EFFECTS OF SENSORY INFORMATION OVER THE MOTOR AND SOMATOSENSORY CORTEX ACTIVITY DURING STANDING

By

JESÚS ALBERTO HERNÁNDEZ SARABIA

Bachelor of Science in Physical Education
Benemérita Universidad Autónoma de Puebla
Puebla, Pue. México
2011

Master of Science in Health and Human Performance
Oklahoma State University
Stillwater, OK
2016

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
May, 2021

EFFECTS OF SENSORY INFORMATION OVER

THE MOTOR AND SOMATOSENSORY CORTEX

ACTIVITY DURING STANDING

Dissertation Approved:

Dr. Jason M. DeFreitas

Dissertation Adviser

Dr. Jay Dawes

Dr. Michael Trevino

Dr. Jennifer Grindstaff

ACKNOWLEDGEMENTS

During my Ph.D. I have learned that the help and support from those who love you are the most important things to graduate; without them, I could not have finished my dissertation and Ph.D.

Firstly, I would like to thank Dr. Jason DeFreitas, for his help and advice, not only during my dissertation but also during y Ph.D. I could not have found a better advisor than him. He has always been willing to help and talk, no matter the time of the day. Secondly, I would like to thank all my lab mates who were always willing to help and be involved in any study; sincerely, I will miss chatting, sharing ideas, sharing frustrations, and collecting data with all of you.

Aside from the lab environment, I would like to thank my family. A mi papá y mamá que se han preocupado por brindarme el mejor regalo del mundo desde el primer día en que abrí los ojos, educación. A mi hermano que siempre ha estado a mi lado apoyándome y siendo fuente de inspiración. A mis tíos y primos que siempre me han ayudado a seguir adelante. Aún recuerdo los largos días de mi madre, en los cuales después de trabajar tenía que ir a la universidad por las tardes a estudiar su maestría. Aún recuerdo que mi hermano tuvo que ir a estudiar su maestría a otra ciudad; ¡¡¡GRACIAS!!!

Also, I would like to thank my beautiful wife, Alejandra, who has been walking with me for the last ten years of my life; without her unconditional love and help, all of this would not have been possible. Thank you for always asking questions during our talks; that has helped to improve my research and this dissertation. I love you, and I am looking forward to ten more years walking by your side.

Lastly, this research was made possible by funding through the Doctoral Student Research Grant from the Central States chapter of the American College of Sports Medicine.

Thank you all. My Ph.D. could not have been possible without your help.

Name: Jesús Alberto Hernández Sarabia

Date of Degree: MAY, 2021

Title of Study: EFFECTS OF SENSORY INFORMATION OVER THE MOTOR AND SOMATOSENSORY CORTEX ACTIVITY DURING STANDING

Major Field: HEALTH, LEISURE AND HUMAN PERFORMANCE

Abstract: The purpose of this study was to identify changes in cortical hemodynamics of motor and somatosensory cortex related to balancing tasks during inhibition of muscle spindles and cutaneous receptors of the dominant leg. Data were obtained from twelve participants (age: 24.8±4.59 years). The study consisted of four randomized order visits to identify cortical hemodynamic changes while standing under normal conditions (Ctrl), with muscle spindles inhibited (MSI), with cutaneous receptors inhibited (CB), and with the muscle spindles and cutaneous receptors inhibited (BOTH). Muscle spindles were inhibited by applying five minutes of vibration over the soleus muscle; pre- and post-vibration (MSI and BOTH) H-reflex amplitude was measured for later statistical analysis. Lidocaine was applied and left over the foot sole for 30 minutes; sensitivity threshold and two-point discrimination variables were obtained under normal conditions (Ctrl) and anesthetic effect (CB and BOTH). Cortical hemodynamics were measured using an fNIRS placed over each participant's head while performing two counterbalanced blocks of bipedal and unipedal standing with the eyes closed. During MSI and BOTH, five minutes of vibration were applied before each block of standing tasks. Statistical analysis consisted of performing different repeated measures ANOVA; then, if needed, post-hoc test consisted of several paired samples t-test (corrected for multiple comparisons). Findings revealed that, compared to pre-, H-reflex amplitude was significantly lower after vibration. Lidocaine findings were inconclusive with a higher sensitivity threshold on the heel during BOTH than Ctrl, but two-point discrimination did not show any significant effect among the visits. Body sway was not different among visits but increased from bipedal to unipedal standing. Cortical hemodynamics revealed that mean oxyhemoglobin activity was not different during bipedal standing among the visits, but it was different during visits that inhibited muscle spindles compared to visits that did not inhibit muscle spindles. In conclusion, muscle spindle inhibition of the soleus muscle can alter the motor and somatosensory cortex's cortical hemodynamics during unipedal standing, but these changes did not influence balance performance. Cutaneous block might not be achieved by applying lidocaine over the foot sole for 30 minutes; therefore, conclusions regarding the cutaneous receptors' influence were not possible.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

Table Page

LIST OF FIGURES

CHAPTER I

INTRODUCTION

1.1. Introduction

Based on the early findings of authors like Sherrington (1910), it is commonly accepted that human standing depends mainly on subcortical and spinal components that regulate balance; for example, Magnus (1926) mentioned that "...the whole righting apparatus… is arranged subcortically in the brainstem, and in this way made independent of direct voluntary influences… By the action of the subcortical mechanisms… the different organs are always brought into the normal relation with the external world" (p. 29). In fact, human standing depends on spinal and subcortical components; nevertheless, there seems to be an involvement of the cerebral cortex over maintenance of standing posture, as shown by recent studies from several authors.

Recent advances in technology have made possible to explore, by using non-invasive techniques, the activity of the brain during different tasks. These non-invasive

techniques can be categorized as 1) brain stimulation techniques (e.g., Transcranial Magnetic Stimulation, and transcranial Direct Current Stimulation); and 2) brain imaging techniques (e.g., Electroencephalography, functional Near Infrared Spectroscopy, Magnetic Resonance Imaging, and Positron Emission Tomography). Using transcranial magnetic stimulation, Taube, Schubert, Gruber, Beck, Faist, and Gollhofer (2006) examined the motor cortex's influence over the *soleus muscle* during a postural compensatory task; the main finding was that magnetic stimulation over the motor cortex influences the *soleus muscle* at long-latency responses during perturbations. Using positron emission tomography, Ouchi, Okada, Yoshikawa, Nobezawa, and Futatsubashi (1999) found that neural activity of the brain was different during several tasks (e.g., bipedal standing was related to the activity of the primary and secondary visual cortex, and standing with eyes closed was related to the activity of the prefrontal cortex). Lastly, using functional near-infrared spectroscopy, authors have reported increased activity over the cerebral cortex while comparing different balance tasks vs. regular standing; specifically, increased neural activity has been reported over the frontal cortex, parietal cortex, and temporal cortex during balance tasks (Herold, Orlowski, Börmel, & Müller, 2017; Karim, Fuhrman, Sparto, Furman, & Huppert, 2013; Mihara, Miyai, Hatakenaka, Kubota, & Sakoda, 2008; Takakura, Nishijo, Ishikawa, & Shojaku, 2015).

Bipedal standing not only depends on the central nervous system but also on the peripheral sensors, as shown by Peterka and Loughlin (2004). Located within the skeletal muscle, the muscle spindles can detect muscle length changes to provide kinesthetic information to the central nervous system. Additionally, kinesthetic information can also be provided by skin receptors like Meissner's corpuscles, Merkel's discs, Pacinian

capsules, and Ruffini's endings. Merkel's disks, known to be slow adaptive I, are sensitive to position and velocity. Ruffini's endings, known to be slow adaptive II, are sensitive to stretching and capable of perceiving changes in motion and direction as long as an external force stretches the skin. Lastly, Meissner's corpuscles and Pacinian capsules, known as fast adaptive I and fast adaptive II, respectively, are known to be able to detect vibration changes; specifically, Meissner's corpuscles can detect low-frequency vibration changes, and Pacinian capsules can detect high-frequency vibrations.

In summary, current evidence points towards a major involvement of cortical regions of the brain during balancing tasks (Beloozerova, Sirota, Orlovsky, & Deliagina, 2005; Herold et al., 2017; Karim et al., 2013; Mihara et al., 2008; Takakura et al., 2015; Taube et al., 2006); and towards a correlation of cortical regions of the brain with somatosensory receptors during balance (Goble, Coxon, Van Impe, Geurts, Doumas, Wenderoth, & Swinnen, 2011a; Goble, Coxon, Van Impe, Geurts, Van Hecke, Sunaert, Wenderoth, & Swinnen, 2011b). Nevertheless, to the author's knowledge, evidence of the effects of inhibition of muscle spindles and skin receptors over the motor cortex, premotor cortex, and somatosensory cortex, during different balance tasks, remains to be known.

1.2. Purpose of the Study

The purpose of this study is to identify changes in cortical hemodynamics of the motor, premotor, somatosensory, and somatosensory association cortex, related to balancing tasks during inhibition of muscle spindles and/or inhibition of cutaneous receptors of the dominant limb.

1.3. Research Questions

1. Does inhibition of the muscle spindles of the *soleus muscle* alter the cortical hemodynamics over the motor, premotor, somatosensory, or somatosensory association cortex during balancing tasks?
2. Does inhibition of cutaneous receptors of the foot sole alter the cortical hemodynamics over the motor, premotor, somatosensory, or somatosensory association cortex during balancing tasks?
3. Does the combined effect of inhibition of the muscle spindles from the *soleus muscle* plus inhibition of cutaneous receptors of the foot sole alter the cortical hemodynamics over the motor, premotor, somatosensory, or somatosensory association cortex during balancing tasks?

1.4. Hypotheses

1. Inhibition of the muscle spindles of the *soleus muscle* will alter the cortical hemodynamics over the motor, premotor, somatosensory, or somatosensory association cortex during balancing tasks.
2. Inhibition of cutaneous receptors of the foot sole will alter the cortical hemodynamics over the motor, premotor, somatosensory, or somatosensory association cortex during balancing tasks.
3. The combined effect of inhibition of the muscle spindles of the *soleus muscle* plus inhibition of cutaneous receptors of the foot sole will alter the cortical hemodynamics over the motor, premotor, somatosensory, or somatosensory association cortex during balancing tasks.

1.5. Significance of the Study

There is evidence that proprioception plays a crucial role in balance, and recent brain imaging methods have shown that different cerebral cortex regions might be involved during different balance tasks. Nevertheless, there is scarce evidence showing balance and cortical activity related to somatosensory stimulation. Therefore, being able to describe the hemodynamic response, during inhibition of the muscle spindles and/or cutaneous receptors, of the motor cortex, premotor cortex, somatosensory cortex, and somatosensory association cortex during balance might help to clarify whether or not the neural activity of the cerebral cortex plays a role in balance in the absence of sensory information. Potentially, and because it is known that old adults show decrements in proprioception, this information could be used as a first step to, later, examine whether or not the cerebral cortex of older adults, compared to adults, plays a major role in balance.

1.6. Limitations

- The selection of participants was not truly random; instead, the participants were recruited from the university by posting flyers, advertising the study in classes, and by e-mail.
- The equipment needed to measure hemodynamic response has the following limitations
    - There is no agreement about how the raw signal should be processed and analyzed.
    - Hemodynamic changes over the regions of interest are relative to baseline measurements; therefore, absolute values are not provided.

    - Ideally, a magnetic resonance image (MRI) should be used to select the appropriate location of the optodes relative to the head of the participant; instead, the 10-20 system and the fOLD software were used.
- The effect of local anesthetic remains constant during the experiment.

1.7. Assumptions

- Participants are sincere when they answer health and pain questionnaires.
- Regions of interest are truly the motor, premotor, and somatosensory cortex.
- All equipment functions properly during all testing sessions.
- The effects of prolonged vibration remain the same during data collection as long as vibration is applied during the same time and over the same muscle.

CHAPTER II

REVIEW OF LITERATURE

The literature review is organized in two subsections. The first subsection will explain how standing posture is maintained by the nervous system, emphasizing what parts of the brain have been shown to be active (or not) during standing and how the muscle spindles and skin receptors have been linked to balance. The second subsection will focus on the anatomy and physiology of the muscle spindles and skin receptors and how they can be excited or inhibited. In each subsection, article summaries are provided in chronological order and then a summary at the end.

2.1. The Nervous System and Maintenance of Standing Posture

Sherrington (1910)

In his novel manuscript, Sherrington mentioned that the standing posture of spinal preparations and decerebrate mammals is maintained by the action of muscles that counteract gravity while standing (e.g., biceps femoris anterior, gastrocnemius, and soleus). Moreover, Sherrington observed that if the region between the anterior colliculus and the hind edge of pons was removed, the muscles' tonic activity during standing ceased. Also, he mentioned that standing posture was possible via proprioceptive

afferents, which activate the previously mentioned muscles and inhibit antagonist muscles' action via tonic inhibition.

Magnus (1926)

Commenting on the different results of studies related to maintenance of standing posture in animals, Magnus (1926) pointed out that "...the whole righting apparatus… is arranged subcortically in the brainstem, and in this way made independent of direct voluntary influences… By the action of the subcortical mechanisms… the different organs are always brought into the normal relation with the external world" (p. 29). Specifically, he mentioned that:

- Unlike spinal preparations, where several reflexes can be elicited (e.g., flexion-reflex, extension-reflex, crossed extension reflex) but no standing position can be maintained, decerebrate preparations (brainstem is kept) can maintain the standing posture.

Keck, Pijnappels, Schubert, Colombo, Curt, and Dietz (1998)

Under the assumption that compensatory response, caused by perturbation of human stance, is mediated at the spinal level by the input of group I and II afferents, and not by the motor cortex; the main objective of the study of Keck and colleagues was to determine to what extent leg muscle compensatory response is influenced by corticospinal inputs. Using transcranial magnetic stimulation (TMS), the authors compared the evoked motor responses of perturbations (before and during) with the equivalent electromyography (EMG) activity of voluntary muscle contraction of the *tibialis anterior muscle*. Findings revealed that the mean onset of the compensatory

response of the *tibialis anterior muscle* was 81 ms, and unlike voluntary muscle contraction, the compensatory response showed less facilitation (relation between evoked motor response and EMG); therefore, less cortical influence over the *tibialis anterior muscle* during perturbation of human stance.

Ouchi et al. (1999)

This study's primary purpose was to investigate the neural activity, using positron emission tomography (PET), of different postures. Recruiting 18 healthy participants (31.8 ± 6.5 yrs.), five different position tasks were examined: 1) supine; 2) standing feet together + eyes open (biEO); 3) unipedal standing + eyes open (uniEO); 4) standing in tandem position + eyes open (TandemEO); and standing feet together + eyes closed (biEC).

Compared to supine, biEO showed activity over primary and secondary visual cortex, left cerebellar anterior lobe, and the anterior vermis; uniEO showed activity in the right cerebellar anterior lobe, anterior vermis, and right posterior lobe; TandemEO showed activity in the cerebellar anterior and posterior vermis, and the inferior occipital, and temporal cortex.

Compared to biEO, TandemEO showed activity over the medial longitudinal cerebellar zone and the red nucleus. Also, compared to biEO, biEC caused activity over the bilateral middle frontal gyri.

Grey, Ladouceur, Andersen, Nielsen, and Sinkjær (2001)

Mainly interested in the medium-latency response (MLR), the authors investigated the effects of stretch velocity, nerve cooling, ischemic block, tizanidine depression of group II afferents, and anesthetic depression of cutaneous afferents, over the soleus stretch reflex while walking (dorsiflexion perturbations during stance 200 ms after heel contact). After comparing the effect of the different conditions over short-latency response (first peak in EMG, 20 ms window) and MLR (a 20 ms window starting 30 ms after short-latency response [SLR] onset), the authors reported the following results:

- Different stretch velocities caused a change in SLR but not in MLR
- Nerve cooling, to slow down conduction velocity of both afferents with more changes over small-diameter fibers (group II) than large-diameter fibers (group Ia), caused a delay in time on the peak of SLR (55±5 ms vs. 58±5 ms) and MLR (78±6 ms vs. 86±6 ms); nevertheless, as expected, the MLR was delayed largely.
- Ischemic block, to influence the activity of Ia afferents, caused a significant decrease in SLR ($p = 0.004$) but did not change MLR significantly ($p = 0.437$)
- After two hours, tizanidine, to depress the activity of group II afferents, caused a reduction of MLR (55% reduction compared to control, p 0.007) and a not significant reduction in SLR ($p = 0.653$).
- Depression of cutaneous afferents of foot and ankle, by using lidocaine, caused a decrement in somatosensory evoked potentials ($p = 0.016$); nevertheless, lidocaine did not cause a significant change in SLR and MLR ($p > .05$).

