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Posture Dependant Changes in Perceptual Threshold During Light Touch Foot Sole Stimulation

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Abstract

Light touch sensitivity of the foot sole is typically measured when individuals are seated or lying down; yet, a critical function of foot sole cutaneous feedback is to support standing and walking activities. The objective of this study was to evaluate the differences in how individuals perceive light touch stimulation across the foot sole when they are in different postures. To accomplish this, we measured the light touch perceptual threshold(LTPT) in standing, seated, and supine postures in 19 volunteers (9 males), using Semmes-Weinstein Monofilaments. Perceptual thresholds were calculated at three foot sole locations (1st metatarsal, lateral arch, and heel) in each posture. Perceptual thresholds were significantly higher in the standing condition compared to the seated and supine conditions across all foot locations; perceptual thresholds were significantly higher while seated compared to supine only at the heel and not at the lateral arch or 1st metatarsal. Our results demonstrate that postural changes significantly influence sensitivity across the foot sole. Thus, performing perceptual threshold assessments on the foot sole while standing may offer more relevant insights into the capacity of foot sole cutaneous afferents to convey light touch information in conditions where such feedback plays a vital role in maintaining balance.

Keywords

Foot sole, Light touch perceptual threshold, Posture, Semmes-Weinstein Monofilaments, Sensory perception, Balance, Gait, Standing, Seated

Summary for Lay Audience

How can humans manage to stay balanced while standing or walking, without consciously thinking about it? Our ability to do so comes down to how our bodies process sensory information from our environment, specifically from the soles of our feet. This thesis delves into how different body postures – standing, sitting, and lying down – affect our ability to sense stimulations at the foot sole, and what this might mean for how we currently understand balance and movement. Using Semmes-Weinstein Monofilaments, which are like very fine, calibrated fishing lines, we tested how easily people could feel light touches on three areas of their foot sole in three different postures. Our participants were a group of young adults who underwent a series of touch sensitivity tests.

We found that when standing, people were less sensitive to touch on their foot sole compared to seated or lying down, and less sensitive when seated than when lying down. This difference in touch sensitivity suggests that our posture plays a significant role in how we perceive sensory information from our feet. Understanding these differences can help us comprehend how our bodies maintain balance. Older adults and people who have had a stroke or have diabetes might have impaired sensitivity in their feet. So, these insights could help us better understand how sensation works at a fundamental level as a guideline for rehabilitation practices and balance-enhancing tools for people with impaired sensitivity. This research shines light on the complex interaction between our body posture and the sensory feedback from our feet, emphasizing its importance in our daily life for activities like standing and walking. The hope is that this study will help guide innovative strategies to improve balance in high-risk populations.

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Table of Contents

List of Figures

List of Tables

List of Appendices

List of Abbreviations

CNS: Central nervous system

COM: Center of Mass

FA1: Fast adapting type 1

FA2: Fast adapting type 2

SA1: Slow adapting type 1

SA2: Slow adapting type 2

EMG: Electromyography

VPT: Vibratory perceptual threshold

LTPT: Light touch perceptual threshold

Chapter 1

1 General Introduction

Gait and balance are imperative in most humans' daily lives. Visual, vestibular, and somatosensory systems each contribute to allow for movement and balance in our everyday lives. Sensory feedback from cutaneous afferents allow us to perceive, and make sense of sensory information that we gather from within our body, and environment at the level of the foot sole.[1–5] What is not well understood is how both posture (body), and external stimuli (environment) intertwine and influence each other. To answer this question, we must first understand the mechanisms by which our body receives, interprets, and utilizes sensory information.

1.1 Postural control

Postural control is a complex and multimodal neural task, in which the goal is to maintain an upright orientation of the body and thereby the center of mass (COM) above the base of the foot support.[6] Bodily systems that mainly contribute to postural control are the visual, vestibular, and somatosensory systems.[4,7,8] The central nervous system (CNS) acts as a conductor, facilitating the interplay between each of these systems which allows for postural control even when the body encounters external stimuli.[9,10] The role of each of these systems has been fairly well researched regarding the specific role that they play in balance control. The CNS plays a critical role in postural control by making sense of and acting upon continuous afferent information received on body position and orientation.[7] Body sway is a common metric used to measure postural control throughout various age demographics, and studies investigating different systems contributing to postural control.[4,10(p2),11,12] Postural control has been shown to decline with age,[11,13] increasing the risk of falls, potentially leading to injury. Modulating postural control via one of the contributing systems (vision, vestibular, and somatosensory) would give us an avenue to offset the decline in postural control that comes with aging. First, we must first know how each system contributes to postural control.

1.2 The role of the visual system in postural control

The visual system is comprised of three distinct elements: the central, ambient, and retinal slip components.[14,15] The central (also known as focal) aspect is primarily focused on perceiving the motion of objects and recognizing them.[14] In contrast, the ambient, or peripheral element, is attuned to the motion within a scene and plays a predominant role in both the perception of self-movement and the regulation of posture.[16] Retinal slip, integral to the perception of motion conveyed to the CNS, serves as an indicator of an individual’s spatial displacement by the CNS, and is used as feedback for compensatory sway.[14,17] The visual system has been speculated to be the predominant system in maintaining postural control.[11,18] One avenue in which the visual system contributes to postural control is by providing critical information about the body’s position in relation to its environment, facilitating the detection of motion and guiding adaptive responses to maintain equilibrium.[19] Gill et al., found that limiting the visual system in a two-legged stance task caused a 3-fold increase in trunk sway.[13] Another study investigating the age-related differences in balance characteristics, found that all age groups (young, middle-aged, and older adults) were subject to increased body sway with their eyes closed, however, the older adults were the most susceptible to increased body sway while limiting visual information.[11] Quiet stance refers to a state of postural control where an individual maintains a standing position with minimal movement or sway. When comparing the central and peripheral aspects of vision, it has been suggested that peripheral rather than central vision plays an essential role in maintaining stable quiet stance.[20] Individuals rely on their peripheral vision to visually stabilize both spontaneous (modulating the physical visual parameters (e.g. support surface)) and visually triggered sway (misinterpretation of visual flow due to self-motion or object motion (e.g. tilting room)), aiding in postural control.[14] However, most individuals are still able to stand upright in the dark so vision cannot be working alone.

1.3 The role of the vestibular system in postural control

The vestibular system is comprised of three semicircular canals which sense rotational movements, and two otolith organs which sense linear accelerations.[21,22] The vestibular system stands out among sensory systems due to its immediate integration of multisensory and multimodal inputs.[23] For instance, it works in conjunction with the proprioceptive system, along with the corollary discharge associated with motor planning.[23] This integration enables the brain to differentiate between self-initiated movements and passive movements of the head.[23] The interplay between visual and proprioceptive inputs with the vestibular system via the central vestibular pathways is crucial for controlling both gaze and posture.[23] Vestibular activity takes into account continuous motor and sensory information primarily received from the skin, muscles, joints, and eyes.[23] In people with bilateral vestibular deficits, it has been shown that there are changes in muscle recruitment dynamics (electromyography (EMG) amplitudes and muscle type) and they respond to balance perturbations 50% slower than young adults.[24] In another study also examining patients with bilateral vestibular loss, it was found that they are capable of maintaining balance on a platform that tilts at low frequencies even without visual cues for orientation; however, they are unable to maintain balance when it tilts at higher frequencies.[25] This ability was credited to a mechanism called somatosensory graviception, involving the receptors in the feet that serve as an adjunct to vestibular graviception observed in people without sensory deficits.

1.4 The role of the somatosensory system in postural control

The soles of the feet are the sole contact point with the environment in an upright stance, making them particularly important in relaying information to the brain about our environment. This information is then utilized to regulate posture and gait.[3,26–28] The ability to perceive sensory information from our surroundings is primarily due to the mechanoreceptors at the contact site of the skin and our environment, and while standing, it is the soles of the feet. A growing amount of literature suggesting that plantar cutaneous input is critical for the control of postural control and gait.[29–31] Somatosensory inputs operate through short- or long-latency reflexes or by conveying information to the brain to modulate the neural circuits controlling balance and gait.[32] Peripheral neuropathy can be described as damage to nerves in the periphery, potentially causing dysfunction in sensation and motor control.[33] In a clinical environment, deficits in postural control are shown in patients with peripheral neuropathy, and stroke.[34–36] Plantar-surface sensitivity of the foot sole also deteriorates with age.[37] It is also possible to modulate somatosensory afferent feedback from the mechanoreceptors of the foot. Cooling or anaesthetizing the soles of the feet while in an upright stance has been shown to increase postural sway.[38,39] It has also been shown that reducing plantar sensation via local cooling significantly modifies gait patterns.[40] The mechanoreceptors in the soles of the feet not only play a role in postural control, but also postural awareness.[1] This is likely due to the strong synaptic coupling from the afferents in the feet and the muscles that supply the leg allowing for quick adjustments to meet changing posturing demands.[2] However, these postural adjustments do not just involve the lower extremity. Research has shown that stimulation of low-threshold mechanoreceptors on the foot dorsum can reflexively activate motoneurons supplying muscles in the upper extremity.[41] Stimulating the sural nerve, responsible for sensation in the outer foot and heel, or tibial nerve near the ankle, at a level just above the motor threshold without causing pain, provokes reflex responses in many muscles in the lower legs.[42,43] The latency of these reflexes are longer than a monosynaptic reflex. They may either enhance or suppress muscle activity and vary depending on the body’s position (whether standing, sitting, or lying down). The effects of such stimulation also differ from one muscle to another and between different muscle fibers, highlighting the extensive and intricate nature of these neural influences.

The role of somatosensation on postural control can also be demonstrated via artificially enhancing or worsening postural performance via the foot sole. For example, switching the surface of a shoe insert from a smooth to a noticeably textured material can modify the activity of muscles in the lower limb during gait.[44] This implies that the sensory input from the cutaneous receptors on the bottom of the foot enhances postural control during movement.[44–46] Other research has also found that mechanical stimulation of the foot sole enhances postural stability.[47] Subsensory vibratory stimulations have also been used to reduce gait variability in older adults[45], and suprasensory vibratory stimulations have been used in custom insoles to reduce postural sway and gait variability.[48,49] The underlying mechanisms of this phenomenon are not fully understood but have been hypothesized to be due to increasing sensory feedback to centers in the brain and spinal cord that control the rhythmicity of movement.[48] The ability to efficiently and effectively modulate postural control and gait parameters using the somatosensorial properties of the foot sole provides reason for future research to further understand how this system works in other naturalistic settings.

