# POSTURAL SWAY AND MUSCLE ACTIVITY DYNAMICS OF STANDING ON SLOPED SURFACES

by

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# Chapter I: Introduction

## Background

The maintenance of upright posture is a fundamental motor task essential for many daily activities. For example, the ability to maintain upright posture is critical for movements such as standing and walking, which allows for giving presentations, vacuuming, dancing, and standing in line to go through security at the airport. While it may seem to be a simple task, upright standing is conducted through a complex system that is dependent upon the proper integration of sensory information and execution of neuromuscular activity through feedforward and feedback control (Mohapatra, Kukkar, & Aruin, 2014). The goal of the postural control system is to preserve stability through keeping the center of mass (COM) within a base of support (BOS) (Błaszczyk, 2016; Latash & Zatsiorsky, 2016; Pollock, Durward, & Rowe, 2000; Winter, MacKinnon, Ruder, & Wieman, 1993). Upright standing yields a high COM position and a small BOS, which produces a mechanically unstable task due to the effect of gravity (Haddad, Rietdyk, Claxton, & Huber, 2013; Masani, Popovic, Nakazawa, Kouzaki, & Nozaki, 2003). Therefore, understanding how upright posture is accomplished is a critical aspect of motor control research with investigations occurring at multiple levels of analysis, most often including kinematics, kinetics, and surface electromyography (sEMG).

While the goal of the postural control system is to keep the COM within a BOS, there is constant variability, or postural sway, in both the medial-lateral (ML) and anterior-posterior (AP) directions during quiet standing (Błaszczyk, 2016). Postural sway in the ML direction has been attributed to movement produced at the hips, while the AP direction has been attributed to movement at the ankles (Winter, Prince, Stergiou, & Powell, 1993). This variability occurs due to natural processes, and the evaluation of the center of pressure (COP) reveals the interaction between the postural control system and disturbances. Although sway is an inherent characteristic of the system, the COM must stay within a small support area in order to prevent the loss of balance.

There are differing views regarding the role of variability. The traditional view interprets variability as noise that needs to be eliminated (Stergiou & Decker, 2011; Stergiou, Harbourne, & Cavanaugh, 2006). Such approaches, which measure the amount, or magnitude, of variability, do not take into consideration the spatial nor temporal context of data points. According to this view, an increase in the amount of postural sway is often interpreted as reduced stability. However, this idea limits the understanding of movement variability, and thus has been challenged in the growing literature base (Collins & De Luca, 1994; Van Emmerik & Van Wegen, 2002). A differing, more modern view describes variability as functional, allowing for a more flexible system (Cavanaugh, Guskiewicz, & Stergiou, 2005; Murillo, Solana, Vera-garcia, Fuertes, & Moreno, 2012; Stergiou & Decker, 2011; Stergiou et al., 2006). This line of research investigates the dynamic structure of the COP trajectory (Gilfriche, Deschodt-Arsac, Blons, & Arsac, 2018; Powell & Williams, 2015; Van Emmerik & Van Wegen, 2002). Research examining the structural component has provided more sensitive measures for identifying postural control system deficits (Stergiou et al., 2006). These studies have classified postural control systems with a more regular COP structure as constrained and maladaptive; whereas those with a more complex structure as more readily adaptable to perturbations (Murillo et al., 2012).

Another component of the postural control system which must not be ignored is the muscle activity “behind the scenes.” Postural muscles, such as the medial and lateral gastrocnemii, soleus, tibialis anterior, peroneus longus, quadriceps, hamstrings, and abdominal muscles help to provide torques necessary to maintain stable, upright posture (Gatev, Thomas, Kepple, & Hallett, 1999; Horak & Nashner, 1986; Mohapatra, Kukkar, & Aruin, 2014; Winter, Patla, & Frank, 1990). When a perturbation (disruption) to balance occurs postural muscles must work to counteract those forces and bring the body back toward equilibrium. These muscles must be utilized to ensure the numerous joints do not collapse while performing standing tasks (Latash & Zatsiorsky, 2016).

Extensive research has been conducted to understand muscle activity during various postural tasks. Previous studies have confirmed that increased task difficulty is associated with increased muscle activity (Ferreira et al., 2011; Murillo et al., 2012; Noé, Amarantini, & Paillard, 2009). Co-contraction of flexors and extensors has been identified as a stability strategy during novel or difficult tasks (Cleworth, Chua, Inglis, & Carpenter, 2016). Additionally, while there have been many investigations conducted regarding the complexity of the COP trajectory few have investigated the complexity of muscle activity (Murillo et al., 2012). Existing studies have suggested reduced complexity in muscle activity as a result of increased task difficulty. Furthermore, some findings have found contrasting results regarding the relationship between COP and muscle activity complexity with some suggestions of an inverse relationship and others of a direct relationship (Morrison, Hong, & Newell, 2007; Murillo et al., 2012). Therefore, there is a need for further investigations to better understand the complexity of muscle activity during balance tasks.