Peterka et al. (2004)

To test for the sensory system contributions, specifically, the proprioceptors' contribution to human standing, Peterka et al. (2004) evaluated if anterior-posterior surface tilting (to challenge proprioceptors) caused changes in body sway. With participants restrained by a backboard (to allow just anterior-posterior sway about ankle joint axes), standing over a surface, eyes closed and playing audiotapes over headphones, the following conditions were examined: 1) fixed-support surface, 2) sway-referencing (support surface tilts towards the same direction of the subject's tilt), and 3) reverse sway-referencing (support surface tilts towards the opposite direction of the subject's tilt). Findings revealed that standing on a fixed-support surface is characterized by low-amplitude body sway; on the other side, sway-referencing and reverse sway-referencing are characterized by large-amplitude body sway. Also, Peterka and colleagues noticed that fixed-support after sway-referencing is characterized by body sway with different frequencies than before sway-referencing.

Beloozerova et al. (2005)

The authors' main objective was to determine whether the activity of pyramidal tract neurons (a tract from the motor cortex) correlates with postural responses of the awake cat. The electrical activity of pyramidal tract neurons, *triceps muscle*, *gastrocnemius muscle*, *soleus muscle*, and *brachialis muscle* was obtained during two conditions on a tilting platform: 1) cat maintaining balance with head looking forward, and 2) cat maintaining balance while head voluntarily moving to the right or left. Findings during both conditions revealed a peak in EMG activity of muscle extensors (all

but *brachialis muscle*) during maximal ipsilateral tilt, pyramidal tract neurons' modulation of firing frequency due to tilting, pyramidal tract neurons' activity related to tilting and head movement, and pyramidal tract neurons' activity related to EMG activity.

Taube et al. (2006)

After noticing conflicting evidence regarding the facilitation of motor evoked potentials (MEPs) and the involvement of the motor cortex while standing, Taube and colleagues proposed that facilitation of MEPs could not only be explained by increased cortical excitability but also by increased excitability of spinal motoneurons. Therefore, the objective of Taube and colleagues was to evaluate the influence of the human motor cortex, during a postural compensatory task, over *soleus muscle* while conditioning H-reflex with TMS. With participants standing on a treadmill, accelerating in posterior direction $60 m/s^2$, evoked reflex peaks of the soleus EMG were obtained during four conditions: 1) stance perturbation, 2) stance perturbation + soleus H-reflex (to assess spinal excitability), 3) stance perturbation + subthreshold TMS (to assess corticospinal excitability), and 4) stance perturbation + soleus H-reflex + subthreshold TMS (to assess excitability of specific corticospinal pathways). Subsequently, to consider reflex responses mediated by Ia afferents (SLR), group II afferents (MLR), and transcortical contributions (Long Latency Response [LLR]), Tauber and colleagues examined the MEP amplitude of each condition at SLR (first EMG peak), MLR (peak from time window 60 to 85 ms), and LLR (peak from time window > 85 ms). Findings revealed a significantly smaller H_{max}-to-M_{max} ratio at SLR than at LLR; MEPs of *soleus muscle* were facilitated during the LLR; TMS after peripheral stimulation caused facilitation of H-reflex amplitudes at LLR, but peripheral stimulation before TMS did not facilitate H-

reflex. In other words, the motor cortex might have an influence over *soleus muscle* at LLR during standing perturbations, as shown by changes in H_{max}-to-M_{max} (arguably caused by presynaptic inhibition of Ia afferents because background EMG activity was similar), MEPs facilitation, and TMS influence over H-reflex.

Deliagina, Zelenin, Beloozerova, and Orlovsky (2007)

Based on examinations over different animals (e.g., cats and rabbits), the authors reviewed and summarized relevant information regarding the functional organization and localization of the postural system in the central nervous system of mammals as follows:

- Regardless of the different modes and theories trying to explain postural stability, it is clear that body posture depends on feedback delivered by sensory inputs (vestibular, visual, and somatosensory).
- The postural system can be seen as several sub-functional units stabilizing head and trunk orientation. For example, studies using rabbits have shown that body posture is maintained after platform tilting by displacing the body towards the opposite direction of tilting (extension of limbs on the side moving down, and flexion of the opposite limbs), then, opposite tilting of two platforms (e.g., an anterior platform to the right while a posterior one to the left) was characterized by the appropriate response by limbs in order to maintain posture (flexion if moving up and extension if moving down).
- Evidence supports the involvement of the brainstem, cerebellum, and spinal cord over posture, mostly because decerebrate animals can still walk and maintain quadrupedal

posture. Also, electrical stimulation over the brainstem and cerebellum has been shown to affect the tone of antigravity muscles.

- Single neuron recordings have proved the involvement of reticulospinal and vestibulospinal pathways over the tone of antigravity muscles as their firing activity changed with the tilt angle of a treadmill while cat walking.
- Even though complex, the interaction between spinal and supraspinal factors can be explained, to some extent, by two closed-loop nervous mechanisms. The first mechanism (L1), located in the spinal cord, gets somatosensory information to generate corrective motor responses (e.g., spinal reflexes). The second mechanism (L2), located between the brainstem and motor cortex, gets information from the somatosensory, visual, and vestibular system to generate corrective motor responses via descending pathways like the reticulospinal and corticospinal.
- There are two supraspinal sources of muscular tone. The first one, sending excitatory drive from the brainstem through reticulospinal pathways, is responsible for activating postural mechanisms when needed (e.g., transitioning from resting to locomotion). The second one, located in the brainstem, causes coordination and modification of different body segments or limbs to maintain standing posture (e.g., different torques of limbs).
- Evidence regarding the involvement of the cerebral cortex over postural control keeps accumulating. For example, it was found that cortical activity of neurons was modulated during postural tasks in rabbits, and, as mentioned before, the activity of pyramidal tract neurons has been seen during maintenance of balance in cats (Beloozerova et al., 2005).

Mihara et al. (2008)

The purpose of the authors was to evaluate whether or not the frontoparietal cortex shows neurovascular activity during a balance task. Using functional near-infrared spectroscopy (fNIRS) over the head, the hemodynamic response of 15 participants (29.4±6.7 yrs.) was compared among three conditions: 1) regular standing (baseline); 2) warned-task; and 3) unwarned-task. Warned and unwarned-tasks consisted of forward and backward perturbations of a platform while the participant was standing with feet width apart; the only difference between both tasks was that during the warned condition, the participants were provided with an auditory warning signal 2 s before perturbations. Statistical analysis revealed significant neurovascular activity in the frontal cortex and parietal cortex. Compared to baseline, warned-task showed an increase of oxyhemoglobin (HbO) over left and right middle frontal gyri, left and right superior frontal gyri, left supplementary motor area, left precentral gyrus, left postcentral gyrus, and left and right superior parietal lobule. Compared to baseline, unwarned-task showed an increase in left and right middle frontal gyri, left and right superior frontal gyri, right precentral gyrus, and right superior parietal lobule. Lastly, a comparison between warned-task vs. unwarned-task revealed that a preceding auditory signal (warning condition) increased HbO in right superior parietal lobule and left supplementary motor area.

Horak and Macpherson (2010)

This book chapter of the "Handbook of Physiology, Exercise: Regulation and Integration of Multiple Systems" summarizes relevant information on maintaining balance. Even though the work of Horak et al. (2010) is more extensive and well detailed, for the purpose of this document, only information related to the involvement of sensory and central neural factors to balance will be mentioned.

- It is known that sensory information, to elicit the appropriate postural responses, is provided by somatosensory (mechanoreceptors, muscle spindles, Golgi tendon organs, and joint receptors), visual, and vestibular receptors (semicircular canals and otolith organs).
- Somatosensory receptors of the feet, legs, trunk, and neck are essential for controlling the trunk, specifically when standing over a stable surface. Also, they can detect perturbations to send a rapid response to maintain equilibrium by causing contraction of the appropriate muscles to be used.
- Otolith organs and semicircular canals are sensitive to head movements, with the only difference that semicircular canals are more sensitive to rapid movements. The vestibular system seems to be more important to maintain body posture while standing on an unstable surface than on a firm surface.
- Vision helps to maintain body posture, as shown by sway increases during limitation of vision; nevertheless, body sway in the absence of vision can be influenced by the surface (tilting vs. not tilting, or normal standing vs. tandem).

- The spinal cord and brainstem are involved in the maintenance of body posture. The spinal cord *per se* cannot produce equilibrium since spinalized cats cannot maintain balance for a long time. Brainstem involvement has been shown in decerebrate cats since they can maintain the tone of antigravity muscles during quadrupedal standing; nevertheless, the brainstem and spinal cord cannot correct for postural disturbances.
- Basal ganglia, which has pathways to the cerebral cortex (primary sensorimotor cortex and supplementary motor area) and brainstem, is involved in posture, as shown in subjects with basal ganglia pathology showing impaired postural alignment and instability. Specifically, basal ganglia might influence tonic postural tone, centrally initiated postural adjustments, and externally triggered reactions.
- The cerebellum might play a role in sensorimotor integration (integrating all the information from sensory sources) since its anterior lobe receives somatosensory inputs and, as shown, a lesion over this lobe can cause ataxia during standing.
- The involvement of the motor cortex remains controversial since studies in cats have shown that primary motor cortex (M1) is not used for postural responses. Regarding the involvement of the primary sensorimotor cortex, it has been argued that it might be involved in posture since MLR and LLR provide enough time to let the primary sensorimotor cortex get involved; nevertheless, that does not necessarily mean that the primary sensorimotor cortex is involved in postural control. Contrarily, the involvement of the secondary motor cortex has been shown during quiet standing.

Goble et al. (2011a); Goble et al. (2011b)

The purpose of the authors was to examine the relationship between brain activity (assessed with Functional Magnetic Resonance Image [fMRI]), stimulation of somatosensory receptors (vibration), and balance in young (M = 26.1 yrs.) and old participants (M = 68.9 yrs.). fMRI data were compared among three conditions: 1) no-vibration, 2) vibration of the tendon (toes), and 3) vibration of bone (tibia), with each condition lasting 21 seconds and vibration delivered at a frequency of ~80 Hz.

Assuming that fMRI contrasts of tendon vibration vs. bone vibration would show cortical and subcortical activity related to muscle spindles stimulation, Goble et al. (2011b) found that, despite age, muscle spindles stimulation was shown in the following areas of the brain: supplementary motor area; contralateral primary sensorimotor cortex; pre-supplementary motor area; right ventral premotor cortex; inferior parietal cortex; right dorsolateral prefrontal cortex; inferior frontal gyrus; basal ganglia; and right orbitofrontal cortex. Regarding age-related differences, the authors found that the right putamen was more active in young than in old adults; nevertheless, the right putamen structure was not significantly different between age groups.

Goble et al. (2011a) examined if brain activity during stimulation of somatosensory receptors predicted balance performance, assessed within a 1-2 week period after fMRI scans. Balance assessment consisted of three trials of 20 seconds while subjects stood over a balance board (no perturbations elicited) with eyes closed. Findings revealed that, as expected, the balance was significantly different between older adults and young subjects, specifically, mean equilibrium score (old: 91.8, young: 93.1) and

anterior-posterior velocity (old: 29.1 cm/s, young: 25.3 cm/s). Brain activity during stimulation of somatosensory receptors was significantly correlated with equilibrium score; specifically, orbitofrontal cortex, right basal ganglia, right anterior insula, right inferior frontal gyrus, pre-supplementary motor area, right dorsal anterior cingulate gyrus, left anterior insula, right supramarginal gyrus, right dorsolateral prefrontal cortex, right ventral premotor cortex, and secondary somatosensory cortex. Also, lower neural activity was associated with better equilibrium scores, and older adults showed an overall greater correlation between equilibrium score performance and neural activity (0.43 – 0.68) compared to young subjects (0.33 - 0.46).

Karim et al. (2013)

Karim et al. (2013) used fNIRS placed over the head's frontal part to measure brain activity changes during different tasks. After placing the fNIRS cap, fifteen healthy participants (28±9 yrs) performed the following balancing tasks in a block-design consisting of 45 seconds of task and 60 seconds of baseline measurements twice per condition: 1) fixed platform (FP) + eyes open (EO) + light on, 2) FP + EO + dark, 3) sway platform (SP) + EO + light on, and 4) SP + EO + dark. Findings revealed increased activity of the cerebral cortex over the temporal-parietal regions when subjects relied on vestibular information. Specifically, changing from condition two to condition four, and from condition three to condition four caused the most significant increment in HbO.

Takakura et al. (2015)

To expand the findings from Karim et al. (2013), the authors of this manuscript examined brain activity during different balance tasks. Using an fNIRS cap, eleven healthy subjects (33.4±7.4 yrs) performed the following balancing tasks in a block-design consisting of 20 seconds trials followed by 60 seconds of baseline measurements five times per condition: 1) FP + EO + fixed surroundings (FS), 2) FP + eyes closed (EC) + FS, 3) FP + EO + sway surroundings (SS), 4) SP + EO + FS, 5) SP + EC + FS, and 6) SP + EO + SS. Compared to condition one, findings revealed activity over the right superior temporal gyri, frontal operculum, and parietal operculum (condition two); over dorsal premotor cortex, and right supramarginal gyrus (condition three); over superior temporal gyri and parietal operculum (condition four), over frontal operculum, supplementary motor area, superior temporal gyri, and parietal operculum (condition five); and over frontal operculum, ventral premotor cortex, dorsal premotor cortex, supplementary motor area, superior temporal gyri, parietal operculum, right supramarginal gyrus, and superior parietal lobules (condition six).

Herold et al. (2017)

The objective of this study was to evaluate the cortical activity of the brain during a balance task by using fNIRS. After placing the fNIRS cap, ten participants proceeded to do the following protocol (three times, same order, 30 seconds per condition): 1) standing position (baseline), 2) standing position (control), 3) standing over a balance board (balance), and 4) standing still (rest). Findings revealed that compared to regular standing, balance over a board caused a significant increment of HbO over the

supplementary motor area and postcentral gyrus with no statistical differences in deoxygenation (HbR) levels.

Surgent, Dadalko, Pickett, and Travers (2019)

Because of recent advances in brain imaging methods, Surgent et al. (2019) reviewed the existing human MRI literature to find brain structures that underlie postural balance. After exclusion criteria (non-humans, use of fMRI, less than eight participants, and low resolution), the authors found 37 relevant manuscripts using MRI, with most of them assessing subjects over 40 years old (25 studies) and populations with impaired balance (24 studies); therefore, caution should be taken regarding conclusions. Findings revealed the involvement of the following brain structures in balance:

- The brainstem and cerebellum, specifically the gray matter of the cerebellum, accounted for most of the involvement. It should be mentioned that 72% of the findings were based on impaired balance populations.
- The frontal region, specifically, orbitofrontal cortex, primary motor cortex, superior frontal gyrus, and supplementary motor areas, showed a lack of consistency regarding structural changes associated with balance performance and training.
- Temporal regions, specifically, the volume of hippocampal gray matter was associated with subjects with special skills (e.g., dancer and slackliners) but with poor balance in subjects over 40 years old (increased vs. decreased volume).
- Subcortical regions were examined in nine studies from people over 40 years. Basal ganglia size (reduction) and white matter hyperintensities were associated with poor

balance. Increased gray matter volume of the thalamus was associated with good balance

- Occipital regions were examined in nine studies with not consistent findings regarding structural changes.
- Parietal regions were examined in seven studies; specifically, the inferior parietal cortex was associated with improved balance.

2.1.1. Summary of "The Nervous System and Maintenance of Standing Posture."

During the last century, there has been a particular interest from investigators over the involvement of the peripheral and central nervous system in standing posture. From early studies using decerebrate and spinalized mammals, some authors noticed that the animals could maintain the quadrupedal stance (e.g., Magnus, 1926; Sherrington, 1910). Specifically, the authors mentioned that, unlike spinal preparations, decerebrate cats with their intact brainstem could maintain the standing posture for a couple of minutes; therefore, they reasoned that standing is reliant on subcortical components of the nervous system

Because of early findings, there is a consensus regarding the major involvement of spinal and subcortical components with minor involvement of the cerebral cortex, if any, over standing balance. Recent advances in non-invasive technology to explore the neural activity of the brain (brain-imaging) and to stimulate the cerebral cortex (e.g., TMS) have revealed an involvement of the cerebral cortex over standing balance; nevertheless, the evidence is scarce and more studies are granted.

Conflicting evidence has been found using TMS over the cerebral cortex. For example, while Keck et al. (1998) found no involvement of the motor cortex over *tibialis anterior muscle* during perturbation of human stance, others, like Beloozerova et al. (2005) and Taube et al. (2006), found an involvement, or at least a correlation (Beloozerova et al., 2005), of the motor cortex over balance. Regarding brain imaging, most of the studies have used MRI and occasionally PET or, more recently, fNIRS. In a recent review regarding MRI studies examining the involvement of brain structures in standing balance, the authors found that the brainstem, cerebellum, and basal ganglia play a role in balance (Surgent et al., 2019). Regarding the cerebral cortex, Surgent et al. (2019) reported inconsistent findings of the involvement of M1, orbitofrontal cortex, and supplementary motor area over balance.