1.5 Posture and somatosensation

The influential role posture has on somatosensation of the foot sole is fairly new and not well understood, although thought to be a combination of peripheral and central nervous system factors. Peripherally, previous literature has examined touch perception on the foot sole in both dorsi- and plantar-flexion in various locations long the foot dorsum and sole.[50] It was found that in regards to touch sensitivity, the foot sole was significantly more sensitive in plantar flexion compared to dorsiflexion. These changes were thought to occur due to changes in skin mechanics such as skin stretch. There has also been research examining vibratory perceptual threshold (VPT) differences in standing and sitting postures across the heel and metatarsals on the foot sole.[26] Across all frequencies targeting each type of mechanoreceptor, and foot sole locations, VPT was higher in the standing posture compared to the seated posture indicating a lower sensitivity while standing. These differences are thought to be attributed to tissue stiffness differences due to the increased pressure on the foot sole, which may alter the stimulation transmission to the cutaneous afferents.[51] Possible adaptation to static pressure while standing may also influence the foot's ability to respond to dynamic stimulation.[51] Although, the latter is unlikely due to FA afferents filtering static stimuli and preferentially responding to dynamic stimuli,[52] and differences in skin properties being more associated with perceptual thresholds regarding stimuli targeting FA afferents.[53] Centrally, stimulation detection thresholds may be modified with changes in posture, similar to the gating of tactile feedback,[54] as well as the increase in threshold that occurs during muscle contraction and movement in monkeys,[55] and humans.[56] In brain imaging research, unlike the hand,[57] it was shown that the foot has relatively low somatotopic selectivity.[58] Therefore, most stimulations at one foot sole region will likely co-activate other regions such as the toe, sole, and heel somatotopic areas in the primary somatosensory cortex.[58] This may be relevant in explaining the differences in perceptual threshold between postures due to the body not being able to easily distinguish between stimulation at a specific foot site compared to the additional sensation associated with standing. Interestingly, this co-activation was not as prominent when stimulating the calf and thigh which may be less associated with upright stance and walking.[58] This is reflected by the more specific activations activation patterns compared to foot stimulation, and the absence of foot somatotopic area activation.

1.6 Properties of glabrous skin foot mechanoreceptors

The cutaneous receptors within the skin provide sensory feedback through four types of mechanoreceptors, each with distinct characteristics.[59] These receptors include Meissner corpuscles (fast adapting type 1 (FA1)), Pacinian corpuscles (fast adapting type 2 (FA2)), Merkel discs (slow adapting type 1 (SA1)), and Ruffini endings (slow adapting type 2 (SA2)). FA afferent fibers are particularly sensitive to the rate of change of mechanical stimuli; they tend to fire in the dynamic phases of skin indentation (onset and offset of the stimulus). However, firing ceases during sustained indentation. SA afferents continue to fire during sustained stimulus indentation and skin stretch.[59–61] Based on their respective field sizes, SA and FA afferents can be further divided into type 1 and type 2 receptors.[62] The receptive field of a mechanoreceptor can be described as the area of skin that when stimulated, causes the associated afferent nerve(s) to fire. Receptive fields are defined as the area where a sensory afferent nerve responds to a stimulus (e.g. indentation) force that is four to five times its firing threshold.[62] Type 1 receptive fields tend to be small with distinct borders, while type 2 tend to be larger with less defined borders.[62,63] SA1 receptors primarily detect sustained pressures and underlie the perception of form and roughness on the skin,[64] whereas SA2 receptors primarily respond to skin stretch.[65] FA1 receptors tend to respond to light touch such as flutters[66] and slips on the skin.[67] FAII receptors are unique in that they can sense light perpendicular touch and are extremely sensitive to stimuli applied within and adjacent to their receptive fields, as well as respond to blowing across the skin.[63,68]

The same classes of mechanoreceptor afferents innervate both the glabrous skin of the hands and the feet.[69,70] However, there are some distinct differences and similarities in their properties and distribution. The mechanoreceptors in the glabrous skin of the hand and feet are similarly separated by firing threshold, but the thresholds are much lower (~10 fold) on the palm of the hand than on the foot sole.[68,69,71] There is also a lower proportion of SA receptors in the foot than in the palm of the hand.[69,72] These differences make sense logically if one considers the functionality of both the hands and the feet. Higher thresholds may be beneficial for the high forces the feet endure during standing and gait, and lower thresholds for the hands for manipulating objects and fine motor control. Receptive fields have been shown to be smaller in the hands than those in the foot sole.[61,68,71] In the hand, it has been shown that there is a higher concentration of SA1 afferents in the tips of the fingers in comparison to the palm of the hand, suggesting the importance of high sensory feedback needed for fine movement at the fingers.[72] Type 1 afferents most densely innervate the toes, then the lateral arch, then the lateral metatarsals; FA2 afferents most densely innervate the lateral arch, then the big toe, then the middle metatarsals; SA2 afferents most densely innervate the lateral metatarsals, then the toes, then the lateral arch. In the feet, there is a significant proximal-distal distribution gradient, with the most cutaneous afferents being located in the toes, than in the metatarsals/arch and heel, and more in the metatarsals/arch than in the heel.[68] These findings are primarily driven by concentrations differences for type 1 afferents, with FA2 and SA2 afferents having a more uniform distribution, similarly to what has been shown in the hand.[72] However, there is a difference in the medial-to-lateral cutaneous afferent distribution on the foot sole compared to the hand. The lateral portion of the metatarsals had significantly more FA1 afferents than the medial portion, with SA1, SA2, and FA2 afferents having a uniform distribution.[68] For the arch, there was more SA1 and FA1 afferents on the lateral side than both the middle and medial side, with FA2 and SA2 having a uniform distribution.[68] The high receptor density in the toes and lateral border of the foot sole might suggest these areas are important sensory locations for standing balance. Within the hand, reflexive control of hand muscles are thought to be associated with the hands structure (SA2 mechanoreceptors) and the interaction with held objects (FA1 mechanoreceptors), potentially assisting in object handling.[73] In the foot, reflexive control of lower leg muscles are most likely connected to information about making contact with the ground (FA1 mechanoreceptors) and continuous ground support contact (SA1 mechanoreceptors), likely assisting in indicating various stages of walking and the reflexive management of posture.[2]

Previous research has demonstrated a positive correlation between skin hardness and firing rate of FA afferents and perceptual thresholds on the foot sole.[63] However, skin hardness and epidermal thickness do not fully account for the variations in sensitivity across the foot sole.[53] The density of cutaneous afferents within the foot sole contribute to the differences in tactile sensitivity (ability to detect small changes in stimulus intensity) and acuity (ability to detect the spatial differences between stimulations)between different foot areas, but is unlikely to be the sole determining factor.[68]

1.7 Sensation and perception of the foot sole

It is important to distinguish the difference between sensation and perception. Sensation occurs when sensory receptors detect sensory stimuli, whereas perception involves the organization, interpretation, and conscious experience of those sensations.[74] Therefore, although our perceptions are built from sensations, not all sensations result in perception. As previously alluded to, foot mechanoreceptors are also responsible for initiating motor responses to somatosensory stimulation, also known as reflex coupling.[2] When discussing reflex coupling it is crucial to differentiate between the perceptual threshold of the foot sole, and the threshold that induces reflex coupling, typically measured with EMG. It has been shown that activity of low-threshold mechanoreceptors in the glabrous skin of the foot can initiate reflexes that increase ongoing EMG activity in muscles that act on the ankle.[2,42,75] Unlike the hand in which SA1 receptors did not show any reflex coupling, all four types of mechanoreceptors in the sole of the foot are capable of reflex coupling.[2,76] It has been shown that there is no difference between the firing thresholds of FA1 and FA2 afferents and perceptual threshold at the foot sole. In contrast, SA1 and SA2 afferents were significantly less sensitive than the perceptual threshold across the foot sole.[63] This finding suggests that it is the FA afferents that dictate the perceptual threshold of the foot sole rather than SA afferents. Being able to modulate ongoing EMG activity with somatosensory stimulation provides a potent avenue for bettering current and creating new rehabilitation practices.

1.8 Tools for perceptual threshold testing

Two of the most common tools used in perceptual threshold research are Semmes-Weinstein Monofilaments, and custom machines using a vibrating probe to stimulate the skin. The former would provide information on a LTPT, and the latter a VPT. The key differences between the two tools are specificity, portability, and complexity. Using vibrations, one can be very specific with the frequency used to stimulate. This is beneficial due to being able to preferentially activate each type of mechanoreceptor.[26,77,78] Whereas, monofilaments are limited to the physical limitations of how fast the investigator can stimulate, and the inability to stimulate at pressures between the calibrated monofilament pressures. Regarding portability, monofilaments are small, take up very little space, and thus, very portable compared to custom vibration machines that are often large, and potentially heavy. Lastly, the complexity between the two is drastically different. Researchers tend to have to build their own machine with a motor and probes, therefore, requiring knowledge on not only how to build the machine, but also create the code to make it functional. Comparatively, monofilaments are very simple to use, and are more of a turnkey tool for researchers. Monofilaments are also much easier for clinicians to use with patients, so research using this tool may be more clinically applicable. To choose which tool to use, one must consider the research question, budget, technical and engineering savviness, and study design.