In order to understand how the body adapts to different sensory stimuli, such as visual or vestibular disturbances, postural control is typically investigated via posturography tests. Due to the sensory inputs from the visual, vestibular, and somatosensory systems, upright posture can be altered with a change in any one of the sensory afferent sources (Assländer & Peterka, 2014).

Therefore, common methods involve investigating a control condition of static standing on a flat surface, as well as perturbations and manipulating constraints. For example, visual constraints of eyes open (EO) versus eyes closed (EC), unexpected platform movements, and altered surface types are regularly used. Previous findings have repeatedly revealed the importance of sensory information in the maintenance of upright posture with previous investigations showing decrements in postural control measures resulting from the removal of vision (Ferreira et al., 2011;Lee, Pacheco, & Newell, 2018; Noé et al., 2009). Similar results have been found with changes in head orientation as well as applied haptic disturbances (Batistela, Oates, & Moraes, 2019;Lee et al., 2018; Pinsault & Vuillerme, 2008). Few studies have investigated the effects of inclined or declined surfaces on postural control. This type of constraint targets the ankle joint and modifies movement strategies which can be observed by the COP and sEMG.

Previous postural control investigations have utilized different methods to investigate how the seemingly simple task is accomplished. Primary methods involve static, unperturbed standing; static, perturbed (expected and unexpected) standing; and voluntary movement (Wang, Ko, Challis, & Newell, 2014; Winter et al., 1990). These investigations have led to the development of different models as well as the identification of postural synergies and strategies. Horak and Nashner (1986) proposed a double inverted pendulum (DIP) model of upright posture to represent the presence of ankle, hip, and combined (ankle and hip) joint movement during AP platform translations. Additionally, Winter (1990) proposed a single inverted pendulum (SIP) model, which simplified upright standing to a single joint, the ankle. The SIP model suggests that unperturbed, quiet standing is dominated by ankle plantarflexion and dorsiflexion (Gatev et al., 1999; Winter et al., 1990). These models gave rise to the well-known ankle and hip strategies that are often used to describe upright posture and are associated with characteristic muscle activity, or synergies. A synergy is often referred to as a set of co-varying elemental variables which aim to stabilize a performance variable (Latash, Krishnamoorthy, Scholz, & Zatsiorsky, 2005). Postural synergies involve groups of muscles working together to stabilize the COM. While these models have allowed for a basic understanding of the postural control system, the use of a multi-link model is essential to capture the many degrees of freedom (DOF) the human body possesses due to the numerous segments, joints, muscles, etc.

The various mechanical, muscular, and neural components of the human body produce a multidimensional postural control system. This complexity creates a core motor control issue known as the DOF problem, which is a core motor control issue. The problem arises because there are infinitely many ways to accomplish a given motor task (Bernstein, 1967). These different options arise because of the body's many components ranging from macroscopic to microscopic including joint rotations, muscle activation, neuronal firing, and many more. One viewpoint describes the DOF problem as redundancy in control while the other suggests abundance. The redundancy perspective suggests there are too many available options thus proving difficult from a control perspective. However, the motor abundance perspective suggests the many DOF allows for beneficial flexibility in the system. Given this complicated nature of the postural control system, it is essential to continue studying new methods to better understand how the body maintains balance. With the exception of some ergonomic investigations, few studies have attempted to understand how standing at inclines and declines influences postural strategies through both COP and EMG analyses (Ganesan, Lee, & Aruin, 2014; Lee, Liang, Chen, Ganesan, & Aruin, 2017). Exploring this sort of task will reveal how the body responds at a neuromuscular level when ankle joint constraints are applied continuously at varying degrees of ankle plantarflexion and dorsiflexion.

**Statement of Purpose**

The primary purpose of this study was to investigate how standing at different degrees of ankle plantarflexion and dorsiflexion influences postural strategies through the examination of muscle activity and postural sway. A secondary purpose was to determine the relationship between muscle activity and postural sway during standing on sloped surfaces. Finally, a tertiary purpose was to investigate how vision influences muscle activity and postural sway during upright standing.