One of the disadvantages of using MRI and fMRI is that the examined participants have to lay down; therefore, real-life tasks cannot be examined. On the opposite side, fNIRS can examine brain activity changes during real-life tasks (e.g., balancing over a board while using an fNIRS cap). Therefore, a couple of studies have been able to examine balance and cerebral cortex activity at the same time, with findings revealing increased activity over some areas of the cerebral cortex while comparing balance tasks vs. regular standing (Herold et al., 2017; Karim et al., 2013; Mihara et al., 2008; Takakura et al., 2015).

Peterka et al. (2004) showed that, unlike regular standing, anterior-posterior tilting (to challenge proprioceptors) causes large-amplitude body sway and that once tilting has stopped, body sway does not return to the previous amplitude (as in regular standing) until later. Regarding the manipulation of the somatosensory system and brain

imaging methods, it has been found that cerebral cortex activity relates to the stimulation of muscle spindles and balance (Goble et al., 2011a; Goble et al., 2011b). Also, compared to normal balance, increased activity over different regions of the cerebral cortex has been found if one or two senses (visual, proprioception, vestibular) are challenged or diminished; therefore, showing a major involvement of the cerebral cortex during standing posture in the absence of enough afferent information.

The different response latencies might explain the main finding differences among conflicting evidence from different authors. In their review, Jacobs and Horak (2007) mentioned different response latencies; that is, perturbations can be characterized as having an SLR component (automatic responses), then, if the perturbation continues, an MLR and LLR component will be present. In other words, in the presence of a perturbation, there will be an automatic response (spinal reflex) with an SLR component, mainly due to the involvement of the L1 closed-loop mechanism (Deliagina et al., 2007), then, if the perturbation continues, supraspinal factors, involving the L2 mechanism (Deliagina et al., 2007), will start to play a role in balance (MLR and LLR).

Concluding, evidence has been accumulating during the last century to show that standing posture in humans involves the activity of spinal, supraspinal, and cortical regions of the central nervous system. Therefore, it is evident that the involvement, and relationship, of cortical regions with factors influencing balance should be examined.

2.2. Anatomy, Physiology, and Plasticity of Muscle Spindles and Cutaneous Receptors

Kolliker (1863)

This article is one of the first to mention the existence of nerve endings in the skeletal muscle, later called muscle spindles. Specifically, the author mentions that his main objective was to investigate the termination of nerves in muscles due to different findings from different authors and found that "…in the frog's muscles the nerve-fibers really branch out at their ends into delicate pale filaments." (Kolliker, 1863, p. 68), and these pale filaments lie parallel to muscle fibers without being part of them.

Sherrington (1894)

In this article, Sherrington provided relevant information about the muscle spindles' function. In addition to Ruffini in 1893 (as mentioned by Sherrington, 1894), it seems to be the first manuscript to mention the sensory function of muscle spindles as shown by sensory nerves arising from the spinal root-ganglion supplying the muscle spindles. Further information provided by Sherrington (1894) about muscle spindles is as follows:

- Muscle spindles are fusiform, and they run parallel to the muscle fibers. They vary in size, two or three spindles within them, length, 0.75 mm to 4 mm, and diameter, 80 μm to 200 μm.
- Anatomical muscle spindles regions can be divided as equatorial (center) and polar regions (ends). Bundles of intrafusal muscle fibers (2 – 12 intrafusal fibers per bundle), making up the muscle spindle, originate from polar regions.

- Three to seven, myelinated and large (7 μm to 18 μm), spinal nerve fibers supply each muscle spindle.

Ruffini (1898)

Based on findings from muscle spindles of cats, Ruffini (1898) identified three types of nerve endings: 1) primary endings, 2) secondary endings, and 3) plate-endings. Later, primary endings were identified with group Ia afferents and secondary endings with group II afferents. In addition to the relevant findings regarding the type of nerve endings, the author summarizes findings from authors like Sherrington, and Kolliker, regarding the anatomy of muscle spindles like their length (3.5 mm – 8 mm), diameter (9 μm to 200 μm), number per muscle (at least 15), and elements (enveloped by a capsule made of lamellae, and elastic fibers).

Adrian and Zotterman (1926)

Adrian et al. (1926) were one of the first ones to show that mechanoreceptors of mammals (based on cats) show two characteristic responses to pressure: 1) high-frequency impulses immediately after pressure; and 2) a decrease in frequency if the pressure is constant during more time. Later this helped to classify mechanoreceptors based on their adaptability (fast or slow).

Adrian and Umrath (1929)

"In 1831… [Filippo] Pacini observed some small ovoidal bodies attached to the digital branches of the median and ulnar nerves … Convinced that the hand corpuscules were related to nerve fibers, Pacini defined them as *tactile ganglia*." (Bentivoglio &

Pacini, 1995, pp. 161-162). Since that day, Pacini and other researchers investigated the anatomy and function of the ovoidal bodies, which later were named after him (Bentivoglio et al., 1995). In 1929, Adrian and Umrath, by recording firings of afferent nerves of Pacini corpuscles of cats, found that they were sensitive to pressure changes; moreover, the frequency of the Pacini corpuscles varied with pressure and declined under constant stimulus (fast adapting response).

B. Matthews (1933)

Because most of the findings, until 1933, of primary and secondary nerve endings' function were based on non-mammalian muscles, Matthews examined the function of nerve endings of the mammalian muscle (cats) by recording their electrical activity. Findings revealed that compared to slower or constant stretching, nerve endings are responsive to fast stretching with higher firing frequencies; secondary endings do not fire during active contraction (called A1 response of flower spray endings), and primary endings are responsive to active contraction (called A2 response of annulo-spiral endings).

Hunt (1951)

The primary purpose of Hunt (1951) was to examine the influence of the small-nerve fibers (later called γ-efferent nerves) that originate in the ventral roots of the spinal cord over the firing modulation of afferent nerves of muscle spindles. Findings, in decerebrated and spinalized cats, revealed that: 1) γ-neurons fire even when a limb is in resting position, and this firing activity depends on the flow of afferent impulses to the spinal cord (probably coming from skin and muscle); 2) the firing behavior of γ-neurons

of flexor muscles during the flexor reflex (increased firing) was different compared to the crossed extensor reflex (decreased firing); 3) the opposite firing behavior occurred in the γ-neurons of muscle extensors; 4) γ-neurons decreased their firing when the muscle was passively stretched and increased when the muscle was shortened.

Eldred, Granit, and Merton (1953)

The purpose of the article of Eldred et al. (1953) was to examine the supraspinal control of the muscle spindles by indirectly observing the influence of γ-neurons over the firing behavior in afferent neurons found in the dorsal root of the spinal cord. Findings in cats revealed that, compared to the intact muscle spindle, de-efferented preparations showed a decrease in firing sensitivity; in other words, if the muscle were to be stretched at the same length, the de-efferented muscle spindle would fire at a lower frequency compared to the intact muscle spindle. Contrary to de-efferented preparations, de-afferented preparations showed increased muscle spindles firing compared to intact muscle spindles. Autogenic inhibition is also shown while comparing de-afferented vs. intact muscle spindle. The intact muscle spindle of the *gastrocnemius* and *soleus muscle* shows an increase in firing frequency as the ankle is flexed to a certain extent, then even if the ankle is stretched to a greater length, the firing frequency decreases, an effect that is not seen in de-afferented preparations; therefore, showing that γ-neurons might be inhibited by afferent neurons (specifically by Golgi Tendon Organs). Lastly, stimulation over the brainstem showed that in intact preparations, the spindles fired and the muscle contracted, then, in de-afferented preparation, the firing frequency increased, compared to intact preparations, but no muscle contraction occurred. According to the author, "This

finding illustrates the independence of afferent support possessed by the supraspinal pathways converging on the γ-neurons." (p. 531).

Eccles, Eccles, and Lundberg (1957)

The findings from Eccles et al. (1957) are relevant because they show that not only is there a homonymous response from Ia afferent volleys (excitatory postsynaptic potentials over the same muscle being stimulated), but also there are heteronymous responses from Ia afferent volleys (excitatory postsynaptic potentials over one muscle but generated by another stimulated muscle nerve).

Boyd (1962)

This manuscript examines the structure and innervation of the muscle spindles. Results were obtained from 78 transversely sectioned muscle spindles and 508 whole muscle spindles obtained from cats. Mainly the author identified two types of muscle spindles: 1) nuclear bag fibers, and 2) nuclear chain fibers; two types of efferent nerves: 1) γ1-neurons, and 2) γ2-neurons; two types of nerve endings: 1) primary sensory endings, and 2) secondary sensory endings; and two types of afferent nerves: 1) group Ia, and 2) group II. Group Ia innervates the primary sensory endings, localized in the nuclear region of both intrafusal fibers; group II innervates the secondary endings of the muscle spindle, localized in the polar regions of the nuclear chain fibers. On the other side, γ1-neurons innervate the nuclear bag fibers, and γ2-neurons innervate nuclear chain muscle fibers.

P. Matthews (1962)

The purpose of this study was to test the hypothesis that the two types of γ-neurons behave differently under static and dynamic conditions. After anesthetizing eight cats, the firings of single group Ia neurons were recorded from the dorsal root while repetitive electrical stimulation to each identified γ-neurons was delivered, and the *soleus muscle* was stretched. At constant length, stimulation of each γ-neurons increased the discharge of group Ia; also, stimulation of some γ-neurons (γ-1, then called γ-dynamic) increased the firing of group Ia during dynamic and static stretching, and stimulation of γ-2, then called γ-static, caused a decreased firing during dynamic stretching but an increased firing during static stretching.

Landgren and Silfvenius (1969); Oscarsson and Rosen (1963)

Landgren et al. (1969) and Oscarsson et al. (1963) explored the projections of I afferents (Ia and Ib) to the cerebral cortex by electrically stimulating the nerves of cats. Specifically, Oscarsson et al. (1963) found projections from the contralateral forelimb to the somatosensory cortex and Landgren et al. (1969) from the contralateral hind limb to the somatosensory cortex.

Iggo and Muir (1969)

Friedrich Sigmun Merkel first described Merkel disks in 1875 (Abraira & Ginty, 2013; Iggo et al., 1969); then Iggo et al. (1969) described the function of the Merkel disks, located in the hairy skin of cats (nowadays is known that Merkel disks are also present in glabrous skin). Merkel disks showed a high firing frequency when a probe was used to draw across the skin quickly but low firing frequency when a probe was placed

on the skin. Also, the Merkel disk showed a dynamic response (high firing) and then a static response (low firing with time).

Knibestöl and Vallbo (1970)

Based on the previous findings of Adrian et al. (1926) and studies finding different mechanoreceptors' responses depending on the species and whether or not the skin has hair, Knibestöl et al. (1970) investigated the electrical activity of mechanoreceptors from the glabrous skin (skin without hair) in men. Findings from the authors' manuscript revealed four types of mechanoreceptors in the glabrous skin: 1) two that fired just during changes in pressure (later called Fast Adapting Type I [FAI] and Fast Adapting Type II [FAII]); and 2) two that fired just during sustained pressure (later called Slowly Adapting Type I [SAI] and Slowly Adapting Type [SAII]).

Goodwin, McCloskey, and Matthews (1972)

To examine the contribution of muscle spindles over kinesthesia (position sense), Goodwin et al. (1972) applied vibration, at 100 Hz frequency and 0.5 mm amplitude, over the tendon of *biceps* or *triceps muscle* of one arm, while moving, to evoke a proprioceptive illusion on blindfolded subjects. During the biceps tendon's vibration, the vibrated arm moved in the direction of flexion and subjects perceived movement but in the opposite direction (extension). Moreover, if the participant was required to follow the movement with the contralateral arm, an error of ~ 40° in the forearms' alignment was detected at the end of the vibration. On the other side, vibration over the *triceps tendon*, the opposite occurred; that is, vibration elicited extension of the forearm, and the participant detected a flexion of the forearm.

Ovalle and Smith (1972)

Findings from authors using a microscope, like Boyd (1962), identified two types of intrafusal fibers: nuclear bag fibers and nuclear chain fibers. Ten years later, due to advances in histochemical studies, Ovalle et al. (1972) found that nuclear bag fibers from cats and monkeys can be sub-divided into two types: "…those containing the acid-base form of myosin ATPase only, and those containing ATPase detectable under both acid and alkaline conditions." (p. 195). Later these types of nuclear bag fibers were called dynamic bag_1 and static bag_2.

Banks (1981)

Even though not the first study to examine the innervation of dynamic bag_1 and static bag_2 by γ-neurons, certainly, it is one of the studies that helped to elucidate the confusion regarding whether or not γ-static can innervate, dynamic bag_1. Findings from muscle spindles of cats revealed that dynamic bag_1 is rarely innervated by γ-static; instead, most of the time γ-static innervate bag2 and nuclear chain fibers. Therefore, as currently known, γ-dynamic innervates dynamic bag_1 and γ-static innervates static bag_2 and nuclear chain fiber.

Roll and Vedel (1982)

The purpose of this manuscript was to examine the effects of tendon vibration frequency over kinesthesia. Using microneurography, Roll et al. (1982) recorded the activity of group Ia from the TA and *extensor digitorum longus* muscles while vibration was applied over the tendon and found that vibration at a frequency from 30 to 50 Hz and

at an amplitude from 0.2 to 0.5, causes group Ia to fire in a one-to-one way. Also, as the vibration frequency increased (>50 up to 120 Hz), Ia showed two or three firings per vibration cycle.

Ribot-Ciscar, Rossi-Durand, and Roll (1998)

In 1998 the after-effects of prolonged vibration over primary endings (Ia group) were examined by Ribot-Ciscar and colleagues. Using microneurography, the authors compared the firing behavior from *tibialis anterior muscle*, *extensor digitorum longus*, and *lateral peroneal muscles* before and after muscle tendon vibration for 30 s (frequency: 80 Hz; amplitude: 0.5 mm). Findings revealed that firings of most of the group Ia nerves (73% of them) were depressed for up to 40 seconds following vibration; after that, the firing behavior of group Ia was similar to before vibration.

Abraira et al. (2013); Johnson (2001); Kaas (2004)

Relevant to this document, these manuscripts review the current findings regarding the function of the four different types of mechanoreceptors found in humans.

- SAI – Merkel's disks
    - Respond to sustained indentation with constant firings but irregular intervals the whole time.
    - Sensitive to points, edges, and curvatures
    - High spatial resolution of up to 0.5 mm and insensitive to stretch or displacement of adjacent skin (2-3 mm around receptor); therefore, sensitive to position and velocity.

- SAII – Ruffini's ending
    - Respond to sustained indentation with constant firings but more stable intervals compared to SAI the whole time. Compared to SAI, they are less sensitive to skin indentation.
    - Sensitive to stretching (more sensitive than SAI)
    - Capable of perceiving motion and direction of an object as long as the object stretches the skin.
    - Together with muscle spindles and joint afferents, they collaborate to detect hand and finger shape.
- FAI – Meissner's corpuscle
    - Capable of detecting changes in low-frequency vibration and movement between the skin and the surface. They might detect surface texture.
- FAII – Pacinian capsule
    - Capable of detecting high-frequency vibrations
    - Help to discriminate vibrations from distant events (tapping a table where the hand is resting)

Kennedy and Inglis (2002)

Considering the findings from Maurer, Mergner, Bolha, and Hlavacka (2001) about the influence of mechanoreceptors of the foot sole over maintenance of balance, and the lack of information regarding the distribution of them in the human foot sole, Kennedy et al. (2002) examined their distribution from 13 healthy subjects (29.6 yrs.). A total of 106 mechanoreceptors in the foot sole were classified as follows: 14% as SAI, 15% as SAII, 57% as FAI, and 14% as FAII.

Mildren, Hare, and Bent (2017)

The main objective of this study was to evaluate the effects of local anesthetic over joint position sense of the ankle. The authors reported that after anesthetization of the posterior part of the ankle, by using EMLA cream (2.5% lidocaine + 2.5% prilocaine), the subjects had a significantly reduced sensitivity compared to before local anesthesia, as shown by using Semmes-Weinstein Monofilaments. Moreover, the reduced sensitivity caused the perception of correctly aligning the ankle being examined (parallel to the contralateral ankle) when in reality, it was not.

2.2.1. Summary of "Anatomy, Physiology, and Plasticity of Muscle Spindles and Cutaneous Receptors."

First discovered in 1863 by Kolliker, the primary function of the muscle spindles is to provide sensory information to the central nervous system (Sherrington, 1894). Anatomically, muscle spindles consist of bundles of specialized muscle fibers, called intrafusal fibers, running parallel to the skeletal muscle, also known as extrafusal fibers in the muscle spindle literature (Sherrington, 1894). Based on microscopic examination, intrafusal fibers can be classified as chain fibers and bag fibers, mainly because of their nucleus resemblance to either a chain or a bag (Boyd, 1962). Ten years later, due to advances in histochemical techniques, Ovalle et al. (1972) subclassified nuclear bag fibers as dynamic (bag_1) and static (bag_2).