Semmes-Weinstein Monofilaments are a well-established and commonly used tool in sensory testing in humans both with and without disease. Perceptual threshold testing is one of the main use cases for the monofilaments.[63] It is important to note that perceptual threshold testing is not an “all-or-none” phenomenon, therefore, a threshold is typically defined as a stimulus intensity that is detected 50% of the time.[79] The gold standard for perceptual threshold testing is the method of constant stimuli. This method can be described as five or more stimuli that are presented at least 20 times each, in a random order.[80] This method is quite time consuming which may lead to inaccurate responses in the latter part of the study session or participants may start to lose focus as time goes on which may negatively influence the results. It is not uncommon for studies to examine multiple foot locations,[26,50,53,63] consequently, using this method would in turn, create a very long protocol. Alternatively, what is commonly used is an adaptive procedure, in which the next stimulus intensity is dependent on the previous response of the participant; this adaptive procedure is also referred to as a 4-2-1 stepping algorithm.[81] The initial steps between monofilament intensities are large and gradually decrease with each response to a given stimulus. This allows the investigator to zone in on a participant's perceptual threshold quickly and accurately. Not only does this reduce the amount of time spent collecting data, but also gives comparable results to the method of constant stimuli.[80–83] However, this technique is not perfect. Given the nature of the algorithm, it subjects the results to anticipation bias. In attempts to mitigate this anticipation bias, an additional stepping algorithm is run simultaneously, and is alternated between.[80] Additionally, variables such as environment humidity can also influence the force produced by each monofilament.[80] It was shown that humidity differences can account for up to 35% difference between measured and calculated data; humidity differences disproportionately affect monofilaments with a higher pressure calibration than smaller. This highlights the importance of measuring and controlling environmental factors when using this tool.

1.9 Objective

Understanding how posture influences perceptual threshold of the foot sole may provide useful information regarding mechanoreceptor functionality and have clinical implications for sensation recovery. Although studies have investigated the role of posture using VPTs in seated and standing, the underlying mechanisms as to why this occurs remains unknown and has yet to be tested using light touch stimulation on all major foot locations. Currently, no research has investigated standing LTPTs, or the lateral arch while standing in general. This thesis aims to determine whether the LTPT of the 1st metatarsal, lateral arch, and heel differs between standing, seated, and supine postures in young adults. Using a modified 4-2-1 stepping algorithm, this study will look at perceptual threshold differences for each foot location compared across all postures using Semmes-Weinstein Monofilaments. The main questions this thesis will address are as follows:

1. Is there a significant difference in light touch perceptual threshold between postures for a given foot location?

2. Is there a significant difference in light touch perceptual threshold between foot locations for a given posture?

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Chapter 2 : Posture Dependent Changes in Perceptual Threshold During Light Touch Foot Sole Stimulation

2 Introduction

The CDC reported that falls were the leading cause of death from unintentional injury among older adults in 2020.[1] Injuries due to falls are a multifactorial problem, mainly stemming from impairments in balance, gait, vision, cognition, and muscle strength. Loss of peripheral somatosensory function is particularly prevalent in falls specifically in aging individuals, stroke patients, and people with diabetes and other causes of peripheral neuropathy.[2–4] In individuals with diabetic neuropathy, the observed somatosensory impairments relate to heightened sensory thresholds in mechanoreceptors and alterations in the properties of afferent fibers.[3,5–7] In stroke patients, sensory impairments can arise from a failure to process sensory signals coming from the periphery.[2,8,9] Sensory impairments in older individuals tend to be from a general deterioration or failure in the peripheral nervous system, ultimately resulting in diminished motor performance and poorer postural control.[10,11] Cooling or anaesthetizing the soles of the feet while standing has been shown to increase postural sway.[12,13] However, sensory testing has primarily been conducted in seated or prone postures,[11,14,15] with limited research being done with a standing condition.[16] This research has primarily used vibratory stimulation and has focused on stimulating the heel and metatarsals. The soles of the feet encounter more than just vibratory stimulus in everyday life. This indicates a need to understand how other stimulation types, such as light touch, are influenced by postures such as standing. Further understanding how posture modulates foot sole cutaneous afferents and sensation may shed light on how these afferents signal dynamic events while standing and be more indicative of sensory performance in a more naturalistic setting and provide a greater mechanistic understanding of losses in balance in people with impaired postural control.

The soles of the feet are the only contact point with our environment while standing, indicating their importance in processing, and relaying sensory information to the body from our environment. This information is then used to regulate postural control, and gait.[16–19] Within the soles of the feet are mechanoreceptors that enable us to pick up sensory information from the environment. Cutaneous feedback from glabrous skin sensation on the hands and feet is mediated by four types of cutaneous afferents, each with unique characteristics.[20] These include fast adapting (FA) type 1 and type 2 afferents that innervate Meissner corpuscles and Pacinian corpuscles respectively, as well as slow adapting (SA) type 1 and type 2 fibers that innervate Merkel discs and Ruffini endings respectively. FA afferent fibers are particularly sensitive to the rate of change of mechanical stimuli; they tend to fire in the dynamic phases of skin indentation (onset and offset of the stimulus). However, firing ceases during sustained indentation. In contrast, SA afferents continue to fire during sustained stimulus indentation and skin stretch.[20–22] There is a decline in cutaneous sensitivity across FA afferents in older adults compared to younger adults, which is speculated to lead to the impairments shown in postural control.[11,14] Using microneurography, it has been shown that stimulation using monofilaments activate FA afferents prior to SA afferents, suggesting that FA afferents are most likely to mediate monofilament perceptual threshold.[23]

Semmes-Weinstein Monofilaments have been used to assess perceptual thresholds in young adults, older adults, and individuals with neurological disorders.[14,23–26] Previous research has shown that sensory perception declines with age, and in adjunct with various neurological disorders.[2,6,11] However, research utilizing properties of cutaneous receptors within the foot sole have created insoles that have been shown to positively modulate gait and balance parameters in older adults, stroke patients, and people with peripheral neuropathy.[27–31] The ability to modulate gait and balance parameters utilizing foot sole somatosensory qualities provides a potent avenue for enhancing balance and gait, and reducing the risk of falls. Still, it is not well understood how sensation is affected by an upright posture.

Changes in stimulus perception across postures may be due to one of, or a combination of central and peripheral factors. Previous literature has investigated vibratory perceptual threshold (VPT) on the metatarsals and heel, in standing and seated postures across various frequencies.[16] It was found that VPT was increased in a standing vs. seated posture for all frequencies and foot locations. These differences are thought to be attributed to tissue stiffness differences due to the increased pressure on the foot sole, which may alter the stimulation transmission to cutaneous afferents,[32] but are not known for certain. Another hypothesis is the possible adaptation to the static pressure while standing, which may influence the foot's ability to respond to dynamic stimulation. However, this is unlikely the case due to FA afferents filtering static stimuli and preferentially responding to dynamic stimuli.[33] In fMRI research, it was shown that the foot has relatively low somatotopic selectivity compared to the hand.[34,35] Stimulation detection thresholds may be modified with changes in posture, similar to the gating of tactile feedback,[36] as well as the increase in threshold that occurs during muscle contraction and movement.[37] These central factors may be relevant in explaining the differences in perceptual threshold between postures due to the body not being able to easily distinguish between stimulation at a specific foot site compared to the additional sensation associated with standing.

As of now, foot sole light touch perceptual threshold (LTPT) while standing has yet to be investigated, which may be important for understanding the mechanism and functional significance of cutaneous feedback relied upon for posture and gait. The aim of this study was to compare LTPTs for the heel, first metatarsal, and lateral arch in standing, seated, and supine postures. Due to the peripheral factors such as increased pressure, and central factors such as low somatotopic selectivity and the gating of tactile feedback, it was hypothesized that LTPT levels at the foot sole would increase for all foot locations going from a supine, to a seated, then to a standing posture.

2.1 Methods

2.1.1 Participants

25 young adults (13 male), ages 20-28 with a mean age of 23.8 years old (SD = ±2.19) participated in the study. Participants were recruited from Western University's mass email recruitment list, as well as posters put up in the Western Interdisciplinary Research Building in London, ON. Participants were free of any neurological conditions that might affect gait or attention and were able to understand and follow instructions in English. All participants provided informed written or electronic consent, and the study was approved by Western University, Health Science Research Ethics Board (Appendix A).

2.1.2 Data collection process

Baseline Tactile Semmes-Weinstein Monofilaments (20-Piece Set) were used to stimulate the foot sole during standing, seated, and supine postures. Perceptual threshold data were collected on the right foot sole for all participants.[38] As a control condition, the lateral side of the right distal index finger was also stimulated in seated and supine postures. For perceptual threshold testing in the supine posture, the participants were directed to lie flat on their back and fixate their gaze towards the ceiling, with their feet positioned just at the edge of the plinth. For the seated posture, participants sat on a foldable chair to support the weight of their upper body and had their legs at a 90-degree angle. In perceptual threshold testing for seated and standing postures, the participants were positioned to have their feet on a custom-made wooden box with one exterior wall removed. The box had an interior central wooden support to ensure the box would withhold larger participants. On top of the wooden box, there were three drilled holes 2mm in diameter[16] (Figure 1), with the interior side of the hole having a beveled edge to allow the monofilament to bend. For seated and standing postures participants were instructed to fixate their gaze on the wall in front of them. While seated, participants were instructed to sit upright with their hands either on their lap or at their sides so that they were not leaning and applying pressure on their legs. For the standing condition, participants were instructed to stand upright without leaning and applying more force on one leg. Data collection took place in a quiet, temperature-controlled room in the Neurorehabilitation Physiology Lab at Parkwood Institute. The room was only occupied by the participant and two research assistants. The first research assistant was responsible for measuring the location of the stimulation sites[38] (Figure 2), as well as delivering the stimulus. The second research assistant was positioned behind an opaque screen and was responsible for managing data collection, monofilament selection, and communicating catch trials. Catch trials were communicated between research assistants via soft taps on the hand of the research assistant delivering stimulus behind the opaque screen. The first research assistant positioned the participants' feet so that the stimulation location lined up with the most convenient hole on the custom box. Before beginning data collection, the participants had one monofilament tested on their hand so they knew what an example stimulation would feel like. Participants were told to focus on the stimulation as much as they could. When it was time to deliver the stimulus, the monofilament was inserted through the hole and approached approximately 3cm of the tested site, and slowly brought towards the skin. Prior to stimulation, the first researcher would count down from three, then stimulate the foot (1 sec on) and follow up by asking the participant if they felt the stimulation or not. The participant would either give a yes or no answer, and that would dictate the following stimulus. Participants were instructed to be at least 90% confident in their responses, and were made aware of the existence of catch trials prior to beginning data collection, similar to previous studies.[23] Monofilament stimulations were applied carefully to avoid any lateral movements or brushes across the skin.