**Hypotheses**

For the declined conditions, it was hypothesized dorsiflexor activity would decrease and plantarflexor muscle activity would increase. For the inclined conditions, it was hypothesized dorsiflexor activity would increase and plantarflexor activity would decrease. Additionally, it was hypothesized as slope deviated from the flat (0°) condition, the amount of postural sway would increase. To address the secondary purpose, it was hypothesized as slope deviated from the flat (0°) condition, sway and muscle activity would work together. To address the final purpose, it was hypothesized the removal of vision would increase the amount of postural sway and muscle activity.

# Chapter II: Literature Review

## Overview

The importance of upright posture was recognized as early as Leonardo da Vinci (1452-1519; Cavallari, Bolzoni, Bruttini, & Esposti, 2016). Giovanni Alfonso Borelli (1608-1679) expanded on da Vinci's ideas and identified the human body as a system involving multiple levers responsible for maintaining the COM within a BOS. Borelli's contributions to the understanding of the human body and its movements identified him as one of the founders of biomechanics (Piolanti et al., 2018). While Borelli was one of the first to identify upright posture as a mechanical problem, further studies were limited until the late 1800s (Cavallari et al., 2016; Latash & Zatsiorsky, 2016).

In order for an object (or person) to balance, the COM must stay within a BOS. The effect of gravity complicates the task in that if the COM, or line of gravity, falls outside the BOS, movement will occur. In inanimate objects, a fall ensues; however, humans have the ability to use their muscles and adapt to the environment (Pollock et al., 2000). Therefore, upright standing is a mechanical problem due to the high COM and small BOS, which is supported by previous findings revealing stability is influenced by an individual's height when measured by variability in the COP trajectory (Alonso et al., 2015). Much research has gone into understanding the human postural control system and reveals the importance of sensory integration for appropriate neuromuscular activity (Lee et al., 2018).

The afferent (sensory) division of the peripheral nervous system (PNS) is responsible for detecting changes relevant to balance; and the efferent (motor) division responds to those changes (Pollock et al., 2000). For example, proprioceptive and somatosensory information from the ankle angle, sole of the foot, and toes influences postural control through COP and muscle activity analyses (Inglis, Kennedy, Wells, & Chua, 2002; Viseux, 2020).

Given the complex design of the body, and thus, the postural control system, continued investigations into various postural tasks are needed to better understand how upright stance is conducted. Research demonstrates postural deficits in individuals with neurological, visual, and vestibular disorders such as Parkinson's disease, Alzheimer's, and diabetic neuropathy. Additionally, concussion and aging are associated with reduced postural stability (Abrahamova & Hlavacka, 2008; Cavanaugh et al., 2006). Therefore, each component in designing a postural control study must be carefully considered to ensure data is valid, reliable, and can be generalized to the wider population.

**Methodology**

Dynamic and static posturography tests are commonly utilized to investigate the postural control of diverse populations (Duarte, Freitas, & Zatsiorsky, 2011). In dynamic protocols, various discrete and continuous perturbations are applied to produce postural responses. Static, quiet standing tasks are often used as a control condition, but constraints can also be applied to investigate postural adaptations over time. While both dynamic and static tasks are commonly used in the study of postural control, the latter will be the focus for the purposes of this study.

Static, or quiet standing tasks are often used to evaluate postural stability (Abrahamova & Hlavacka, 2008; Dutt-Mazumder, Slobounov, Challis, & Newell, 2016; Hatton, Dixon, Martin, & Rome, 2009). During these tasks, participants are asked to "stand as still as possible" and to focus on a specified visual target (Bonnet, 2015; Caballero, Barbado, & Moreno, 2015). Postural control can be manipulated by using various perturbations and task constraints. It is commonly accepted the removal of vision (a visual constraint) induces an increase in the amount of postural sway in comparison to conditions when vision is available. Moreover, result discrepancies are often attributed to the weighting of visual information in the given task (Lee, Pacheco, & Newell, 2018). The removal of vision is often combined with other common methods of perturbing the postural control system including the use of altered surface types, such as foam and wobble boards (Abrahamova & Hlavacka, 2008; Braun Ferreira et al., 2011; Cimadoro, Paizis, Alberti, & Babault, 2013; Mohapatra et al., 2014; Noé et al., 2009). These modifications increase the task difficulty and thus the attentional demands required to maintain upright posture (Paillard & Noé, 2015). Standing on an incline or decline is a common task people must perform but has been minimally investigated in the postural control literature. Few studies have attempted to understand how different degrees of plantarflexion (declines) and dorsiflexion (inclines) influence postural sway and muscle activity.