The afferent division of muscle spindles, innervating the dorsal root of the spinal cord, consists of group Ia and group II afferent nerves originating from equatorial (center) and polar regions (end) of intrafusal fibers, respectively. Specifically, group Ia originates

from both intrafusal fibers' primary endings, and group II originates from secondary endings of the nuclear chain fibers (Boyd, 1962; Ruffini, 1898). The efferent division of muscle spindles, projecting from the spinal cord's ventral root, consists of dynamic-γ and static-γ efferent nerves innervating intrafusal fibers (Boyd, 1962). Specifically, dynamic-γ innervates the bag fibers and static-γ innervates chain and static bag fibers (Banks, 1981; Boyd, 1962; P. Matthews, 1962).

As previously mentioned, the main function of the muscle spindles is to provide sensory information; specifically, muscle spindles are capable of contributing to kinesthesia (Goodwin et al., 1972). The ability of muscle spindles to detect muscle length changes is possible because of their efferent and afferent nerves' combined action. For example, stimulation of *dynamic-γ* will increase the firing in *primary endings* during rapid stretching; conversely, stimulation of *static-γ* will cause steady firing in both endings during static stretching (B. Matthews, 1933; P. Matthews, 1962). Moreover, spinal and supraspinal sources can modulate the sensitivity of muscle spindles. Hunt (1951) found that γ-efferents can keep firing under different conditions even without the influence of supraspinal sources; therefore, the afferent sources might be capable of influencing such firing behavior at the spinal level. Alternatively, supraspinal sources can also modulate the action of γ-efferents, as shown by Eldred et al. (1953).

In addition to muscle spindles, other sensory sources can also provide sensory information to the central nervous system, like skin receptors. Skin receptors can be classified by their adaptability to external perturbations as slow adaptive and fast adaptive (Abraira et al., 2013; Johnson, 2001; Kaas, 2004). From the previously mentioned

classification, Knibestöl et al. (1970) helped to subclassify the mechanoreceptors based on their electrical activity, like SAI, SAII, FAI, and FAII. Merkel's disks, classified as SAI, are sensitive to position and velocity. Ruffini's endings, classified as SAII, are sensitive to stretching and capable of perceiving changes in motion and direction as long as an external force is stretching the skin. Lastly, Meissner's corpuscles and Pacinian capsules, classified as FAI and FAII, respectively, are known to be able to detect vibration changes; specifically, Meissner's corpuscles can detect low-frequency vibration changes, and Pacinian capsules can detect high-frequency vibrations

CHAPTER III

METHODOLOGY

3.1. Participants

After approval by the Oklahoma State University Institutional Review Board for human participant research, 16 apparently healthy participants (Mean±Standard Deviation, eight male: 25.13±4.32 yrs., eight female: 22.57±4.61 yrs.) were recruited. Potential participants were excluded if they had a current or recent (during the past six months) lower extremity injury impeding stability or movement, any open wound on the foot being examined (their dominant foot after being asked with what leg they would kick a ball), any known cardiovascular or neuromuscular disease, or severe cognitive impairment. All participants completed an informed consent, a pre-exercise health and exercise status questionnaire, and anthropometric data were obtained before the experiment started during the first visit. After data processing, all statistical analyses were based on 12 participants (24.8±4.59 yrs.).

3.2 Research Design

This study used a within-subjects cross-over design with four visits, per participant, to the Applied Neuromuscular Physiology Laboratory and a minimum of 24 hours of rest between visits. The four visits were randomized using Google random number generator (Google Inc., California, US) and assigning numbers to conditions as follows: 1) testing under normal conditions (Control Visit); 2) testing with muscle spindles inhibited (MSI Visit); 3) testing with cutaneous receptors inhibited (CB Visit); 4) testing with muscle spindles and cutaneous receptors inhibited (BOTH Visit). Muscle spindles were temporarily inhibited via prolonged vibration, and cutaneous receptors were temporarily inhibited via topical anesthetic (see details in section 3.4.3). A visual depiction of the experimental design can be seen in Figure 1.

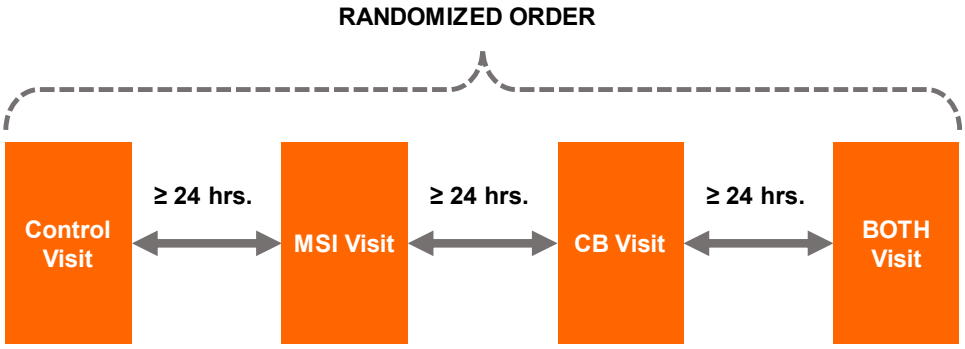


Figure 1 Experimental design of the study. MSI: Muscle Spindle Inhibition, CB: Cutaneous Receptors Inhibition, BOTH: Muscle Spindle Inhibition and Cutaneous Receptors Inhibition.

3.3. Experimental Procedures

3.3.1. General Procedures and Control Visit

The purpose of this visit was to obtain data of participants under normal conditions to be compared with the other visits. Therefore, no inhibition of muscle spindles and/or cutaneous receptors were performed.

Upon arrival, an EMG sensor was placed over the *soleus muscle*, muscle spindles and cutaneous receptors were tested over the dominant leg, as mentioned in section 3.4.3.3 and 3.4.3.4, to obtain H-reflex, M-wave, sensitivity threshold (ST), and two-point discrimination (TPD). After muscle spindles' and cutaneous receptors' testing, an fNIRS cap (NIRx Medical Technologies, LLC, Berlin, DE) was placed over the head of the participant to measure the hemodynamic response of the regions of interest (see section 3.4.1 for details) while doing the balance tasks (see section 3.4.2 for details).

3.3.2. MSI Visit

The purpose of this visit was to obtain data of participants with muscle spindles of the dominant leg inhibited. Therefore, no inhibition and testing of cutaneous receptors were performed.

MSI visit was similar regarding EMG and fNIRS placement. After EMG placement, the dominant leg's muscle spindles were tested before and after vibration to obtain H-reflexes (see section 3.4.3.3 and 3.4.3.1 for details). After muscle spindles testing and fNIRS cap placement, the participant proceeded to do the balance tasks with the exception that the block pattern was modified by applying five minutes of vibration over the dominant *soleus muscle* before two balance tasks (e.g., vibration+A+B+vibration+B+A) (see section 3.4.2 for details about balance tasks).

3.3.3. CB Visit

The purpose of this visit was to obtain data of participants with cutaneous receptors of the dominant leg inhibited. Therefore, no inhibition and testing of muscle spindles were performed.

CB visit was similar regarding fNIRS placement. After applying and removing lidocaine (see section 3.4.3.2 for details), cutaneous receptors were immediately tested, as mentioned in section 3.4.3.4, to obtain ST and TPD. After cutaneous receptors' testing, the participants proceeded to do the balance tasks (see section 3.4.2 for details).

3.3.4. BOTH Visit

The purpose of this visit was to obtain data of participants with muscle spindles and cutaneous receptors of the dominant leg inhibited.

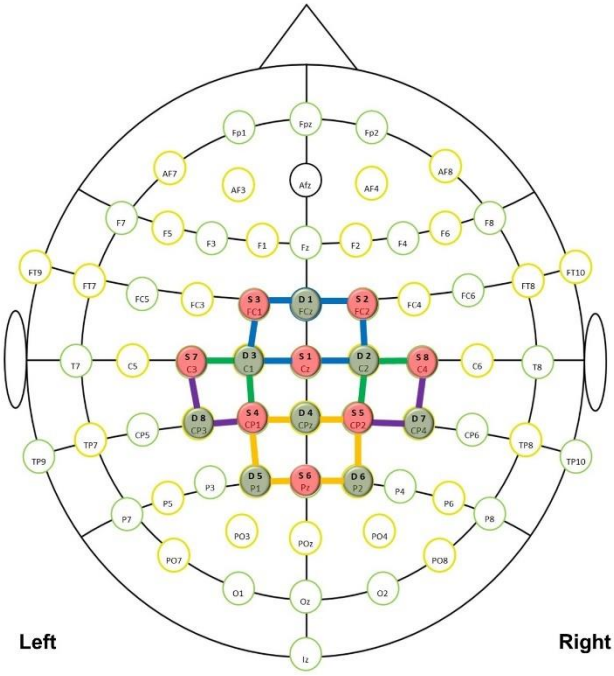
BOTH visit was similar regarding EMG and fNIRS placement. Cutaneous receptors were inhibited and then tested after 30 min (see section 3.4.3.2 and 3.4.3.4 for details). Muscle spindles of the dominant leg were tested before and after vibration, as mentioned in section 3.4.3.1. and 3.4.3.3, to obtain H-reflexes; then the participants proceeded to do the balance tasks with the exception that the block pattern was modified by applying five minutes of vibration over the dominant *soleus muscle* before two balance tasks (e.g., vibration+A+B+vibration+B+A).

3.4. Instrumentation and Measurements

3.4.1. Hemodynamic Response

Before obtaining the hemodynamic response, the fNIRS Optodes' Location Decider software (fOLD) (Zimeo Morais, Balardin, & Sato, 2018) was used to generate a montage of 20 channels (8 sources x 8 detectors) based on the anatomical specificity of each channel to the regions of interest (ROIs) for this study (right premotor cortex [R_PreM], left premotor cortex [L_PreM], right motor cortex [R_M1], left motor cortex

[L_M1], right somatosensory association cortex [R_SA], left somatosensory association cortex [L_SA], right somatosensory cortex [R_S1], and left somatosensory cortex [L_S1]). Then, the circumference, the mid-distance from Nasion to Inion, and the mid-distance from preauricular point to preauricular point of the head of each participant were measured to know the cap size and the location of the center of the head (the place where the optode "Cz" will be placed according to the 10-20 system). Once the fNIRS cap was in place, and following the recommendations of Orihuela-Espina, Leff, James, Darzi, and Yang (2010), data obtained from a continuous wave-fNIRS (NIRx Medical Technologies, LLC, Berlin, DE) was recorded using Aurora fNIRS Software (Aurora v. 1.4, NIRx Medical Technologies, LLC, Berlin, DE) during the whole session at 13.95 Hz. During the different balance tasks, time markers were manually generated in Aurora fNIRS Software (Aurora v. 1.4, NIRx Medical Technologies, LLC, Berlin, DE) for posterior analysis of the hemodynamic response. The montage used in this study can be seen in Figure 2.



Source	Detector	ROI	Specificity (%)
Cz	C2	R_PreM	55.39
FC2	C2	R_PreM	82.46
FC2	FCz	R_PreM	62.95
Cz	C1	L_PreM	56.45
FC1	C1	L_PreM	81.46
FC1	FCz	L_PreM	73.21
CP2	C2	R_M1	24.07
C4	C2	R_M1	36.77
CP1	C1	L_M1	31.56
C3	C1	L_M1	34.98
CP2	CP4	R_S1	19.29
C4	CP4	R_S1	44.88
CP1	CP3	L_S1	21.70
C3	CP3	L_S1	50.66
Pz	P2	R_SA	93.86
CP2	P2	R_SA	92.64
CP2	CPz	R_SA	77.85
Pz	P1	L_SA	91.59
CP1	P1	L_SA	92.32
CP1	CPz	L_SA	79.35

Figure 2 Visual depiction of the montage used in the study. Montage based on the 10-20 system position with eight sources (red circles) and eight detectors (green circles). Regions of interest (ROI) obtained using "Brodmann Atlas" from fOLD (Zimeo Morais et al., 2018). The specificity percentage of each ROI is shown in the table to the left of the figure. R_PreM: right premotor cortex, L_PreM cortex: left premotor cortex, R_M1: right motor cortex, L_M1: left motor cortex, R_S1: right somatosensory cortex, L_S1: left somatosensory cortex, R_SA: right somatosensory association cortex, L_SA: left somatosensory association cortex

Once data had been collected, the data was analyzed using an open-source Matlab-based graphical user interface program (HomER3 v1.29.11) (Huppert, Diamond, Franceschini, & Boas, 2009). To obtain the hemodynamic response, the raw data was processed as follows:

- Noise saturation inspection (per channel): It is known that good quality data should show the heartbeat over the raw data (Hocke, Oni, Duszynski, Corrigan, Frederick, & Dunn, 2018); therefore, raw data without the presence of heartbeats was be considered noisy. After visual inspection, data were examined for noise saturation with the *hmrR_PruneChannels* function using the following inputs parameters:

dRange = [5.00E-04, 1.00E+00], as recommended by NIRx Medical Technologies; SNRthresh: 6.67, a value obtained to allow a ~15% coefficient of variation using the equation mentioned by Carius, Hörnig, Ragert, and Kaminski (2020); and SDrange = [0.0, 45.0]. Each channel determined to be noisy was not used for posterior analyses (Orihuela-Espina et al., 2010); also, if more than four channels per trial were noisy (<80% of channels), then all that trial was not used for posterior processing and analysis.

- Raw to OD: Raw data was converted to optical density (OD) data using the *hmrR_Intensity2OD* function.
- Motion Artifact Correction: Based on the work of Molavi and Dumont (2012), the *hmrR_MotionCorrectWavelet* function removed and corrected motion artifacts. For this study, the influence of two input parameters was examined: iqr = 0.1 as used by Brigadoi, Ceccherini, Cutini, Scarpa, Scatturin, Selb, Gagnon, Boas, and Cooper (2014); and iqr = 0.8, as used by Di Lorenzo, Pirazzoli, Blasi, Bulgarelli, Hakuno, Minagawa, and Brigadoi (2019). After visual examination and comparison of OD signal without motion artifact correction, OD signal with motion wavelet correction at iqr = 0.1, and OD signal with motion wavelet correction at iqr = 0.8, it was decided to use an iqr of 0.8 for future analysis.
- Filtering: OD data was bandpass filtered using the *hmr_RBandpassFilt* function using the following parameters: hpf (5th-order high-pass filter) = 0.01 and lpf (3rd-order low-pass filter) = 0.09 Hz, as recommended by Pinti, Scholkmann, Hamilton, Burgess, and Tachtsidis (2019).

- OD to hemodynamic concentrations: The *hmrR_OD2Conc* function was used to convert OD data to HbO, HbR, and total hemoglobin data (HbT). A partial pathlength factor (ppf) = [1.0, 1.0], to avoid the assumption of uniform absorption over the tissue (e.g., ~6 ppf or differential pathlength factor), was used as recommended by Homer3 developers.
- Hemodynamic response: The *hmrR_BlockAvg* function was used to obtain the hemodynamic response and block average of each task per subject and visit. The following time range inputs parameters were used to obtain a baseline before the task and the hemodynamic response during (20 sec) and after the task (10 sec): trange = [-5.0 30.00]. Once the hemodynamic responses were obtained, each block average per subject was exported for posterior analysis (see section 3.5.4).

3.4.2. Balance Tasks and Body Sway Index

Each balance task was performed while standing over a posturography platform (Balance System SD 950-440, Biodex Medical Systems, Shirley, NY, USA) with eyes closed to avoid external cues for 20 seconds. Between tasks, ~13 seconds of rest (10-sec rest + 3-sec countdown) were provided to allow the hemodynamic response to return to baseline levels. The order of the balancing tasks followed a counter-balanced block design pattern (e.g., A-B-B-A) with resting periods, as mentioned before. The balancing tasks and resting time were as follows:

- Bipedal standing: With the surface of the posturography platform fixed, feet width apart, and palms of hands over the hips, the participants were instructed to maintain balance.

- Unipedal standing: With the surface of the posturography platform fixed, the dominant foot over the platform, hip of the non-dominant foot flexed (~25º) and foot sole avoiding contact with the platform, and palms of hands over the hips, the participants were instructed to maintain balance.
- Resting period: During the resting period, the participants were standing over the posturography platform fixed with arms relaxed and eyes open. During this period, subjects were not instructed to maintain balance; instead, they were instructed not to move unless necessary.

Each task data (excluding the resting period) was stored in the posturography platform's internal memory. Then, the body sway index per task was obtained.

3.4.3. Proprioceptors Inhibition and Testing

3.4.3.1. Muscle Spindles Inhibition

As previously mentioned, at least 40 seconds of vibration can depress the firing activity of muscle spindles (Ribot-Ciscar et al., 1998); moreover, it has been shown that two minutes of vibration (Van Boxtel, 1986) and 30 minutes of vibration (Ekblom & Thorstensson, 2011; Lapole, Canon, & Pérot, 2012a; Lapole, Deroussen, Pérot, & Petitjean, 2012b; Ushiyama, Masani, Kouzaki, Kanehisa, & Fukunaga, 2005) can cause an H-reflex depression (depression of the stretch reflex); therefore, five minutes of sinusoidal vibration were applied over *soleus muscle* using a percussion hammer (Foredom Percussion Hammer, Bethel, CT, USA) with an amplitude of 1.5 mm set at a frequency ~ 66-70 Hz.