As the perceptual threshold has been shown to change with variation in skin temperature,[39] and monofilament force calibration with room humidity,[40] these were recorded prior to testing for each condition using a MAXIMUM No-Contact Infrared Thermometer. Room ambient temperature was also recorded for consistency. The margin of error for this device is ±2°C.

Figure 1: Top-down view of the box used for seated and standing postures. Each hole is 2mm in diameter and were distributed evenly on each half of the box.

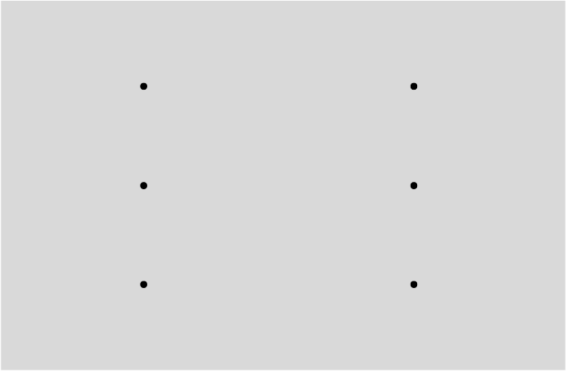
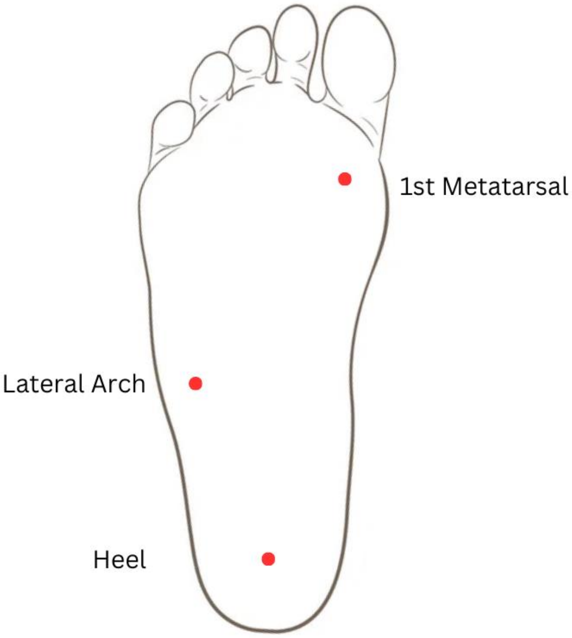


Figure 2: Foot sole test locations. The heel location was marked 15% anteriorly along the length of the foot and 50% the width. The lateral arch location was marked 15% the along the width of the the center of the arch from the lateral border, and 50% the length from the base of the heel to the 5th metatarsophalangeal joint. The 1st metatarsal was 15% the length along the metatarsals from the medial

boarder and 15% the length from the base of the heel to the 1st metatarsophalangeal joint.



2.1.3 Randomization

In attempt to remove any potential order effects, the order of posture and foot location conditions were randomized for each participant. First, the posture being assessed was determined. Next, all three sites were collected for the given posture before moving onto the next. The hand trials were always the last condition for the respective posture. This procedure was chosen to balance between study randomization and duration of study appointments; switching between postures takes a significant amount of time. Randomization was achieved using a custom excel script.

2.1.4 Perceptual threshold testing

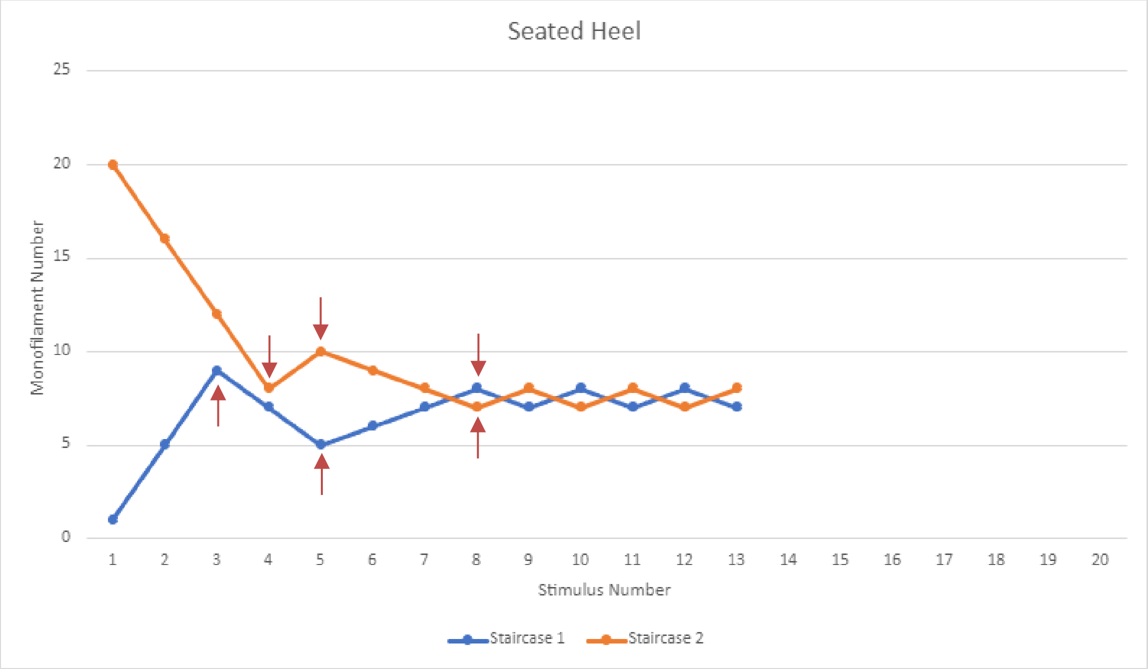
A set of 20 Semmes-Weinstein Monofilaments ranging from 0.008 grams to 300 grams were used for determining the perceptual thresholds for each postural, and foot location conditions. The monofilaments come pre-calibrated to deliver a specific amount of force with each application. An application was considered successful if during the application, the monofilament was applied with a force great enough to surpass its bending threshold. Semmes-Weinstein Monofilaments are designed so that with any amount of bending the monofilament endures, it will apply the same amount of pressure.

A modified 4-2-1 stepping algorithm[23,24,40] was used to assess the participants' perceptual thresholds in a reliable and timely manner. The modified stepping algorithm consists of two interwoven staircases: a top-down staircase, and a bottom-up staircase (Figure 3). The top-down staircase starts at the thickest monofilament (300 grams), and the bottom-up staircase at the thinnest monofilament (0.008 grams). For this procedure, each monofilament was assigned its own number or "step", with step number one being the lightest monofilament, to step 20 being the thickest. Regarding the top-down staircase, if the participant answered "yes" to feeling the first stimulation, the next monofilament used would be four steps lighter. This process continues until the participants say they did not feel the stimulus. This point – where the given response did not match the previous response – is known as a "turnaround point". After the first turnaround point in the top-down series, the stimulus intensity increased by two steps until they started to feel the stimulation again, this would be the second turnaround point. After the second turnaround point, stimulus intensity then decreased by only one step. All subsequent turnaround points for the given staircase increased or decreased by one step until the algorithm was finished. Each staircase required eight turnaround points before ending. The bottom-up staircase followed the same stepping algorithm, except started at step one (lightest monofilament) and started with an increase in intensity.

The two staircases were interwoven such that each stimulation alternated between the top-down, and bottom-up staircase. This allowed the two staircases to be conducted in parallel, while remaining independent from one another. The interweaving of the staircases also served to help prevent anticipation bias, such that the participant was more likely to perceive the stimulation intensity as random rather than a definite or set pattern. The stepping algorithm was recorded on a custom excel spreadsheet that was designed to automatically compute the next monofilament thickness depending on whether the participant felt the previous stimulation or not, as well as when enough turnaround points were encountered.

To discourage participants from guessing whether they felt the stimulation or not, catch trials were implemented into the protocol. A catch trial would follow the exact same procedure as a typical trial, but no stimulus would be delivered. Five catch trials were pseudo randomly implemented into the stepping algorithm discussed above. The first catch trial was always within the first three stimulations, with the other four catch trials being distributed throughout the first 20 trials. The randomization was completed one time for each of the sites in each of the postures. The order of the catch trials was the same between participants.

Figure 3:An example of a modified 4-2-1 stepping algorithm for the heel while seated. The orange line represents the "top-down" staircase, and the blue the "bottom-up" staircase. Red arrows are pointing to the first three turnaround points.



2.1.5 Perceptual threshold determination

For each site and postural condition, the perceptual threshold was calculated as the average force applied at the last five turnaround points for each staircase, totaling 10 turnaround points between both staircases. The first three turnaround points were not used in the calculation due to the stepping algorithm requiring a deviation of more than one step. In theory, the final five turnaround points should be alternating around the participants' perceptual threshold. If a participant failed more than one catch trial in a condition, that condition was excluded.[24,40]

2.1.6 Statistical analysis

Raw data from the stepping algorithm was first converted into grams for each participant before running statistical analyses. Two-way repeated measures analysis of variance (ANOVA) tests were performed to assess whether the perceptual threshold varied significantly with posture at a given foot location, using an a priori significance level of $p < 0.05$. Additional analyses were carried out to examine if the perceptual threshold differed significantly across different sites within the same posture, with significance also assessed at $p < 0.05$. Post-hoc pairwise comparisons were performed using the IBM SPSS Statistics software (version 29.0.2.0 (20)), and p-values were adjusted using the Bonferroni method.

