius (MG) – Right		
3	Rectus Femoris (RF) – Left		
4	Biceps Femoris (BF) – Left		

4.0 Anthropometric Data

Hip diameter ___________cm

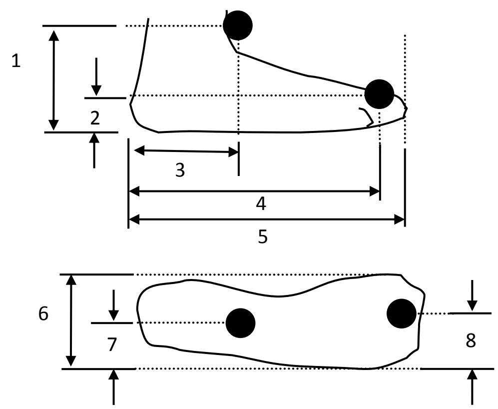
Knee diameter: Left ______ Right ______cm

Ankle diameter: Left ______ Right ______cm

Heel diameter: Left ______ Right ______cm

Marker distances

1. Right ______ Left ______
2. Right ______ Left ______
3. Right ______ Left ______
4. Right ______ Left ______
5. Right ______ Left ______
6. Right ______ Left ______
7. Right ______ Left ______
8. Right ______ Left ______



5.0 Data Sheet

Weight________

	Trial #	Drop	Direction	Sensation	Opto Track Trial #	FP Trial #	Comments
Vibratory Threshold/Control	**1**	***1**	**Lateral**	**Vibration**			
	2	3	Lateral				
	3	**Flat**					
	4	4	Lateral				
	5	***1**	**Anterior**	**Vibration**			
	6	Flat					
	7	**Flat**					
	8	3	Anterior				
	9	***1**	**Anterior**	**Vibration**			
	10	2	Lateral				
	11	***1**	**Lateral**	**Vibration**			
	12	3	Lateral				
	13	***1**	**Lateral**	**Vibration**			
	14	Flat					
	15	***1**	**Lateral**	**Control**			
	16	4	Lateral				
	17	**3**	**Anterior**	**Control**			
	18	4	Anterior				
	19	***1**	**Lateral**	**Control**			
	20	Flat					
	21	***1**	**Anterior**	**Control**			

	22	4	Anterior				
	23	***1**	**Lateral**	**Vibration**			
	24	3	Anterior				
	25	***1**	**Lateral**	**Control**			
	26	4	Lateral				
	27	***1**	**Lateral**	**Cooling**			
	28	3	Lateral	Cooling			
	29	***Flat**		**Cooling**			
	30	4	Lateral				
	31	***1**	**Anterior**	**Cooling**			
	32	Flat					
	33	***Flat**		**Cooling**			
	34	4	Lateral				
	35	***1**	**Anterior**	**Cooling**			
	36	2	Lateral				
	37	***1**	**Lateral**	**Cooling**			
	38	3	Lateral				
	39	***1**	**Lateral**	**Cooling**			
	40	Flat					
	41	***1**	**Lateral**	**Cooling**			
	42	4	Lateral				

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