3.4.3.2. Cutaneous Receptors Inhibition

To inhibit skin receptors, a local anesthetic (topical lidocaine 4%) was applied over the foot sole of the dominant leg after cleansing with alcohol (Isopropyl 70%); then, after 30 minutes, the local anesthetic was removed with a hand towel.

3.4.3.3. Muscle Spindles Testing

Electromyography: After preparing the surface of the skin by removing hair, abrading, and cleansing with alcohol (Isopropyl 70%), three disposable surface electrodes (Cadwell Industries, Inc., Keenewick, WA, USA) were placed as mentioned by Leis and Schenk (2013). The active electrode was placed at the *soleus* and *medial gastrocnemius muscle* junction, the reference electrode over the Achilles tendon, and the ground electrode between the active electrode and the posterior tibial nerve while the participant was laying down in a prone position.

H-reflex and M-waves: With the subject laying down in a prone position and ankle in a 110 degrees plantar flexion, a bipolar probe connected to a stimulation cart (Cadwell Sierra summit, Cadwell Industries, Inc., Keenewick, WA, USA) was used to deliver percutaneous electrical stimulation. Before placing the cathode, the optimal position was determined by delivering a single stimulus at low intensity (5-10 mA). With the cathode and anode placed over the posterior tibial nerve in the popliteal fossa, an M_{Max} was identified by increasing the stimulus intensity in a stepwise fashion, by five mA, until the M-wave peak-to-peak reached a plateau. On the other hand, the H-reflex (peak-to-peak amplitude) was identified by applying three stimuli per time point, at a 20% intensity relative to M_{Max}. In some participants, a stimulus at 20% intensity relative

M_{Max} did not elicit a noticeable H-reflex even before vibration; thus, the lowest possible intensity when an H-reflex was noticeable was used before and after vibration during the same visit. The time points used after the onset of the first electrical nerve stimulation were 0sec, 25sec, and 50sec. Later, offline data analysis was performed using a custom-made Matlab script (Matlab R2018b, MathWorks, Inc., Natick, MA, USA). Firstly, the data was filtered with a zero-phase shift, 4th-order Butterworth filter with a bandpass of 10 – 500 Hz. Secondly, once the EMG signal was filtered, the signal of the three trials per time point was plotted to identify the peak-to-peak amplitude of each H-reflex. To identify the amplitude, the principal investigator manually detected each H-reflex's positive and negative peaks, then the data point values of each H-reflex were exported to a ".xls" file to calculate the average peak-to-peak amplitude per time point.

3.4.3.4. Cutaneous Receptors Testing

Using Von Frey filaments (Baseline Fold-Up Monofilaments, Fabrication Enterprises, Inc, White Plains, NY, USA), the sensitivity of the foot sole, specifically, skin of the first metatarsal and calcaneus (Heel), were examined by using the 4-2-1-search method as mentioned in Dyck, O'brien, Kosanke, Gillen, and Karnes (1993). A two-point discrimination test per region was performed using the descending-ascending method, as mentioned by Zimney, Dendinger, Engel, and Mitzel (2020). The sensitivity threshold was calculated based on the smallest force perceived in at least two out of three trials, and two-point discrimination was calculated based on the average of the ascending and descending values of the last reported two-points felt by the participant.

3.5. Statistical Analyses

All statistical analyses were performed using an open-source program (JASP v. 0.14.1.; JASP Team, 2020).

3.5.1. H-Reflex

A two-way (visit [Ctrl vs. MSI vs. BOTH] x time [pre_0 sec vs. pre_25 sec vs. pre_50 sec]) repeated measures analysis of variance (ANOVAs) was performed to examine potential H-reflex amplitude (peak-to-peak) differences at baseline between visits (before vibration). A two-way (visit [MSI vs. BOTH] x time [pre_0 sec vs. pre_25 sec vs. pre_50 sec vs. post_0sec vs. post_25sec vs. post_50sec]) repeated measures ANOVA was performed to examine the effects that five minutes vibration over the soleus muscle has over H-reflex amplitude (peak-to-peak). When appropriate, Bonferroni corrected dependent samples t-tests were performed.

3.5.2. Sensitivity Threshold and Two-Point Discrimination

Separate two-way (visit [Control vs. CB vs. BOTH] x location [Heel vs. first metatarsal]) repeated measures ANOVAs were performed to examine the effects of lidocaine on the sensory threshold and two-point discrimination. When appropriate, Bonferroni corrected dependent samples t-tests were performed.

3.5.3. Body Sway Index

The mean body sway index per task and visit was calculated, then a two-way (visit [Control vs. MSI vs. CB vs. BOTH] x task [bipedal vs. unipedal]) repeated measures ANOVA was performed to examine potential differences between visits. Also,

to examine if there was a familiarization, a one-way (visit order [1st visit vs. 2nd visit vs. 3rd visit vs. 4th visit]) repeated measures ANOVA was used. When appropriate, Bonferroni corrected dependent samples t-tests were performed.

3.5.4. Hemodynamic Response

A custom-made Matlab script (Matlab R2018b, MathWorks, Inc., Natick, MA, USA) was used to obtain the mean HbO (HbO_{mean}) from the hemodynamic response files. To obtain the HbO_{mean}, the Matlab script (Matlab R2018b, MathWorks, Inc., Natick, MA, USA) obtained, per channel, the average value from the onset of each task to the end of each task (20 sec. window), then the mean HbO was normalized to a 5 seconds window before the onset of each task. To obtain the HbO_{mean} per ROI x task, the HbO_{mean} per channel x task was averaged based on the specificity percentage of each channel; for example, the HbO_{mean} of the right premotor cortex during unipedal standing was obtained by averaging the HbO_{mean} of the source-detector channels from R_PreM ROI (see Figure 2). A two-way (visit [Control vs. MSI vs. CB vs. BOTH] x ROI [R_PreM vs. L_PreM vs. R_M1 vs. L_M1 vs. R_SA vs. L_SA vs. R_S1 vs. L_S1]) repeated measures ANOVA was performed per task (bipedal or unipedal) to examine the effects of inhibition of sensory information on the hemodynamic response of HbO. When differences were found among visits, Bonferroni corrected dependent samples t-tests were performed (differences among ROIs were not examined since it is not the main interest of this research). Moreover, if differences between visits were found, Bonferroni corrected dependent samples t-tests were used to compare the effects of visits using vibration (MSI and Both) vs. no vibration visit (Ctrl and CB) and to compare the effects of lidocaine (CB and Both) vs. no lidocaine visits (Ctrl and MSI). To evaluate potential differences per

ROI between significantly different visits, several dependent samples t-tests were performed and then false discovery rate corrected (Benjamini & Hochberg, 1995), as recommended for brain imaging studies by Glickman, Rao, and Schultz (2014); and Singh and Dan (2006). Brain images with significant t-values per ROI after false discovery rate correction were created using the Brain Function Mapping Tool from Wang, Yan, Wen, Yu, and Li (2016).

CHAPTER IV

RESULTS

4.1. Descriptive Statistics

From the initially recruited participants, four of them withdrew before completing the required number of visits to the Applied Neuromuscular Physiology Laboratory due to discomfort or inability to complete the study; therefore, twelve participants (eight male and four female) completed the four visits and were considered for statistical analysis (variable: Mean±Standard Deviation; age: 24.8.±4.59 yrs; weight: 80.86±18.72 kg; height: 174.75±9.10 cm). All participants identified their right leg as their dominant limb; therefore, all the tests were performed on the right leg.

4.2. Effects of Vibration on H-reflex Amplitude

After elimination of outliers and Greenhouse-Geisser correction, a two-way (visit [Ctrl vs. MSI vs. BOTH] x time [pre_0 sec vs. pre_25 sec vs. pre_50 sec]), repeated measures ANOVA showed that, at baseline (before vibration) there was not a significant visit x time interaction, $F(1.73,17.34) = 0.532$, $p = 0.531$, for H-reflex amplitude. Also,

there was not a significant main effect of visit, $F(1.63,16.34) = 1.114$, $p = 0.34$; and time, $F(1.29,12.94) = 0.402$, $p = 0.589$, for the H-reflex amplitude.

Comparing H-Reflex amplitude before and after vibration, and after outliers elimination and Greenhouse-Geisser correction when needed, a two-way (visit [MSI vs. BOTH] x time [pre_0sec vs. pre_25sec vs. pre_50sec vs. post_0sec vs. post_25sec vs. post_50sec), repeated measures ANOVA showed a non-significant interaction of visit x time, $F(1.06,8.48) = 0.193$, $p = 0.686$. Main effects examination revealed that visit was not different, $F(1,8) = 0.121$, $p = 0.737$; but time was different, $F(1.12,8.93) = 5.729$, $p = 0.038$. After Bonferroni correction ($p < 0.005$), comparison between pre- and post-vibration revealed that amplitude of H-reflex was lower after vibration (4.24±3.88 mV vs. 2.12±2.76 mV); specifically, between pre_0sec vs. post_0sec (4.19±4.00 mV vs. 1.82±2.74 mV). Changes in H-reflex amplitude per visit are presented in Table 1.

4.3. Effects of Lidocaine on Sensitivity

Statistical test of sensitivity threshold revealed that after examination of sphericity and Greenhouse-Geisser correction when needed, the two-way (visit [Ctrl vs. CB vs. BOTH] x location [Heel vs. first metatarsal]), repeated measures ANOVA showed a significant interaction of visit x location, $F(2,18) = 4.424$, $p = 0.021$. Simple main effects examination revealed that visit had an effect on Heel, $F(2,18) = 5.251$, $p = 0.016$; but not on first metatarsal, $F(2,18) = 0.25$, $p = 0.781$. Posterior analysis, after Bonferroni correction, revealed a significant difference between Ctrl vs. Both (0.63±0.66 gr. vs. 2.36±2.57 gr.; $p = 0.012$).

After sphericity examination, no Greenhouse-Geisser correction was needed while comparing the Two-point discrimination score; furthermore, the two-way (visit [Ctrl vs. CB vs. BOTH] x location [Heel vs. first metatarsal]), repeated measures ANOVA showed a non-significant interaction of visit x location, $F(2,18) = 0.951$, $p = 0.405$. Main effects examination revealed that visit was not different, $F(2,18) = 1.315$, $p = 0.293$; but location was different, $F(1,9) = 23.021$, $p < 0.001$ (Heel: 17.58±4.40 mm. vs. First metatarsal: 13.56±4.83 mm.). Changes in sensitivity threshold and two-point discrimination per visit are presented in Table 1.

Table 1. H-reflex Amplitude, Sensitivity Threshold, Two-Point Discrimination, and Body Sway Index per Visit.

	Control	MSI	CB	Both
	Mean ± SD	**Mean ± SD**	**Mean ± SD**	**Mean ± SD**
H-reflex Amplitude (mV)				
Pre 0sec	4.41 ± 4.23	3.99 ± 4.00	-----	4.38 ± 4.17
Pre 25sec	4.30 ± 4.08	4.12 ± 3.97	-----	4.23 ± 3.92
Pre 50sec	4.06 ± 4.27	4.35 ± 4.09	-----	4.34 ± 3.99
Post 0sec	-----	2.52 ± 3.50	-----	0.99 ± 1.08
Post 25sec	-----	2.95 ± 3.51	-----	1.38 ± 1.46
Post 50sec	-----	3.08 ± 3.59	-----	1.52 ± 1.50
Sensitivity Threshold (g)				
Heel	0.63 ± 0.66	-----	2.22 ± 3.02	2.36 ± 2.57
1st Metatarsal	0.47 ± 0.41	-----	0.46 ± 0.41	0.46 ± 0.31
Two-point Discrimination (mm)				
Heel	17.54 ± 3.49	-----	17.88 ± 5.48	17.33 ± 4.57
1st Metatarsal	15.42 ± 5.35	-----	11.60 ± 2.07	13.33 ± 5.71
Body Sway Index				
Bipedal	1.03 ± 0.34	1.23 ± 0.39	1.21 ± 0.43	1.43 ± 0.60
Unipedal	4.74 ± 2.04	4.77 ± 2.06	4.48 ± 1.51	4.43 ± 1.56

MSI: Muscle Spindle Inhibition, CB: Cutaneous Receptors Inhibition, BOTH: Muscle Spindle Inhibition and Cutaneous Receptors Inhibition.

4.4. Balance and Hemodynamic Response

After sphericity examination no Greenhouse-Geisser correction was needed while comparing Body Sway Index; furthermore, the two-way (visit [Ctrl vs. MSI vs. CB vs. BOTH] x task [Bipedal vs. Unipedal]), repeated measures ANOVA showed a non-significant interaction of visit x location, $F(3,27) = 1.017$, $p = 0.401$. Main effects examination revealed that visit was not different, $F(3,27) = 0.085$, $p = 0.967$; but task was different, $F(1,9) = 73.615$, $p < 0.001$. Further examination revealed a non-significant main effect of visit order, $F(3.63) = 0.060$, $p = 0.980$. Changes in body sway index per visit are presented in Table 1.

Comparing the HbO_{mean} during bipedal, a two-way (visit [Control vs. MSI vs. CB vs. BOTH] x ROI [R_PreM vs. L_PreM vs. R_M1 vs. L_M1 vs. R_SA vs. L_SA vs. R_S1 vs. L_S1]), repeated measures ANOVA showed a non-significant interaction of visit x ROI, $F(21,84) = 1.304$, $p = 0.196$. Main effects examination revealed that ROI, $F(7,28) = 1.952$ $p = 0.098$, and visit were not different, $F(3,12) = 1.615$, $p = 0.238$.

Comparing the HbO_{mean} during unipedal, a two-way (visit [Control vs. MSI vs. CB vs. BOTH] x ROI [R_PreM vs. L_PreM vs. R_M1 vs. L_M1 vs. R_SA vs. L_SA vs. R_S1 vs. L_S1]), repeated measures ANOVA showed a non-significant interaction of visit x ROI, $F(21,84) = 1.027$, $p = 0.442$. Main effects examination revealed that ROI was not different, $F(7,28) = 0.666$, $p = 0.698$; but visit was different, $F(3,12) = 4.101$, $p = 0.032$. After Bonferroni correction a significant difference was found between Ctrl vs. MSI, $t(47) = 3.736$, $p < 0.006$; Ctrl vs. Both, $t(71) = 6.584$, $p < 0.006$; CB vs MSI, $t(57) = 7.063$, $p < 0.006$; CB vs. Both, $t(68) = 11.392$, $p < 0.006$; and MSI vs. Both, $t(59) =$

5.029, p < 0.006. Also, a significant difference was found between vibration visits vs. no vibration visits, t(116) = -10.29, p< 0.006, and a not significant difference between lidocaine visits vs. no lidocaine visits, t(129) = -0.912, p = 0.36. Significant differences after false discovery rate corrected samples t-test comparing each ROI between significantly different visits can be seen in Figure 3. Also, three heat maps of the significant differences after false discovery rate can be seen in Figure 4 (MSI vs CB, and Both vs CB), Figure 5 (vibration vs no vibration visits), and Figure 6 (lidocaine vs no lidocaine).