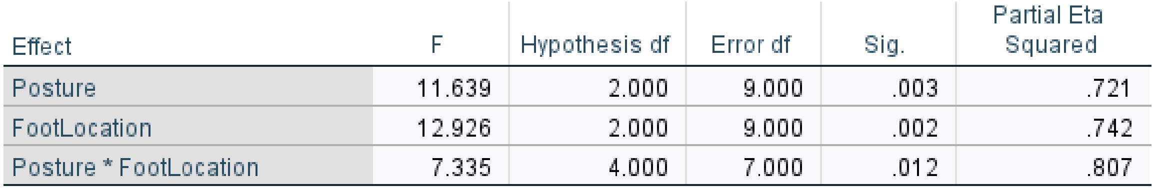
2.2 Results

Average foot sole temperature was 26.6 °C and ranged between 23.1-29.6°C, which is normal for a healthy population.[41] Six participants' data were excluded from this study, n=5 were excluded due to an insufficient number of data points to accurately determine their perceptual threshold, and n=1 did not adhere to the protocol (n = 19, 9 Male). Previous literature with similar procedures to this study have removed outliers defined as ±3 SD from the mean.[38] For this study, only the outliers that were ±5 SD from the mean were removed (14 of 190 data points) to include as much data as possible since 6 participants' data could not be used. This meant that four outliers that fell outside of the ±3 SD range but inside the ±5 SD range were included in analysis. Six of the 14 data points were from the same participant who had much higher perceptual thresholds across all conditions, and 6 in total coming from the metatarsal foot location. There were no sex differences in perceptual threshold for any postural or foot location condition ($p > 0.05$). Male and female participants were combined for data analysis.

2.2.1 Perceptual threshold testing

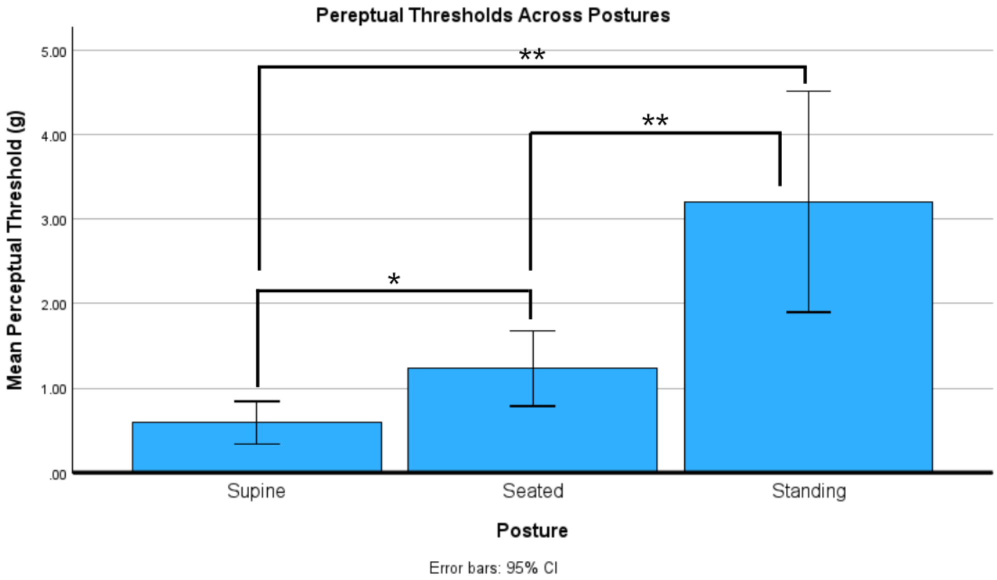
Across all foot sole locations, light touch perceptual threshold (LTPT) was higher in the standing posture compared to the seated and supine posture, and higher in the seated posture compared to the supine posture. Full ANOVA results for the foot can be seen in Table 1. There were was no significant differences found between each of the hand conditions ($F(1,19) = 0.0516$, $p = 0.8227$, $\eta^2 = 8.5563e-06$) so it was not further explored. Statistically, there were significant main effects of posture on LTPT ($F(2,9) = 11.639$, $p = 0.003$, $\eta^2 = 0.721$). Post hoc analyses indicated higher thresholds (lower sensitivity) while standing compared to seated ($p = 0.008$), and supine ($p = 0.002$), as well as seated compared to supine ($p = 0.036$) across all foot locations (Figure 4).

Table 1: Two-way repeated measures ANOVA results



Effect	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Posture	11.639	2.000	9.000	.003	.721
FootLocation	12.926	2.000	9.000	.002	.742
Posture * FootLocation	7.335	4.000	7.000	.012	.807

Figure 4: Perceptual threshold estimate marginal means for each posture in grams (statistical significance is indicated as *p < 0.05, **p < 0.01, ***p < 0.001). Homogeneity of variance was tested with Mauchly's test for sphericity, and greenhouse geisser corrections were applied to the data.



There was a statistically significant main effect of foot location on perceptual threshold as well (F(2,9) = 12.926, p = 0.002, η² = 0.742). Post hoc analyses indicated significantly higher LTPTs at the heel compared to both the 1st metatarsal (p = 0.002) and lateral arch (p = <0.001), and at the 1st metatarsal compared to the lateral arch (p = 0.006) (Figure 5). A significant interaction effect between posture and foot location was observed (F(4,7) = 7.335, p = 0.012, η² = 0.807). This interaction can be broken down into two separate graphs to examine the perceptual threshold differences for all foot locations for each posture (Figure 6), as well as the perceptual threshold differences for all postures for each foot location (Figure 7). For the first comparison (Figure 6), post hoc analyses showed there were significant differences within all three postures. While standing, there were significant differences between the heel and both the 1st metatarsal (p = 0.013) and lateral arch (p = 0.002), as well as between the 1st metatarsal and lateral arch (p = 0.015). For the seated posture, there were significant differences between the heel and both the 1st metatarsal (p = 0.003) and the lateral arch (p = 0.002), as well as between the 1st metatarsal and lateral arch (p = 0.004). Lastly, for the supine posture there were significant differences between the lateral arch and heel (p = 0.017) and 1st metatarsal (p = 0.004), but not between the heel and 1st metatarsal (p = 0.195).

Figure 5: Estimated marginal means perceptual threshold for each foot location (statistical significance is indicated as *p < 0.05, **p < 0.01, ***p < 0.001). Homogeneity of variance was tested with Mauchly's test for sphericity, and greenhouse geisser corrections were applied to the data.

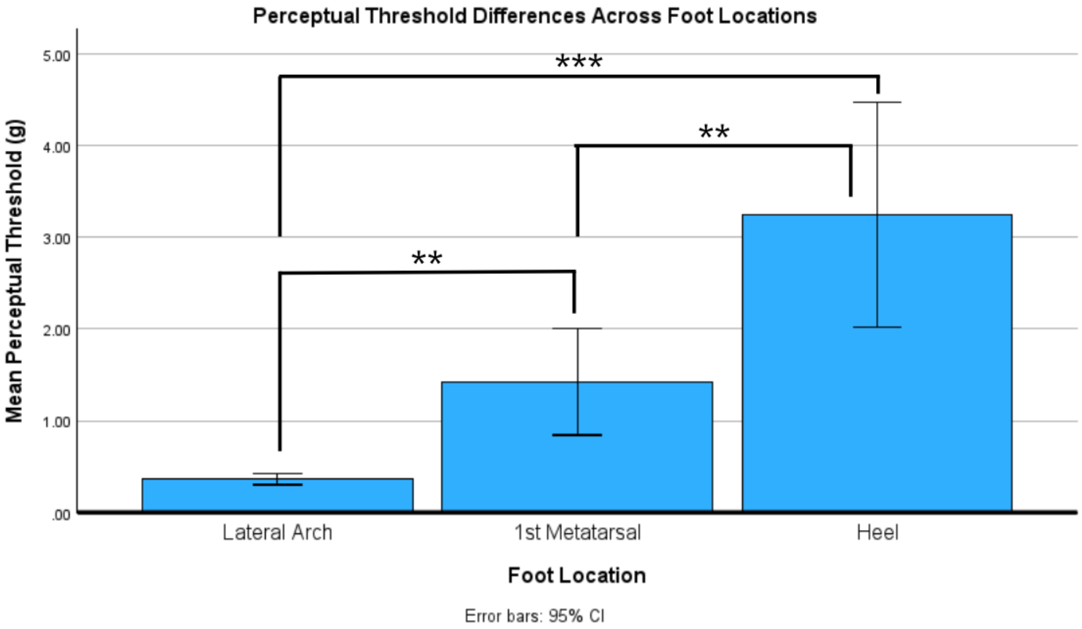
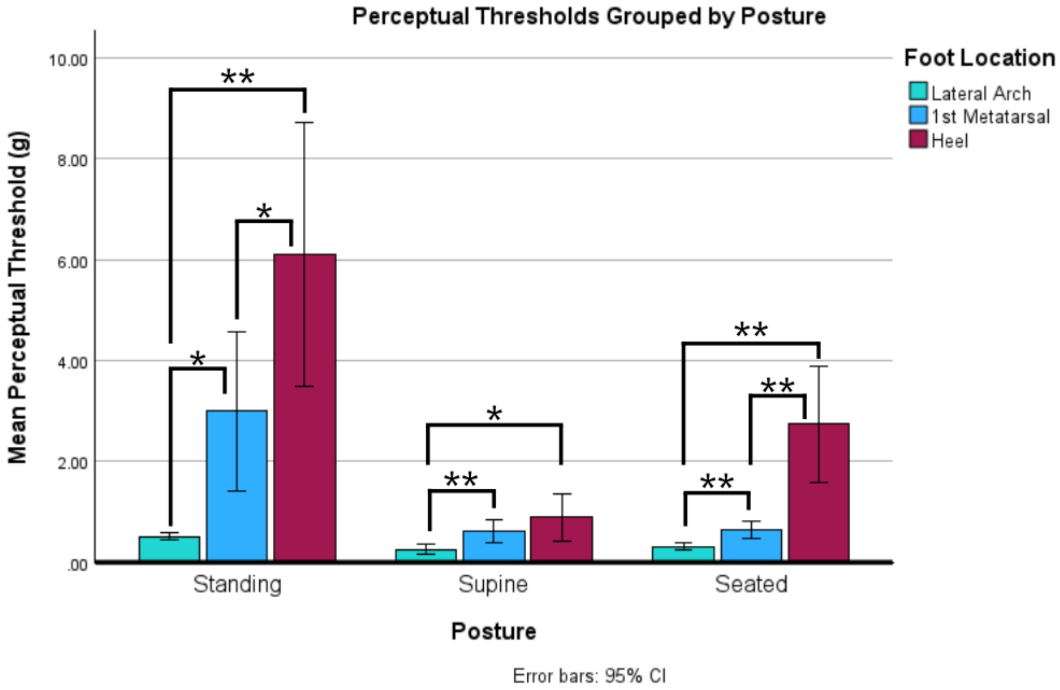
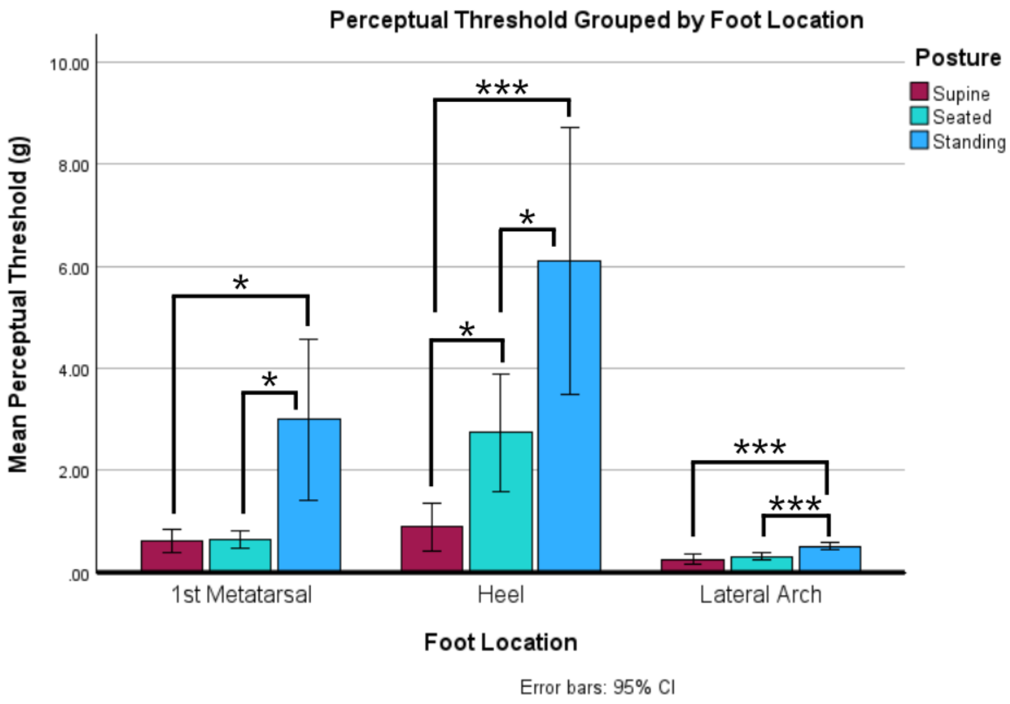