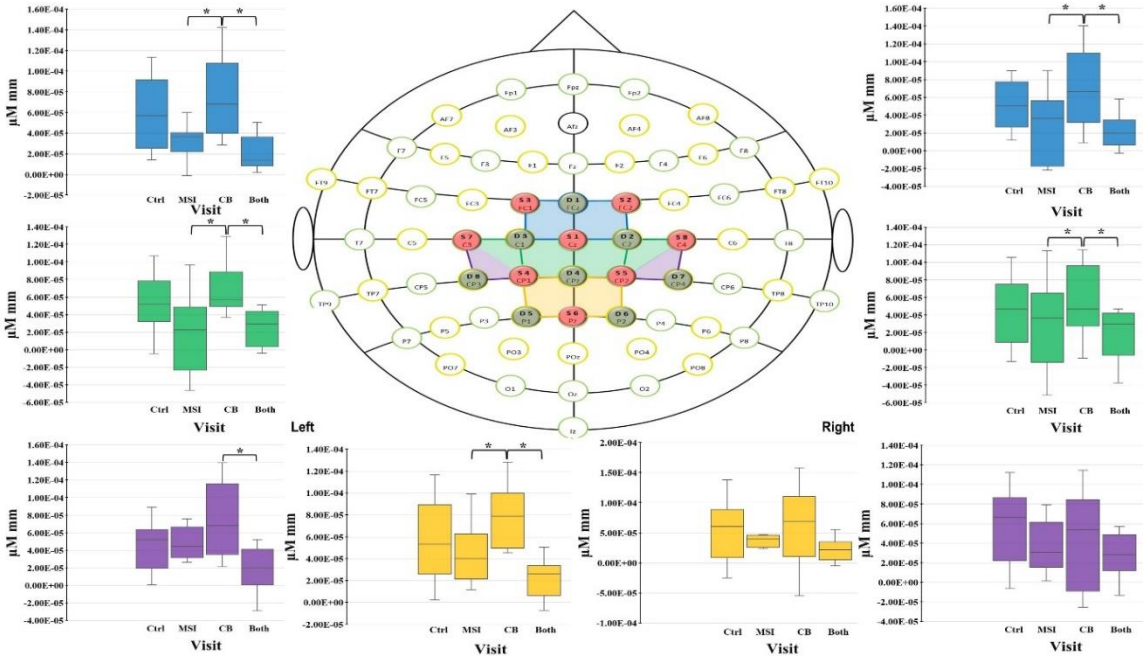
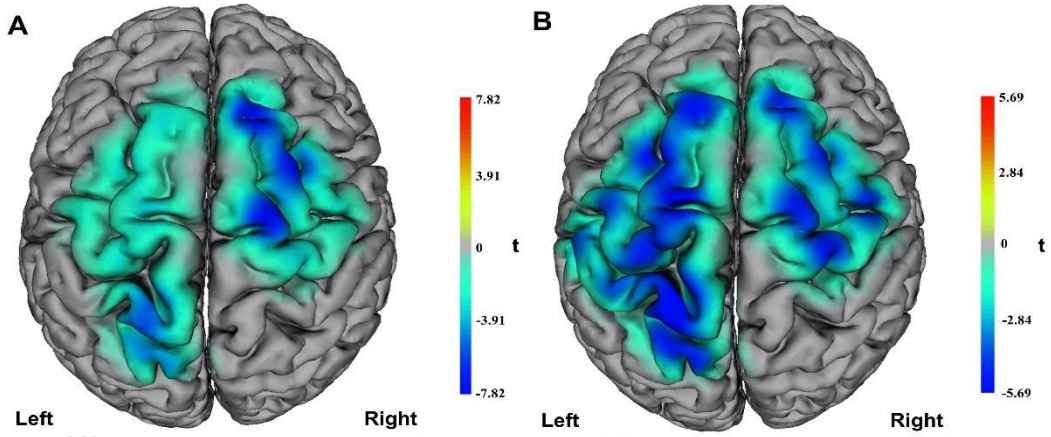


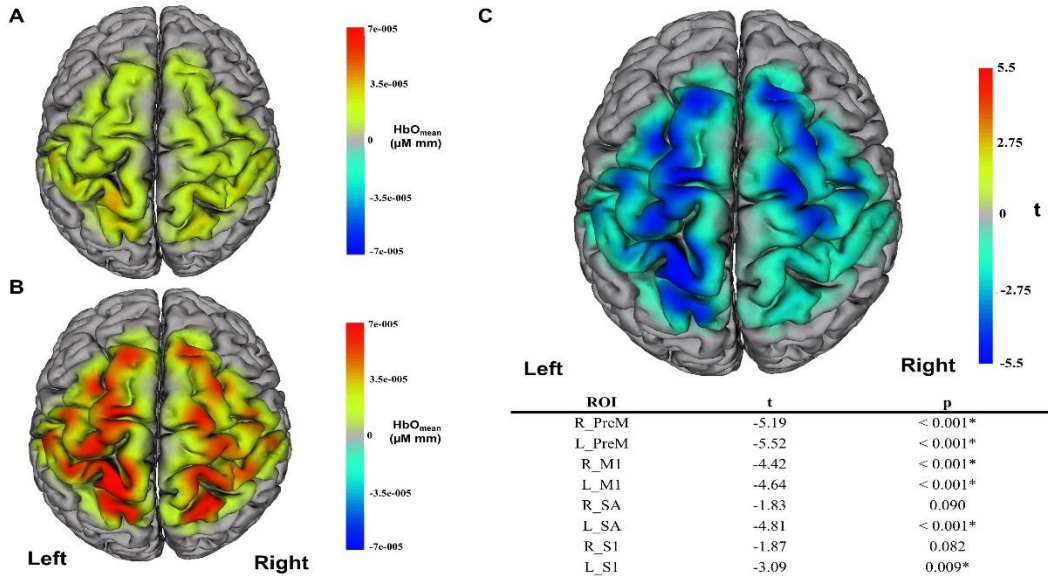
Figure 3. Comparison of mean oxyhemoglobin (HbO_{mean}) changes per visit during unipedal balance task. The regions of interest are shown per side in blue (premotor cortex), green (motor cortex), purple (somatosensory cortex), and yellow (somatosensory association). MSI: Muscle Spindle Inhibition, CB: Cutaneous Receptors Inhibition, BOTH: Muscle Spindle Inhibition and Cutaneous Receptors Inhibition. *Significant differences after False Discovery Rate correction.



ROI	t	p
R_PreM	-7.82	<0.001
L_PreM	-3.42	0.014
R_M1	-3.16	0.016
L_M1	-2.98	0.025
L_SA	-4.68	0.003

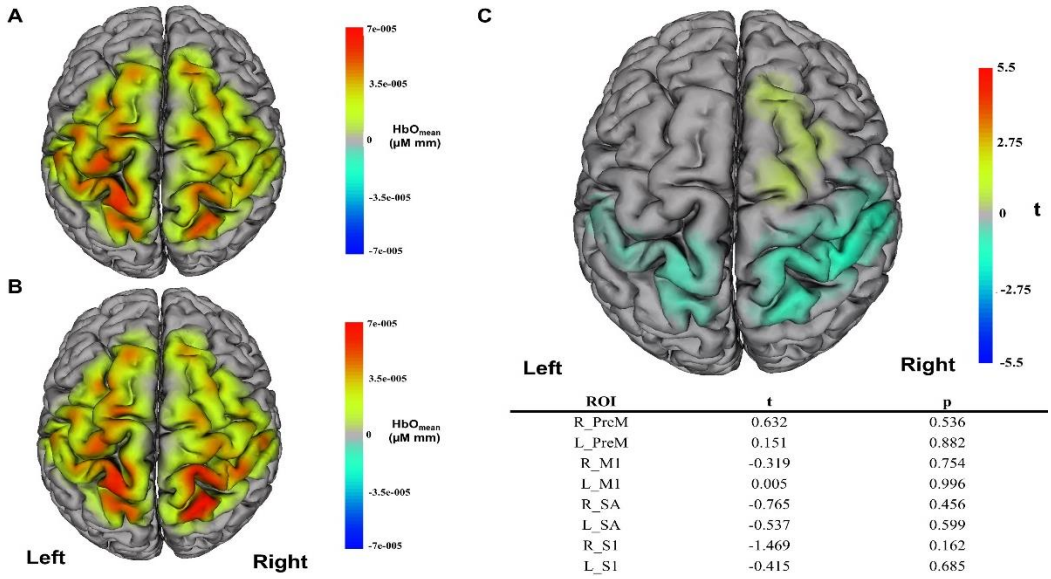
ROI	t	p
R_PreM	-5.04	0.001
L_PreM	-5.69	< 0.001
R_M1	-5.26	0.001
L_M1	-4.83	0.002
L_SA	-5.12	0.001
L_S1	-3.93	0.004

Figure 4. Heat map (t-values) of the mean hemodynamic response during unipedal standing. A) Comparison between muscle spindle inhibition vs. cutaneous block visit. B) Comparison between both vs. cutaneous block visit. A negative t-value means a lower HbOmean comparing visit#1 vs. visit#2



ROI	t	p
R_PreM	-5.19	< 0.001*
L_PreM	-5.52	< 0.001*
R_M1	-4.42	< 0.001*
L_M1	-4.64	< 0.001*
R_SA	-1.83	0.090
L_SA	-4.81	< 0.001*
R_S1	-1.87	0.082
L_S1	-3.09	0.009*

Figure 5. Heat map of cortical activity comparing vibration visits vs. no vibration visits during unipedal standing. A: Cortical activity of vibration visits, expressed as HbO_{mean}, during unipedal standing. B) Cortical activity of no vibration visits, expressed as HbO_{mean}, during unipedal standing. C) Heat map (t-values) of cortical activity comparison between vibration vs. no vibration visits; a negative t-value means a lower HbOmean during vibration visits compared to no vibration visits. *Statistically significant difference after FDR correction.



ROI	t	p
R_PreM	0.632	0.536
L_PreM	0.151	0.882
R_M1	-0.319	0.754
L_M1	0.005	0.996
R_SA	-0.765	0.456
L_SA	-0.537	0.599
R_S1	-1.469	0.162
L_S1	-0.415	0.685

Figure 6. Heat map of cortical activity comparing lidocaine visits vs. no lidocaine visits during unipedal standing. A) Cortical activity of lidocaine visits, expressed as HbO_{mean}, during unipedal standing. B) Cortical activity of no lidocaine visits, expressed as HbO_{mean}, during unipedal standing. C) Heat map (t-values) of cortical activity comparison between lidocaine vs. no lidocaine visits; a negative t-value means a lower HbOmean during lidocaine visits compared to no lidocaine visits.

CHAPTER V

DISCUSSION

The purpose of this research project was to identify changes in cortical hemodynamics of the motor, premotor, somatosensory, and somatosensory association cortex, related to balancing tasks during inhibition of muscle spindles and/or cutaneous receptors of the dominant limb. After elimination of noisy data and outliers detection, the statistical analyses revealed that: 1) H-reflex amplitude decreased after 5 minutes of vibration, specifically comparing pre_0sec vs. post_0sec; 2) lidocaine applied over the foot sole for thirty minutes had different effects with heel sensory threshold different between Ctrl and Both, but no differences among visits on the two-point discrimination for either heel or first metatarsal; 3) body sway was not different among visits, but it was different between tasks (bipedal vs. unipedal); and 4) there was not a difference in HbO_{mean}, among visits during bipedal tasks, but there was a difference among visits during unipedal standing, specifically between visits inhibiting muscle spindles (MSI and Both) vs. visits not manipulating muscle spindles (Ctrl and CB).

5.1. Muscle Spindle Inhibition and H-Reflex

As expected, H-Reflex amplitude was not different before vibration while comparing among visits. Moreover, after five minutes of vibration, H-reflex amplitude decreased significantly, as shown by the difference of the main effect between pre-vibration vs. post-vibration amplitudes (4.24±3.88 mV vs. 2.12±2.76 mV). Although the posterior analysis revealed a difference between one comparison pairs (pre_0sec > post_0sec), certainly H-reflex amplitude was higher before than after vibration, as shown in all the pairwise comparisons; in fact, before Bonferroni correction, all the pre vs. post comparisons had a $p < 0.05$. Thus, indicating a decrease in Ia afferent activity and, possibly, a decrement in reflex excitability from *soleus muscle* while standing (Lapole et al., 2012a) after five minutes of vibration.

Similar to the finding in this study, H-reflex amplitude decrements have been reported after vibrating the muscle belly for 2 minutes (Van Boxtel, 1986) and the Achilles tendon for at least 30 minutes (Ekblom et al., 2011; Lapole et al., 2012a; Lapole et al., 2012b; Ushiyama et al., 2005).

5.2. Foot Sole Sensitivity

Unlike muscle spindles' testing, where a decrement in H-reflex amplitude was evident, the cutaneous receptors testing showed inconclusive and contradictory findings. On one side, the sensitivity threshold revealed a visit x location interaction with the visit having an effect on the heel and a specifically higher sensitivity threshold during Both (2.36 ± 2.57 gr) compared to Ctrl (0.63 ± 0.66 gr). On the other side, the two-point discrimination revealed no significant interaction and difference between visits but a

significant difference between locations. Moreover, although not significant, on the first metatarsal location, the participants were able to identify two points at lower amplitude during Both (13.33 ± 5.71 mm) and CB (11.60 ± 2.07 mm) compared to Ctrl (15.42 ± 5.35 mm), a contradictory finding if a diminished sensitivity were to be expected after applying lidocaine. Therefore, as previously mentioned, the effects of lidocaine over the foot sole remain inconclusive.

Local anesthesia might be elicited using topical and injectable methods (Giordano, Nelson, Kohen, Nijhawan, & Srivastava, 2015). Injecting lidocaine to diminish the activity of the cutaneous afferents of the foot and ankle, Grey et al. (2001) found that lidocaine caused a decrement in somatosensory evoked potentials. Using EMLA cream (2.5% lidocaine + 2.5% prilocaine), Mildren et al. (2017) found that EMLA caused a reduction of the participants' posterior ankle sensitivity. Unlike the previously mentioned authors, in this study, the application of a local anesthetic showed inconclusive findings; the differences might be explained by the amount of time the lidocaine was left over the skin and the type of anesthetic used. Firstly, injectable anesthesia might be more efficient than topical anesthesia (Giordano et al., 2015). Lastly, unlike Mildren et al. (2017), instead of using EMLA cream wrapped over the skin for 105 minutes, in this study, lidocaine was applied and left, but not wrapped, for 30 minutes over the skin. As Sobanko, Miller, and Alster (2012) mentioned, EMLA absorption might be enhanced by one of its components, and plastic wrapping and time might have helped increase the anesthetic effect in Mildren et al. (2017).

5.3. Balance and Cerebral Cortex Hemodynamics

Analyzing the body sway index, the statistical analysis revealed no differences among visits, but there was a significant difference between tasks, with bipedal standing (1.22 ± 0.46) showing less body sway index than unipedal standing (4.61 ± 1.74). Moreover, comparing HbO_{mean} of the different tasks revealed the visit factor was different during unipedal standing but not for bipedal standing. Specifically, the visits when muscle spindle inhibition was used (MSI and Both) had a lower HbO_{mean} than the visits when the muscle spindles were not inhibited (Ctrl and CB).

Different studies have found that cutaneous receptors play a role during standing while others have not. For example, applying mechanical stimulation over the foot sole of both legs, Kavounoudias, Roll, and Roll (2001) found that slight stimulation while standing cause posterior tilting in healthy adults. Also, Magnusson, Enbom, Johansson, and Pyykkö (1990) found that after diminishing sensory input through ice immersion of the feet, the participants' body sway while standing with eyes closed was greater compared to before ice immersion. Unlike the previously mentioned authors, other authors have not found any difference in balance (measured as center of pressure excursion) after diminishing feet sensation (e.g., McKeon & Hertel, 2007). In this study, body sway index was not different between control and any visit intended to block or diminish sensation was found (CB and BOTH). The lack of difference in body sway might be explained by the inconclusive findings regarding the lidocaine (4%) effects over the dominant limb's foot sole. Also, HbO_{mean} was not different during bipedal, as previously mentioned, and during unipedal task comparing control vs. CB visit ($p = 0.94$).

Regarding the influence of muscle spindles on balance, different procedures have been used to test proprioceptors' influence while standing. Some authors like Herold et al. (2017); Karim et al. (2013); Lin, Barker, Sparto, Furman, and Huppert (2017); and Takakura et al. (2015) have used movable surfaces to challenge the proprioceptors; others like Čapičikova, Rocchi, Hlavačka, Chiari, and Capello (2006); and Duclos, Maynard, Barthelemy, and Mesure (2014) have used vibration applied over the *soleus muscle* and Achilles tendon during standing, respectively. All the previously mentioned authors found that, compared to baseline (eyes open on a fixed surface), body sway (measured as the center of pressure displacement or anterior-posterior displacement) increased when the proprioceptors were challenged. Moreover, specific to the comparisons performed in this study, Karim et al. (2013); and Takakura et al. (2015) found that body sway was higher (measured as displacement of center of pressure or center of gravity) during bipedal standing on a sway platform with diminished vision, compared to bipedal standing on a fixed platform with diminished vision (SP+EO+dark vs. FP+EO+dark, and SP+EC+FS vs. FP+EC+FS, respectively).

To the author's knowledge, few authors have examined the aftereffects of local vibration of the *soleus muscle* on balance performance (to elicit a depression of the muscle spindles activity of the muscle). In that sense, Ema, Kanda, Shoji, Iida, and Akagi (2020) compared unipedal balance with eyes open before and after 30 minutes of vibration (80 Hz) over the myotendinous junction of the right *soleus muscle*. Ema et al. (2020) reported that, compared to before vibration, the young participants showed a significant increase in center of pressure speed after vibration; therefore, balance performance decreased after vibration. Unlike Ema et al. (2020), in this study, the

statistical analysis did not reveal any significant difference, in body sway index, between control and any visit meant to inhibit muscle spindle activity from the soleus muscle (MSI and Both visits). Some methodological differences might explain the different findings between both studies: 1) unlike the 30 minutes applied before balance by Ema and colleagues (2020), in this study, five minutes of vibration were applied before a block of two balance tasks, and, although the H-reflex decreased for ~ 50 seconds, the statistical analysis after Bonferroni correction revealed just a significant difference immediately after vibration. 2) it is not clear if there was a postural modulation in both studies, as Lapole et al. (2012a) showed, since H-Reflexes were not examined while standing. 3) It may be assumed that 30 minutes of vibration elicited an H-reflex depression (see muscle spindle inhibition and H-reflex section); nevertheless, Ema and colleagues (2020) did not compare any H-reflex amplitude before and after vibration. 4) Although several studies have found that vibration $\geq$ 60 Hz preferably stimulates Ia afferents (Ribot-Ciscar et al., 1998; Roll et al., 1982; Roll, Vedel, & Ribot, 1989), vibration over the muscle belly might just stimulate and depress the muscle spindles, and vibration over the myotendinous junction might stimulate and depress the muscle spindles plus the Golgi tendon organs.