Figure 6: Estimated marginal means perceptual threshold comparisons grouped by posture (statistical significance is indicated as *p < 0.05, **p < 0.01, ***p < 0.001)



For the second comparison (Figure 7), post hoc analyses showed significant differences in perceptual threshold at the 1st metatarsal between standing and both seated (p = 0.016) and supine (p = 0.020) postures, but not between seated and supine postures (p = 1.0). The same can be said about the lateral arch, with significant differences being found between both standing and seated (p = 0.001) and supine (p = 0.001) postures, but not between seated and supine postures (p = 0.833). Lastly, for the heel, significant differences were found between standing and both supine (p = 0.001) and seated (p = 0.024) postures, as well as between seated and supine postures (p = 0.014). Across all participants, only eight out of 1045 total catch trials were failed with two coming from the hand conditions and six coming from the foot conditions.

Figure 7: Estimated marginal means perceptual threshold comparisons grouped by foot location (statistical significance is indicated as *p < 0.05, **p < 0.01, ***p < 0.001)



2.3 Discussion

This study aimed to investigate the effects of posture on the light touch perceptual threshold (LTPT) of the foot sole in young adults across various postures and foot locations. This is the first study to examine the LTPT while standing, as well as the perceptual threshold of the lateral arch while standing with any stimulation modality.

2.3.1 Posture dependent changes in light touch perceptual threshold

In this experiment, perceptual threshold was measured at the foot sole in three different locations (heel, 1st metatarsal, and the lateral arch). These locations were chosen due their receptor density differences,[23] and their weight-bearing role in upright posture regulation.[42] Standing, seated, and supine postures were also specifically chosen due to the unique physical characteristics these positions apply to the foot sole. In the supine posture, the participant's foot sole was free of any pressure or surface contact, with the only stimulation being the monofilament. The seated posture provided an environment where the foot sole had full surface contact with the wooden box, but only had slight pressure from the weight of the lower limb. Lastly, the standing posture had the full weight of the participant as well as surface contact from the wooden box. Utilizing Semmes-Weinstein Monofilaments we found significant differences in LTPT across most postural and foot location conditions, indicating a potential influence of body posture on sensory perception at the foot sole. For most foot locations the largest perceptual threshold was found while standing, followed by seated, then supine for each foot location except for the 1st metatarsal and heel. Similar results have been shown previously using vibrations instead of light touch.[38] For all postures, the lateral arch was the most sensitive, followed by the 1st metatarsal and lastly the heel, with the largest differences coming from within the seated and standing postures. Again, similar results have been shown previously while using vibrations instead of light touch,[16,38] further supporting the idea that posture can modulate sensory perception.

2.3.2 Possible mechanisms behind differences in perception across postures

Location differences in sensitivity on the foot sole were originally thought to be due to differences in the density of receptors at different locations of the foot sole.[43] However, recent literature refutes this showing the medial arch to be the most sensitive part of the foot despite having the lowest density of receptors.[44] Previous research has explored various factors contributing to the varying sensitivity across the foot sole, including the impact of mechanical differences at different locations. A study found that the mechanical characteristics of the skin on different parts of the foot correlate with both the sensitivity threshold and the initial firing of FAI afferents.[23] Specifically, the skin on the medial arch is the softest part of the foot sole, whereas the skin on the heel is the hardest.[38,45] This suggests that the perception of touch through FAI afferents is influenced more by mechanical properties than by the density of those areas. Other mechanisms that may be responsible for these changes are thought to be due to peripheral factors such pressure, skin stretch, and tissue stiffness.[32,38,46] The role of skin's mechanical properties in explaining the variations in sensitivity between the glabrous on the feet and hands, as well as among different areas of the foot sole, has been suggested in previous studies.[43,47] Most research to this point has utilized computer simulations and animal studies to explore how the mechanics of the skin affect both afferent responses and perceptual sensitivity thresholds. For instance, studies using a biomechanical model of the fingertip have demonstrated that the mechanical characteristics of the skin can influence how mechanical vibrations are conveyed to the mechanoreceptors beneath the skin.[48]

Central mechanisms, such as changes in body posture, can alter detection thresholds for stimulation, akin to how tactile feedback is modulated.[36] This is similar to the observed increase in threshold during muscle contraction and movement seen in both monkeys and humans.[37,49] In brain imaging studies, the foot displays less somatotopic selectivity compared to the hand. This indicates that stimulating one area on the foot sole is likely to activate adjacent cortical areas such as the toes, sole, and heel in the primary somatosensory cortex.[34,35] This phenomenon could help explain why perceptual thresholds vary with posture, as the brain may find it challenging to differentiate between stimuli at a specific site on the foot and the broader sensations associated with standing. These areas show more specific activation patterns during stimulation and do not activate the foot's somatotopic areas, highlighting a difference in how the brain processes stimuli related to different body parts.

As previously stated, physical properties of the foot sole such as tissue stiffness differences and increased pressure on the foot sole may also play a role in the observed changes by altering stimulus transmission to the cutaneous afferents.[32] Weight distribution changes between postures may be a contributing factor in the results of this study. A study found that the majority of the body’s weight is transferred through the heel (60.5%), the midfoot (7.8%) and through the forefoot (28.1%) while standing.[42] These pressure and pressure related mechanical skin changes in stance may be a primary driving factor for the perceptual threshold differences seen between each of the foot locations across the postures. The lateral arch had the lowest magnitude of change, followed by the metatarsal, then the heel (Figure 7). The only significant difference in perceptual threshold between the lateral arch and 1st metatarsal regarding postural changes was between standing and supine. These differences may be explained partly by the pressure changes the foot undergoes as previously alluded to. Pressure minimally increases in these two foot locations going from a supine to seated posture, but are partly responsible, and increase somewhat proportionately for the weight going through each foot location while standing. This idea can be further supported by what we saw at the heel across postural conditions (Figure 7). There was consistent and gradual, significant increase in perceptual threshold going from a supine to seated and seated to standing posture. The heel is responsible for most of the weight of the lower limb in a normal seated position, which may be responsible for the difference seen in the supine to seated condition. The heel also bears most of the body's weight while standing,[42] which might explain the significant increase in perceptual threshold in the seated to standing postural comparison. Increased weight-bearing through the forefoot and heel may also lead to increased skin hardness due to callouses. Skin hardness has also been shown to negatively influence foot sole perceptual threshold.[38] However, since we did not control for skin hardness, and are unable to control for possible central factors, we are unable to make and conclusions about the possible mechanisms responsible for the changes in perceptual threshold across foot locations and postures.