Aside from the previously mentioned manuscript, the lack of balance difference between control, MSI, and Both, might be explained by proprioceptive illusions of movement elicited by local vibration during the five minutes of vibration before the balancing tasks. In that sense, Goodwin et al. (1972) reported that while vibration was applied at 100 Hz over the biceps or triceps tendon, the participants misjudged the elbow angle. In fact, under the assumption that local vibration elicits proprioceptive illusions of

movement, the previously mentioned authors (Čapičikova et al., 2006; Duclos et al., 2014) found differences during balancing tasks comparing vibration vs. no vibration. Moreover, although it can be assumed that muscle spindles remained depressed for ~50 sec, it is possible that such depression was not enough to elicit a substantial difference in body sway. For example, Duclos et al. (2014) showed that after local vibration stopped (20 sec. vibration), the participants had center of pressure values similar to baseline values after ~ 12 sec for bipedal standing. Nevertheless, caution should be taken due to differences in the amount of time the local vibration was applied and the balance tasks on this study and the study from Duclos et al. (2014).

Regarding HbO changes, Karim et al. (2013) reported more HbO activity over the temporal-parietal cortex (Brodmann Area: 40 and 48) while transitioning from bipedal standing on FP+EO+dark to SP+EO+dark. Also, to expand the findings from Karim et al. (2013), Takakura et al. (2015) examined the temporal, frontal, and parietal cortices in the right hemisphere. After comparing bipedal standing on FP+EC+FS vs. SP+EC+FS, the statistical analysis revealed 1) no significant HbO activity over the supplementary motor area and somatosensory cortex; and 2) a significantly larger HbO activity over the frontal operculum and superior temporal gyrus (cortical areas receiving vestibular afferents, as assumed by Takakura et al. 2005). Like Takakura et al. (2015), in this study, no difference in HbO was found in any motor or sensory area while comparing bipedal standing with eyes closed among the different visits (Ctrl, MSI, and Both).

As mentioned in Chapter 2, early studies with cats showed that muscle spindle afferents have projections to the cerebral cortex; specifically, to the contralateral somatosensory cortex (Landgren et al., 1969; Oscarsson et al., 1963). In humans,

proprioceptive information is sent to the central nervous system via two pathways: 1) spinal cord-thalamus-cerebral cortex, and 2) spinal cord-cerebellum-thalamus-cerebral cortex (Naito, Morita, & Amemiya, 2016). Although the sensory activity from Golgi tendon organs and cutaneous receptors may contribute to brain imaging findings while applying vibration over the muscle-tendon, studies using vibration have shown the projections of muscle spindle afferents to the cerebral cortex of human beings (e.g., Goble et al., 2011a). Specifically, in their review, Naito et al. (2016) reported motor and somatosensory cortical representations related to proprioceptive movement illusions elicited during vibration of tendons of the limbs. Thus it is clear that vibration can cause increased neural activity over the ROIs examined in this study (increased HbO).

The findings from unilateral standing showed that after vibration, HbO changes were lower in visits that inhibited muscle spindles than visits that did not inhibit muscle spindles. To explain the findings, it is necessary to examine the current studies exploring the cortical activity during and after vibration. During vibration, as previously mentioned, there is increased activity over the motor and somatosensory cortex (Naito et al., 2016). On the other side, the aftereffects of vibration are not yet evident. For example, Lapole et al. (2012b) reported no change in cortical excitability immediately after Achilles tendon vibration (time: 60 min; amplitude: 0.2 mm; frequency: 50 Hz) but an increase in cortical excitability one hour after vibration stopped. Opposite findings have been reported by Farabet, Souron, Millet, and Lapole (2016) after vibration over the *tibialis anterior muscle* (time: 30 min; amplitude: 1 mm; frequency: 100 Hz); that is, the authors reported a decrement in cortical excitability after 30 min of vibration over the *tibialis anterior muscle*. Unfortunately, to my knowledge, there are no studies using brain imaging

methods evaluating the aftereffects of vibration; therefore, assuming that more cortical excitability from TMS studies is related to increases in HbO and less cortical excitability from TMS studies is related to decrements in HbO, this study would be in agreement with the findings from Farabet et al. (2016); nevertheless, caution should be taken because of differences in vibrated muscle, vibration time, amplitude, and frequency used.

Lastly, the fatiguing effects of nerve stimulation and vibration might offer another explanation to the findings in this study regarding HbO decrements after inhibiting muscle spindles from *soleus muscle*. Although unlikely due to the intensity used in this study, fatigue from electrical stimulation has been reported by Alexandre, Derosiere, Papaiordanidou, Billot, and Varray (2015). Alexandre and colleagues (2015) reported that after 17 electrical stimulations of the plantar flexors, at maximally tolerated intensity, the HbO of M1 and S1 decreased compared to baseline values. Also, reasoning about the induced force decrements after local vibration (20 - 30 min), Souron, Besson, Millet, and Lapole (2017) mentioned that such decrements in force might be due to a reduction in "…neural drive occurring at a spinal and/or supra-spinal level" (p. 1944).

5.4. Limitations

First, one of the limitations of this study is that H-reflex was measured while the participants were in prone position and, although there was a decrement in H-reflex amplitude after five minutes of vibration, it remains to be known if there was a modulation of the H-reflex amplitude during standing. For example, Lapole et al. (2012a) reported that, although H-reflex amplitude decreased after 60 minutes of vibration, the H-reflex amplitude changed from sitting to standing position.

Additionally, another limitation of this study is that only one leg and muscle were vibrated, and although the vibration was applied at a constant frequency and amplitude, it remains to be known if the pressure applied over the muscle plays a role in muscle inhibition; that is, during standing the pressure applied over the soleus muscle might have changed due to limitations of the device being used (no strap used to maintain constant pressure over the muscle belly).

Regarding lidocaine, one of the limitations was the time the anesthetic was left over the foot sole and the percentage of lidocaine the ointment contained (4%); as previously mentioned, it seems plausible that with more time and a higher percentage of lidocaine (e.g., 5%) the anesthetic effect would have been noticeable. Moreover, the findings from this study might not be generalized to other areas of the foot sole since the sensitivity threshold and the two-point discrimination were only measured over the first metatarsal and the heel.

Lastly, this study did not examine the EMG activity of different lower limb muscles involved during standing, mainly because recording EMG activity during standing would imply removing and placing the surface EMG detectors, and preparing the skin of the participants, over the soleus muscle once vibration over the muscle had stopped, an activity that would imply allowing recovery of the previously inhibited muscles spindles.

5.5 Conclusion

The primary finding of this study was that inhibition of muscle spindles from the *soleus muscle* of the dominant leg, as shown by the differences in H-reflex amplitude

before and after five minutes of vibration, alter the cortical hemodynamics of the bilateral premotor and motor cortex, and the contralateral somatosensory association and somatosensory cortex during unipedal standing but not during bipedal standing. Although muscle spindle inhibition altered the cortical hemodynamics during unipedal standing, the cortical activity changes did not seem to influence the performance of balance (measured as body sway index) since there were no differences between visits that inhibited and did not inhibit muscle spindles of the *soleus muscle*. It is possible that the lack of differences in body sway might be due to a slow recovery of the H-Reflex amplitude immediately after the vibration stopped (comparisons after Bonferroni correction showed that H-reflex amplitude was significantly depressed immediately after vibration but not 25 and 50 seconds after vibration stopped). In that sense, longer vibration times ($\geq$ 20 min) may elicit differences in balance compared to control conditions, as shown by Ema et al. (2020).

It should also be pointed out that although cortical activity was lower during unipedal standing with muscle spindles inhibited, that does not necessarily mean that cortical activity of the regions of interest analyzed here was lower compared to baseline levels (bipedal standing with eyes open); in other words, this study does not disprove early findings using fNIRS during different balance conditions. Moreover, the lack of increased cortical activity over the motor and somatosensory cortex (compared to unipedal standing when vibration was not applied) does not necessarily mean that all the cerebral cortex had the same cortical activity; in other words, the findings should not be extrapolated to conclude that when muscle spindles are inhibited the whole cerebral cortex shows less cortical activity during unipedal standing.

The other findings from this study revealed that topical lidocaine (4%) applied over the foot sole for 30 minutes might not be enough to inhibit the cutaneous receptors' activity, as shown by mixed findings regarding sensitivity threshold and two-point discrimination point. Also, this study found no differences in cortical activity and balance between visits using lidocaine and not using it. In that sense, conclusions regarding the influence of cutaneous receptors over balance and cerebral cortex activity can not be made since lidocaine did not seem to inhibit cutaneous receptors. The mixed findings might grant a future study using a topical applied during more time (~ 60 minutes) with a higher concentration of lidocaine, or other ointment meant to inhibit cutaneous receptors (e.g., lidocaine 5% or EMLA).

Future studies meant to examine the cerebral cortex hemodynamics while muscle spindles are inhibited should measure changes in oxyhemoglobin during and after prolonged vibration, mainly to help elucidate and complement previous findings, as mentioned in the discussion section of this study. Moreover, future studies might use brain imaging and brain stimulation techniques to examine the effects of prolonged vibration (during and after vibration) over the cerebral cortex and different regions of interest. For example, because the frontoparietal cortex seems to play a role during standing (Mihara et al., 2008), a future study might evaluate the frontoparietal cortex's neural activity during standing while muscle spindles are inhibited. Lastly, to understand human standing, future studies using brain imaging techniques with higher spatial resolution might be granted to explore the neural activity of subcortical components (e.g., brain stem, thalamus, and cerebellum) when muscle spindles and other proprioceptors are inhibited.

REFERENCES

Abraira, V. E., & Ginty, D. D. (2013). The sensory neurons of touch. *Neuron, 79*(4), 618-639. doi: https://doi.org/10.1016/j.neuron.2013.07.051

Adrian, E. D., & Umrath, K. (1929). The impulse discharge from the pacinian corpuscle. *The Journal of Physiology, 68*(2), 139. doi: https://doi.org/10.1113/jphysiol.1929.sp002601

Adrian, E. D., & Zotterman, Y. (1926). The impulses produced by sensory nerve endings: Part 3. Impulses set up by touch and pressure. *The Journal of Physiology, 61*(4), 465-483. doi:https://doi.org/10.1113/jphysiol.1926.sp002308

Alexandre, F., Derosiere, G., Papaiordanidou, M., Billot, M., & Varray, A. (2015). Cortical motor output decreases after neuromuscular fatigue induced by electrical stimulation of the plantar flexor muscles. *Acta Physiologica, 214*(1), 124-134. doi: https://doi.org/10.1111/apha.12478

Banks, R. (1981). A histological study of the motor innervation of the cat's muscle spindle. *Journal of Anatomy, 133*(Pt 4), 571.

Beloozerova, I. N., Sirota, M. G., Orlovsky, G. N., & Deliagina, T. G. (2005). Activity of pyramidal tract neurons in the cat during postural corrections. *Journal of Neurophysiology, 93*(4), 1831-1844. doi:https://doi.org/10.1152/jn.00577.2004

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society, 57*(1), 289-300. doi: https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

Bentivoglio, M., & Pacini, P. (1995). Filippo Pacini: a determined observer. *Brain Research Bulletin, 38*(2), 161-165. doi:https://doi.org/10.1016/0361-9230(95)00083-Q

Boyd, I. A. (1962). The structure and innervation of the nuclear bag muscle fibre system and the nuclear chain muscle fibre system in mammalian muscle spindles. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 245*(720), 81-136. doi:https://doi.org/10.1098/rstb.1962.0007

Brigadoi, S., Ceccherini, L., Cutini, S., Scarpa, F., Scatturin, P., Selb, J., . . . Cooper, R. J. (2014). Motion artifacts in functional near-infrared spectroscopy: a comparison of motion correction techniques applied to real cognitive data. *Neuroimage, 85*, 181-191. doi:https://doi.org/10.1016/j.neuroimage.2013.04.082

Čapičikova, N., Rocchi, L., Hlavačka, F., Chiari, L., & Capello, A. (2006). Human postural response to lower leg muscle vibration of different duration. *Physiological Research, 55*.

Carius, D., Hörnig, L., Ragert, P., & Kaminski, E. (2020). Characterizing cortical hemodynamic changes during climbing and its relation to climbing expertise. *Neuroscience Letters, 715*, 134604. doi:https://doi.org/10.1016/j.neulet.2019.134604

Deliagina, T. G., Zelenin, P. V., Beloozerova, I. N., & Orlovsky, G. N. (2007). Nervous mechanisms controlling body posture. *Physiology & Behavior, 92*(1-2), 148-154. doi:https://doi.org/10.1016/j.physbeh.2007.05.023

Di Lorenzo, R., Pirazzoli, L., Blasi, A., Bulgarelli, C., Hakuno, Y., Minagawa, Y., & Brigadoi, S. (2019). Recommendations for motion correction of infant fNIRS data applicable to multiple data sets and acquisition systems. *Neuroimage, 200*, 511-527. doi:https://doi.org/10.1016/j.neuroimage.2019.06.056

Duclos, N. C., Maynard, L., Barthelemy, J., & Mesure, S. (2014). Postural stabilization during bilateral and unilateral vibration of ankle muscles in the sagittal and frontal planes. *Journal of Neuroengineering Rehabilitation, 11*(1), 1-10. doi:https://doi.org/10.1186/1743-0003-11-130

Dyck, P. J., O'brien, P., Kosanke, J., Gillen, D., & Karnes, J. (1993). A 4, 2, and 1 stepping algorithm for quick and accurate estimation of cutaneous sensation threshold. *Neurology, 43*(8), 1508-1508. doi:https://doi.org/10.1212/WNL.43.8.1508

Eccles, J., Eccles, R. M., & Lundberg, A. (1957). The convergence of monosynaptic excitatory afferents on to many different species of alpha motoneurones. *The Journal of Physiology, 137*(1), 22-50. doi:https://doi.org/10.1113/jphysiol.1957.sp005794

Ekblom, M. M. N., & Thorstensson, A. (2011). Effects of prolonged vibration on H-reflexes, muscle activation, and dynamic strength. *Medicine & Science in Sports & Exercise, 43*(10), 1933-1939. doi:10.1249/MSS.0b013e318217d720

Eldred, E., Granit, R., & Merton, P. A. (1953). Supraspinal control of the muscle spindles and its significance. *The Journal of Physiology, 122*(3), 498-523. doi:https://doi.org/10.1113/jphysiol.1953.sp005017

Ema, R., Kanda, A., Shoji, M., Iida, N., & Akagi, R. (2020). Age-related differences in the effect of prolonged vibration on maximal and rapid force production and balance ability. *Frontiers in Physiology, 11*, 1406. doi:https://doi.org/10.3389/fphys.2020.598996

Farabet, A., Souron, R., Millet, G. Y., & Lapole, T. (2016). Changes in tibialis anterior corticospinal properties after acute prolonged muscle vibration. *European Journal of Applied Physiology, 116*(6), 1197-1205.