2.3.3 Limitations

This is the first time LTPT has been examined in a standing. However, it did come with some limitations. Future studies should incorporate a larger sample size to help determine if the outliers encountered in this study were anomalies or were caused by an inherent flaw in study design and/or tools used. Measures for skin hardness and thickness should be taken to rule out the relationship between changes in perceptual thresholds with posture. It may be beneficial to have a shorter study duration (>1 hour) to help with maintaining attention, as well as a measure of attention throughout the study. Attention has been shown to modulate perceptual threshold,[50] thus, may be possible explanation for some of the outliers due to a loss off attention from a lengthy and repetitive protocol. A participant's loss of attention may cause inconsistent perceptual thresholds and is thought to be shown when comparing participant's increased thresholds in specific conditions against the more uniform thresholds observed in their other assessments. For example, a participant may have a perceptual threshold of 1g at the heel (least sensitive location), while standing (least sensitive posture) but had a perceptual threshold of 40g on the lateral arch (most sensitive foot location) while seated (second most sensitive posture), while producing "normal" perceptual thresholds for the lateral arch across the other two postures. Regarding the one participant who produced numerous significant outliers, these differences may be due to unknown underlying sensory and/or attentional deficits, or an anomaly with substantially higher skin hardness or thickness than average. However, previous research suggests that skin hardness and thickness have a minor influence on monofilament perceptual thresholds in young adults.[38] We are unable to determine the exact causes with our study design.

2.4 Conclusion and future directions

Foot sole perceptual threshold has never been measured on a fully loaded foot using light touch, and never on the lateral arch while standing with any perceptual threshold testing method. Using a modified 4-2-1 stepping algorithm with Semmes-Weinstein Monofilaments, we were able to show that there are perceptual threshold differences across all postural comparisons for the heel, and in standing versus supine for the lateral arch and first metatarsal. This suggests that variations in weight-bearing pressure across different postures at each foot location may provide a viable explanation for the perceptual differences observed in this study, as well as in the existing body of literature on this topic.[16,23] Cutaneous afferents innervating the foot sole have been shown to be influential in postural control, and gait,[51–53] and are able to be modulated to enhance balance and gait parameters.[27–29] Further understanding of how sensory perception of the foot sole changes while standing may help guide current rehabilitation practices aimed at regaining functional sensitivity in a clinical setting or older adults, and products aiming to enhance balance and gait outcomes.[27,28,30]

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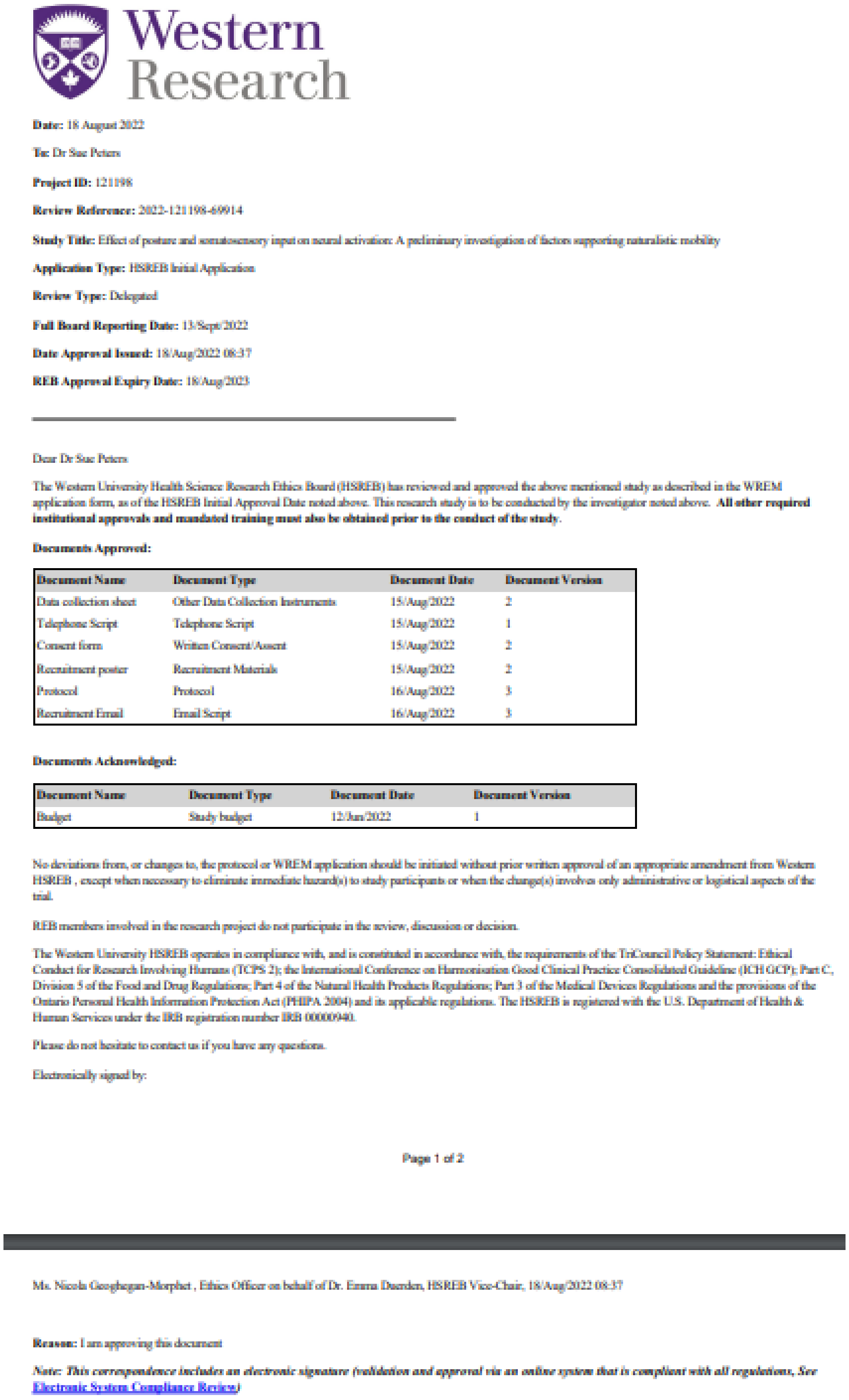
Appendices

Appendix A: Approval from the Western University Health Sciences Research Ethics Board.



Western Research

Date: 18 August 2022

To: Dr Sue Peters

Project ID: 121198

Review Reference: 2022-121198-69914

Study Title: Effect of posture and somatosensory input on neural activation: A preliminary investigation of factors supporting naturalistic mobility

Application Type: HSREB Initial Application

Review Type: Delegated

Full Board Reporting Date: 13/Sept/2022

Date Approval Issued: 18/Aug/2022 08:37

REB Approval Expiry Date: 18/Aug/2023

Dear Dr Sue Peters

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above mentioned study as described in the WREM application form, as of the HSREB Initial Approval Date noted above. This research study is to be conducted by the investigator noted above. **All other required institutional approvals and mandated training must also be obtained prior to the conduct of the study.**

Documents Approved:

Document Name	Document Type	Document Date	Document Version
Data collection sheet	Other Data Collection Instruments	15/Aug/2022	2
Telephone Script	Telephone Script	15/Aug/2022	1
Consent form	Written Consent/Assent	15/Aug/2022	2
Recruitment poster	Recruitment Materials	15/Aug/2022	2
Protocol	Protocol	16/Aug/2022	3
Recruitment Email	Email Script	16/Aug/2022	3

Documents Acknowledged:

Document Name	Document Type	Document Date	Document Version
Budget	Study budget	12/Jun/2022	1

No deviations from, or changes to, the protocol or WREM application should be initiated without prior written approval of an appropriate amendment from Western HSREB , except when necessary to eliminate immediate hazard(s) to study participants or when the change(s) involves only administrative or logistical aspects of the trial.

REB members involved in the research project do not participate in the review, discussion or decision.

The Western University HSREB operates in compliance with, and is constituted in accordance with, the requirements of the TriCouncil Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2); the International Conference on Harmonisation Good Clinical Practice Consolidated Guideline (ICH GCP); Part C, Division 5 of the Food and Drug Regulations; Part 4 of the Natural Health Products Regulations; Part 3 of the Medical Devices Regulations and the provisions of the Ontario Personal Health Information Protection Act (PHIPA 2004) and its applicable regulations. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Please do not hesitate to contact us if you have any questions.

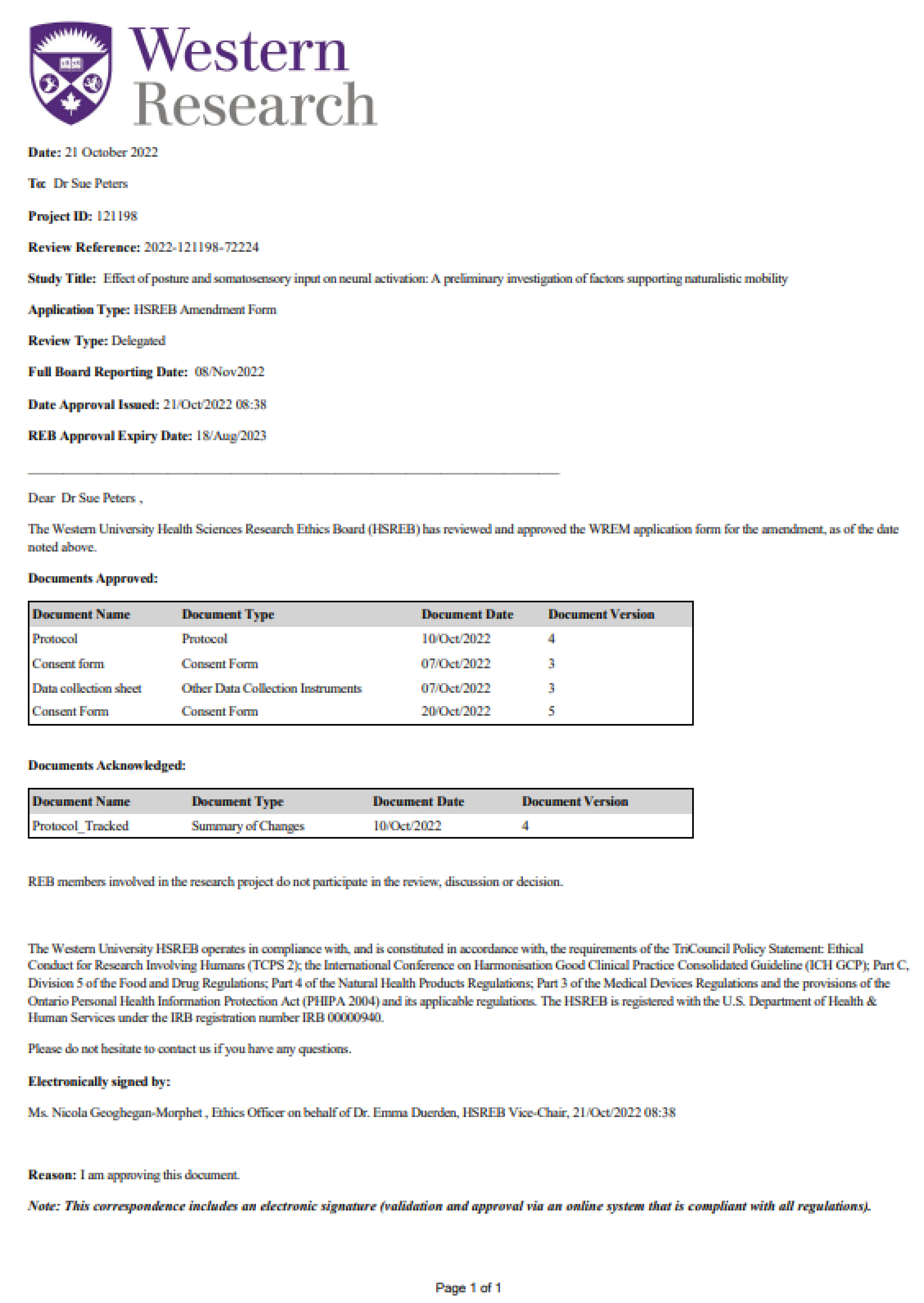
Electronically signed by:

Page 1 of 2

Ms. Nicola Geoghegan-Morphet , Ethics Officer on behalf of Dr. Emma Duerden, HSREB Vice-Chair, 18/Aug/2022 08:37

Reason: I am approving this document

Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations, See Electronic System Compliance Review)



Western Research

Date: 21 October 2022

To: Dr Sue Peters

Project ID: 121198

Review Reference: 2022-121198-72224

Study Title: Effect of posture and somatosensory input on neural activation: A preliminary investigation of factors supporting naturalistic mobility

Application Type: HSREB Amendment Form

Review Type: Delegated

Full Board Reporting Date: 08/Nov2022

Date Approval Issued: 21/Oct/2022 08:38

REB Approval Expiry Date: 18/Aug/2023

Dear Dr Sue Peters ,

The Western University Health Sciences Research Ethics Board (HSREB) has reviewed and approved the WREM application form for the amendment, as of the date noted above.

Documents Approved:

Document Name	Document Type	Document Date	Document Version
Protocol	Protocol	10/Oct/2022	4
Consent form	Consent Form	07/Oct/2022	3
Data collection sheet	Other Data Collection Instruments	07/Oct/2022	3
Consent Form	Consent Form	20/Oct/2022	5

Documents Acknowledged:

Document Name	Document Type	Document Date	Document Version
Protocol_Tracked	Summary of Changes	10/Oct/2022	4

REB members involved in the research project do not participate in the review, discussion or decision.

The Western University HSREB operates in compliance with, and is constituted in accordance with, the requirements of the TriCouncil Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2); the International Conference on Harmonisation Good Clinical Practice Consolidated Guideline (ICH GCP); Part C, Division 5 of the Food and Drug Regulations; Part 4 of the Natural Health Products Regulations; Part 3 of the Medical Devices Regulations and the provisions of the Ontario Personal Health Information Protection Act (PHIPA 2004) and its applicable regulations. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Please do not hesitate to contact us if you have any questions.

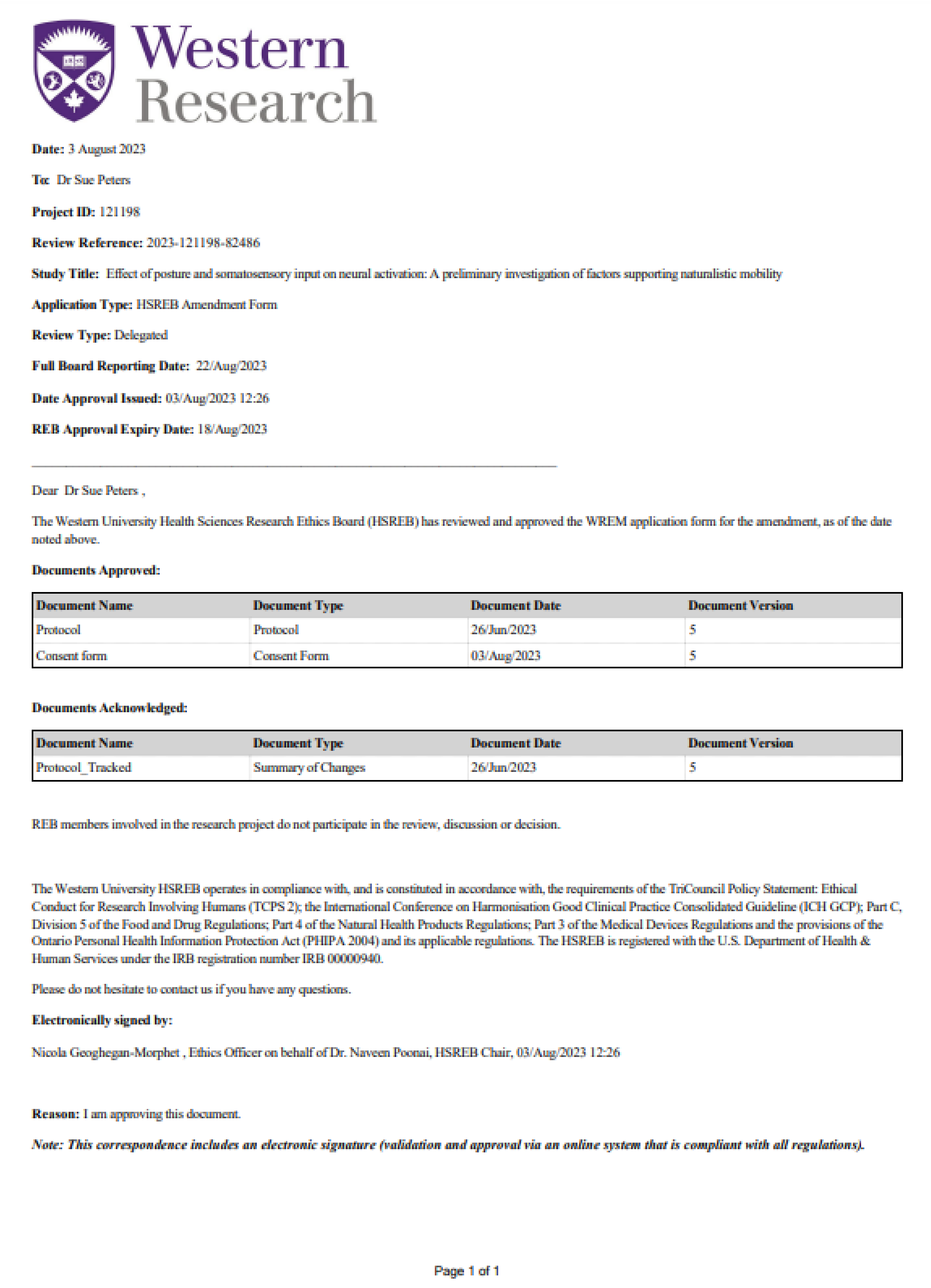
Electronically signed by:

Ms. Nicola Geoghegan-Morphet , Ethics Officer on behalf of Dr. Emma Duerden, HSREB Vice-Chair, 21/Oct/2022 08:38

Reason: I am approving this document.

Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).

Page 1 of 1



Date: 3 August 2023

To: Dr Sue Peters

Project ID: 121198

Review Reference: 2023-121198-82486

Study Title: Effect of posture and somatosensory input on neural activation: A preliminary investigation of factors supporting naturalistic mobility

Application Type: HSREB Amendment Form

Review Type: Delegated

Full Board Reporting Date: 22/Aug/2023

Date Approval Issued: 03/Aug/2023 12:26

REB Approval Expiry Date: 18/Aug/2023

Dear Dr Sue Peters ,

The Western University Health Sciences Research Ethics Board (HSREB) has reviewed and approved the WREM application form for the amendment, as of the date noted above.

Documents Approved:

Document Name	Document Type	Document Date	Document Version
Protocol	Protocol	26/Jun/2023	5
Consent form	Consent Form	03/Aug/2023	5

Documents Acknowledged:

Document Name	Document Type	Document Date	Document Version
Protocol_Tracked	Summary of Changes	26/Jun/2023	5

REB members involved in the research project do not participate in the review, discussion or decision.

The Western University HSREB operates in compliance with, and is constituted in accordance with, the requirements of the TriCouncil Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2); the International Conference on Harmonisation Good Clinical Practice Consolidated Guideline (ICH GCP); Part C, Division 5 of the Food and Drug Regulations; Part 4 of the Natural Health Products Regulations; Part 3 of the Medical Devices Regulations and the provisions of the Ontario Personal Health Information Protection Act (PHIPA 2004) and its applicable regulations. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Please do not hesitate to contact us if you have any questions.

Electronically signed by:

Nicola Geoghegan-Morphet , Ethics Officer on behalf of Dr. Naveen Poonai, HSREB Chair, 03/Aug/2023 12:26

Reason: I am approving this document.

Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).

Page 1 of 1

Curriculum Vitae

Name:	Justin Watts
Post-secondary Education and Degrees:	University of Western Ontario London, Ontario, Canada 2016-2020 B.A. Honours Specialization in Kinesiology
	The University of Western Ontario London, Ontario, Canada 2022-Present M.Sc. Neuroscience Candidate
Honours and Awards:	Dean’s Honour List Western University 2019-2020
Related Work Experience	Graduate Research Assistant Neurorehabilitation Physiology Lab The University of Western Ontario 2023-2024
	Teaching Assistant The University of Western Ontario 2022-2023
	Teaching Assistant The University of Western Ontario 2022-2023