Giordano, C. N., Nelson, J., Kohen, L. L., Nijhawan, R., & Srivastava, D. (2015). Local anesthesia: evidence, strategies, and safety. *Current Dermatology Reports, 4*(3), 97-104. doi:https://doi.org/10.1007/s13671-015-0110-9

Glickman, M. E., Rao, S. R., & Schultz, M. R. (2014). False discovery rate control is a recommended alternative to bonferroni-type adjustments in health studies. *Journal of Clinical Epidemiology, 67*(8), 850-857. doi:https://doi.org/10.1016/j.jclinepi.2014.03.012

Goble, D. J., Coxon, J. P., Van Impe, A., Geurts, M., Doumas, M., Wenderoth, N., & Swinnen, S. P. (2011a). Brain activity during ankle proprioceptive stimulation predicts balance performance in young and older adults. *Journal of Neuroscience, 31*(45), 16344-16352. doi:https://doi.org/10.1523/JNEUROSCI.4159-11.2011

Goble, D. J., Coxon, J. P., Van Impe, A., Geurts, M., Van Hecke, W., Sunaert, S., . . . Swinnen, S. P. (2011b). The neural basis of central proprioceptive processing in older versus younger adults: an important sensory role for right putamen. *Human Brain Mapping, 33*(4), 895-908. doi:https://doi.org/10.1002/hbm.21257

Goodwin, G. M., McCloskey, D. I., & Matthews, P. B. (1972). Proprioceptive illusions induced by muscle vibration: contribution by muscle spindles to perception? *Science, 175*(4028), 1382-1384. doi:10.1126/science.175.4028.1382

Grey, M. J., Ladouceur, M., Andersen, J. B., Nielsen, J. B., & Sinkjær, T. (2001). Group II muscle afferents probably contribute to the medium latency soleus stretch reflex during walking in humans. *The Journal of Physiology, 534*(3), 925-933. doi:https://doi.org/10.1111/j.1469-7793.2001.00925.x

Herold, F., Orlowski, K., Börmel, S., & Müller, N. G. (2017). Cortical activation during balancing on a balance board. *Human Movement Science, 51*, 51-58. doi:https://doi.org/10.1016/j.humov.2016.11.002

Hocke, L. M., Oni, I. K., Duszynski, C. C., Corrigan, A. V., Frederick, B. d., & Dunn, J. F. (2018). Automated Processing of fNIRS Data—a visual guide to the pitfalls and consequences. *Algorithms, 11*(5), 67. doi:https://doi.org/10.3390/a11050067

Horak, F. B., & Macpherson, J. M. (2010). Postural orientation and equilibrium. *Comprehensive Physiology*, 255-292. doi:https://doi.org/10.1002/cphy.cp120107

Hunt, C. C. (1951). The reflex activity of mammalian small-nerve fibres. *The Journal of Physiology, 115*(4), 456-469. doi:https://doi.org/10.1113/jphysiol.1951.sp004681

Huppert, T. J., Diamond, S. G., Franceschini, M. A., & Boas, D. A. (2009). HomER: a review of time-series analysis methods for near-infrared spectroscopy of the brain. *Applied Optics, 48*(10), D280-D298. doi:https://doi.org/10.1364/AO.48.00D280

Iggo, A., & Muir, A. R. (1969). The structure and function of a slowly adapting touch corpuscle in hairy skin. *The Journal of Physiology, 200*(3), 763-796. doi:https://doi.org/10.1113/jphysiol.1969.sp008721

Jacobs, J. V., & Horak, F. B. (2007). Cortical control of postural responses. *Journal of Neural Transmission, 114*(10), 1339. doi:https://doi.org/10.1007/s00702-007-0657-0

Johnson, K. O. (2001). The roles and functions of cutaneous mechanoreceptors. *Current Opinion in Neurobiology, 11*(4), 455-461. doi:https://doi.org/10.1016/S0959-4388(00)00234-8

Kaas, J. H. (2004). Somatosensory system. *The Human Nervous System*, 1059-1092.

Karim, H., Fuhrman, S. I., Sparto, P., Furman, J., & Huppert, T. (2013). Functional brain imaging of multi-sensory vestibular processing during computerized dynamic posturography using near-infrared spectroscopy. *Neuroimage, 74*, 318-325. doi:https://doi.org/10.1016/j.neuroimage.2013.02.010

Kavounoudias, A., Roll, R., & Roll, J. P. (2001). Foot sole and ankle muscle inputs contribute jointly to human erect posture regulation. *The Journal of Physiology, 532*(3), 869-878. doi:https://doi.org/10.1111/j.1469-7793.2001.0869e.x

Keck, M. E., Pijnappels, M., Schubert, M., Colombo, G., Curt, A., & Dietz, V. (1998). Stumbling reactions in man: influence of corticospinal input. *Electroencephalography and Clinical Neurophysiology/Electromyography and Motor Control, 109*(3), 215-223. doi:https://doi.org/10.1016/S0924-980X(98)00009-5

Kennedy, P. M., & Inglis, J. T. (2002). Distribution and behaviour of glabrous cutaneous receptors in the human foot sole. *The Journal of Physiology, 538*(3), 995-1002. doi:https://doi.org/10.1113/jphysiol.2001.013087

Knibestöl, M., & Vallbo, Å. B. (1970). Single unit analysis of mechanoreceptor activity from the human glabrous skin. *Acta Physiologica Scandinavica, 80*(2), 178-195. doi:https://doi.org/10.1111/j.1748-1716.1970.tb04783.x

Kolliker, A. V. (1863). Croonian lecture-On the termination of nerves in muscles, as observed in the frog; and on the disposition of the nerves in the frog's heart. *Proceedings of the Royal Society of London*(12), 65-84. doi:https://doi.org/10.1098/rspl.1862.0011

Landgren, S., & Silfvenius, H. (1969). Projection to cerebral cortex of group I muscle afferents from the cat's hind limb. *The Journal of physiology, 200*(2), 353-372. doi:https://doi.org/10.1113/jphysiol.1969.sp008698

Lapole, T., Canon, F., & Pérot, C. (2012a). Acute postural modulation of the soleus H-reflex after Achilles tendon vibration. *Neuroscience letters, 523*(2), 154-157. doi:https://doi.org/10.1016/j.neulet.2012.06.067

Lapole, T., Deroussen, F., Pérot, C., & Petitjean, M. (2012b). Acute effects of Achilles tendon vibration on soleus and tibialis anterior spinal and cortical excitability. *Applied Physiology, Nutrition, and Metabolism, 37*(4), 657-663. doi:https://doi.org/10.1139/h2012-032

Leis, A. A., & Schenk, M. P. (2013). *Atlas of nerve conduction studies and electromyography*: Oxford University Press.

Lin, C.-C., Barker, J. W., Sparto, P. J., Furman, J. M., & Huppert, T. J. (2017). Functional near-infrared spectroscopy (fNIRS) brain imaging of multi-sensory integration during computerized dynamic posturography in middle-aged and older adults. *Experimental brain research, 235*(4), 1247-1256.

Magnus, R. (1926). Some results of studies in the physiology of posture. *Lancet, 211*(ii), 531-536.

Magnusson, M., Enbom, H., Johansson, R., & Pyykkö, I. (1990). Significance of pressor input from the human feet in anterior-posterior postural control: the effect of hypothermia on vibration-induced body-sway. *Acta Oto-Laryngologica, 110*(3-4), 182-188. doi:https://doi.org/10.3109/00016489009122535

Matthews, B. (1933). Nerve endings in mammalian muscle. *The Journal of Physiology, 78*(1), 1-53. doi:https://doi.org/10.1113/jphysiol.1933.sp002984

Matthews, P. (1962). The differentiation of two types of fusimotor fibre by their effects on the dynamic response of muscle spindle primary endings. *Quarterly Journal of Experimental Physiology and Cognate Medical Sciences: Translation and Integration, 47*(4), 324-333. doi:https://doi.org/10.1113/expphysiol.1962.sp001616

Maurer, C., Mergner, T., Bolha, B., & Hlavacka, F. (2001). Human balance control during cutaneous stimulation of the plantar soles. *Neuroscience Letters, 302*(1), 45-48. doi:https://doi.org/10.1016/S0304-3940(01)01655-X

McKeon, P. O., & Hertel, J. (2007). Diminished plantar cutaneous sensation and postural control. *Perceptual and Motor Skills, 104*(1), 56-66. doi:https://doi.org/10.2466/pms.104.1.56-66

Mihara, M., Miyai, I., Hatakenaka, M., Kubota, K., & Sakoda, S. (2008). Role of the prefrontal cortex in human balance control. *Neuroimage, 43*(2), 329-336. doi:https://doi.org/10.1016/j.neuroimage.2008.07.029

Mildren, R. L., Hare, C. M., & Bent, L. R. (2017). Cutaneous afferent feedback from the posterior ankle contributes to proprioception. *Neuroscience Letters, 636*, 145-150. doi:https://doi.org/10.1016/j.neulet.2016.10.058

Molavi, B., & Dumont, G. A. (2012). Wavelet-based motion artifact removal for functional near-infrared spectroscopy. *Physiological Measurement, 33*(2), 259. doi:https://doi.org/10.1088/0967-3334/33/2/259

Naito, E., Morita, T., & Amemiya, K. (2016). Body representations in the human brain revealed by kinesthetic illusions and their essential contributions to motor control and corporeal awareness. *Neuroscience Research, 104*, 16-30. doi:https://doi.org/10.1016/j.neures.2015.10.013

Orihuela-Espina, F., Leff, D. R., James, D. R., Darzi, A. W., & Yang, G.-Z. (2010). Quality control and assurance in functional near infrared spectroscopy (fNIRS)

experimentation. *Physics in Medicine & Biology, 55*(13), 3701. doi:https://doi.org/10.1088/0031-9155/55/13/009

Oscarsson, O., & Rosen, I. (1963). Projection to cerebral cortex of large muscle-spindle afferents in forelimb nerves of the cat. *The Journal of Physiology, 169*(4), 924-945. doi:https://doi.org/10.1113/jphysiol.1963.sp007305

Ouchi, Y., Okada, H., Yoshikawa, E., Nobezawa, S., & Futatsubashi, M. (1999). Brain activation during maintenance of standing postures in humans. *Brain, 122*(2), 329-338. doi:https://doi.org/10.1093/brain/122.2.329

Ovalle, W. K., & Smith, R. S. (1972). Histochemical identification of three types of intrafusal muscle fibers in the cat and monkey based on the myosin ATPase reaction. *Canadian Journal of Physiology and Pharmacology, 50*(3), 195-202. doi:https://doi.org/10.1139/y72-030

Peterka, R. J., & Loughlin, P. J. (2004). Dynamic regulation of sensorimotor integration in human postural control. *Journal of Neurophysiology, 91*(1), 410-423. doi:https://doi.org/10.1152/jn.00516.2003

Pinti, P., Scholkmann, F., Hamilton, A., Burgess, P., & Tachtsidis, I. (2019). Current status and issues regarding pre-processing of fNIRS neuroimaging data: an investigation of diverse signal filtering methods within a general linear model framework. *Frontiers in Human Neuroscience, 12*, 505. doi:https://doi.org/10.3389/fnhum.2018.00505

Ribot-Ciscar, E., Rossi-Durand, C., & Roll, J.-P. (1998). Muscle spindle activity following muscle tendon vibration in man. *Neuroscience Letters, 258*(3), 147-150. doi:https://doi.org/10.1016/S0304-3940(98)00732-0

Roll, J. P., & Vedel, J. P. (1982). Kinaesthetic role of muscle afferents in man, studied by tendon vibration and microneurography. *Experimental Brain Research, 47*(2), 177-190.

Roll, J. P., Vedel, J. P., & Ribot, E. (1989). Alteration of proprioceptive messages induced by tendon vibration in man: a microneurographic study. *Experimental Brain Research, 76*(1), 213-222.

Ruffini, A. (1898). On the minute anatomy of the neuromuscular spindles of the cat, and on their physiological significance. *The Journal of Physiology, 23*(3), 190-208. doi:https://doi.org/10.1113/jphysiol.1898.sp000723

Sherrington, C. S. (1894). On the anatomical constitution of nerves of skeletal muscles; with remarks on recurrent fibres in the ventral spinal nerve-root. *The Journal of physiology, 17*(3-4), 210-258. doi:https://doi.org/10.1113/jphysiol.1894.sp000528

Sherrington, C. S. (1910). Flexion-reflex of the limb, crossed extension-reflex, and reflex stepping and standing. *The Journal of Physiology, 40*(1-2), 28-121. doi:https://doi.org/10.1113/jphysiol.1910.sp001362

Singh, A. K., & Dan, I. (2006). Exploring the false discovery rate in multichannel NIRS. *Neuroimage, 33*(2), 542-549. doi:https://doi.org/10.1016/j.neuroimage.2006.06.047

Souron, R., Besson, T., Millet, G. Y., & Lapole, T. (2017). Acute and chronic neuromuscular adaptations to local vibration training. *European Journal of Applied Physiology, 117*(10), 1939-1964. doi:https://doi.org/10.1007/s00421-017-3688-8

Surgent, O. J., Dadalko, O. I., Pickett, K. A., & Travers, B. G. (2019). Balance and the brain: A review of structural brain correlates of postural balance and balance training in humans. *Gait & Posture*. doi:https://doi.org/10.1016/j.gaitpost.2019.05.011

Takakura, H., Nishijo, H., Ishikawa, A., & Shojaku, H. (2015). Cerebral hemodynamic responses during dynamic posturography: analysis with a multichannel near-infrared spectroscopy system. *Frontiers in Human Neuroscience, 9*, 620. doi:https://doi.org/10.3389/fnhum.2015.00620

Taube, W., Schubert, M., Gruber, M., Beck, S., Faist, M., & Gollhofer, A. (2006). Direct corticospinal pathways contribute to neuromuscular control of perturbed stance. *Journal of Applied Physiology, 101*(2), 420-429. doi:https://doi.org/10.1152/japplphysiol.01447.2005

Ushiyama, J., Masani, K., Kouzaki, M., Kanehisa, H., & Fukunaga, T. (2005). Difference in aftereffects following prolonged Achilles tendon vibration on muscle activity during maximal voluntary contraction among plantar flexor synergists. *Journal of Applied Physiology, 98*(4), 1427-1433. doi:https://doi.org/10.1152/japplphysiol.00613.2004

Van Boxtel, A. (1986). Differential effects of low-frequency depression, vibration-induced inhibition, and posttetanic potentiation on H-reflexes and tendon jerks in the human soleus muscle. *Journal of Neurophysiology, 55*(3), 551-568. doi:https://doi.org/10.1152/jn.1986.55.3.551

Wang, Y., Yan, J., Wen, J., Yu, T., & Li, X. (2016). An intracranial electroencephalography (iEEG) brain function mapping tool with an application to epilepsy surgery evaluation. *Frontiers in Neuroinformatics, 10*, 15. doi:https://doi.org/10.3389/fninf.2016.00015

Zimeo Morais, G. A., Balardin, J. B., & Sato, J. R. (2018). fNIRS optodes' location decider (fOLD): a toolbox for probe arrangement guided by brain regions-of-interest. *Scientific Reports, 8*(1), 1-11. doi:https://doi.org/10.1038/s41598-018-21716-z

Zimney, K., Dendinger, G., Engel, M., & Mitzel, J. (2020). Comparison of reliability and efficiency of two modified two-point discrimination tests and two-point estimation tactile acuity test. *Physiotherapy Theory and Practice*, 1-10. doi:https://doi.org/10.1080/09593985.2020.1719563

APPENDICES

Appendix A – Approval Letter

Oklahoma State University Institutional Review Board

Date:	08/19/2020
Application Number:	IRB-20-310
Proposal Title:	Effects of Sensory Information Over the Motor and Somatosensory Cortex Activity During Standing
Principal Investigator:	Jesus Hernandez Sarabia
Co-Investigator(s):	Rob Maclennan
Faculty Adviser:	Jason Defreitas
Project Coordinator:	
Research Assistant(s):	
Processed as:	Expedited
Expedited Category:	

Status Recommended by Reviewer(s): Approved
Approval Date: 08/19/2020

The IRB application referenced above has been approved. It is the judgment of the reviewers that the rights and welfare of individuals who may be asked to participate in this study will be respected, and that the research will be conducted in a manner consistent with the IRB requirements as outlined in section 45 CFR 46.

This study meets criteria in the Revised Common Rule, as well as, one or more of the circumstances for which continuing review is not required. As Principal Investigator of this research, you will be required to submit a status report to the IRB triennially.

The final versions of any recruitment, consent, and assent documents bearing the IRB approval stamp are available for download from IRBManager. These are the versions that must be used during the study.

As Principal Investigator, it is your responsibility to do the following:

1. Conduct this study exactly as it has been approved. Any modifications to the research protocol must be approved by the IRB. Protocol modifications requiring approval may include changes to the title, PI, adviser, other research personnel, funding status or sponsor, subject population composition or size, recruitment, inclusion/exclusion criteria, research site, research procedures and consent/assent process or forms.
2. Submit a status report to the IRB when requested
3. Promptly report to the IRB any harm experienced by a participant that is both unanticipated and related per IRB policy.
4. Maintain accurate and complete study records for evaluation by the OSU IRB and, if applicable, inspection by regulatory agencies and/or the study sponsor.
5. Notify the IRB office when your research project is complete or when you are no longer affiliated with Oklahoma State University.

If you have questions about the IRB procedures or need any assistance from the Board, please contact the IRB Office at 405-744-3377 or irb@okstate.edu.

Sincerely,
Oklahoma State University IRB

VITA

Jesús Alberto Hernández Sarabia

Candidate for the Degree of

Doctor of Philosophy

Thesis: EFFECTS OF SENSORY INFORMATION OVER THE MOTOR AND SOMATOSENSORY CORTEX ACTIVITY DURING STANDING.

Major Field: Health, Leisure, and Human Performance

Biographical:

Education:

Completed the requirements for the Doctor of Philosophy in Health, Leisure, and Human Performance at Oklahoma State University, Stillwater, Oklahoma in May, 2021.

Completed the requirements for the Master of Science in Health and Human Performance at Oklahoma State University, Stillwater, Oklahoma in Dec, 2016.

Completed the requirements for the Bachelor of Science in Physical Education at Benemérita Universidad Autónoma de Puebla, Puebla, Pue., México in Dec, 2011.

Experience:

Graduate research/teaching associate Aug. 2015 – Present
School of Kinesiology, Applied Health, and Recreation
Oklahoma State University

Professional Memberships:

American College of Sports Medicine (ACSM)
Central States Chapter of the American College of Sports Medicine (CSACSM)
National Strength and Conditioning Association (NSCA)
Society for Neuroscience (SfN)