**Measurement**

The quantitative assessment of postural control involves kinematic, kinetic, and electrophysiological analyses. Kinematic investigations often use motion capture technology to collect three-dimensional (3D) data. From these data, inter-joint coordination can be identified to describe an individual's (or groups') postural performance. The process of investigating kinetics involves using either one or two force platforms to collect force and moment data in the x, y, and z directions (ML, AP, and transverse planes, respectively). The resulting COP trajectory is utilized to evaluate postural sway. Finally, electrophysiological analysis involves electromyography (EMG), which can be used to identify postural strategies and coordination patterns. More complex studies combining the use of these measurement techniques are more robust and can provide a more holistic approach to the study of this system.

Traditional studies use linear measures during data analysis due to the view that variability is the result of random noise which should be eliminated by the control system. More recently however, researchers have realized this may not be the case. Therefore, it is now common to utilize non-linear analyses to investigate the COP position trajectories and root mean square (RMS) values of the EMG signal (Morrison et al., 2007; Murillo et al., 2012).

**The Degrees of Freedom**

Nikolai Bernstein, a Russian neurophysiologist, formulated the degrees of freedom (DOF) problem, which remains one of the primary focuses in motor control research (Bernstein, 1967). This problem exists due to the complexity of the human body as well as its relationship to the environment. Proper motor functioning relies on successful chains of events occurring from the central nervous system (CNS) to the effector(s) and back. There exists more elements than needed to accomplish a given motor task (Latash, Scholz, & Schöner, 2007). For example, there are more joints than necessary to stand upright and multiple muscles that cross each joint which can produce varying amounts of torques (Park, Reimann, & Schöner, 2016). The many DOF give rise to the fundamental problem's primary question of what is controlled and coordinated (Turvey, 1990). For example, which segments, joints, or muscles are controlled and coordinated to maintain the COM within a BOS?

Coordination involves properly bringing together elements of a system which helps with controlling the DOF (Turvey, 1990). For example, it has long been understood the CNS does not control muscles individually but unites them in groups to accomplish different tasks (Latash, 2008). According to Gelfand and Tsetlin (1966), motor performance (behavior) results from synergies, which are a form of structural unit. Each structural unit is organized based on a task and is composed of elements required to accomplish that task. Therefore, elemental variables compose synergies, which are used to stabilize performance variables. In postural control studies, performance variables could include COP or COM position or head orientation with elemental variables dependent upon the level of analysis. For example, if the performance variable of interest is the COP position trajectory, one can investigate the activation of different muscles as elemental variables.

There are two approaches to understanding the DOF problem: the first assumes a central controller is responsible for producing a single optimal solution, and the second assumes a central controller facilitates multiple solutions (Latash, 2008). Body segments, joint angles, and muscle activations are simply a few levels of analysis that can be investigated to better understand movement control and coordination.

***Redundancy vs. Abundance***

The multitude of options provided by the DOF was long described as redundancy in the system, and thus provided a "motor redundancy" (MR) problem demanding a solution. This problem results from the idea that in order for a movement to occur, each element must be controlled to produce a specific output/unique solution. On the other hand, Gelfand and Latash (1998) proposed the principle of abundance suggesting the infinitely many options provide flexibility and adaptability for a healthy system. While this principle has only recently been proposed and argued amongst scholars, Bernstein himself showed there is no optimal solution and even highly trained individuals show large variations between repetitions of the same task (Bernstein, 1967). Even then, the findings of motor variability supported motor abundance (MA) over motor redundancy (Latash, 2000, 2008, 2012).

**Motor Redundancy.** The MR problem originates from attempting to apply tenets of control theory to biological systems. This idea posits there exists a central controller which must regulate each element to produce a certain output. There are many reasons control theory should be carefully considered in its application to human movements. In this vein, the human body is considered "sub-optimal" due to the nonlinearity, elasticity, and slowness of the musculature, which allows for movement production (Latash, 2008). The DOF further complicate the process, and this perspective places extreme demands on the controller, the CNS: it must have the ability to anticipate all possible outcomes in order to properly produce and correct for movements.

**Hierarchical Control.** Some examples of MR problems include inverse kinematics, dynamics, and physiological control signals (Latash, 2008). In order to address the problems of inverse kinematics, inverse dynamics, and physiological control signals associated with hierarchical control, the force-control approach, schema theory and generalized motor programs (GMP) have been applied (Ives, 2014; Latash, 2008). The force-control approach refers to the idea of the brain sending control signals to the spinal neurons based on previously computed muscle forces needed to accomplish the motor task. Briefly, schema theory proposes GMPs (general neural representations of motor tasks) and schemata (memory components allowing the recognition and recalling of motor tasks) are stored in higher brain centers and used to send descending signals. This idea relies on invariant features and parameters. Invariant features such as relative timing, force, and sequencing are associated with a group of actions (Ives, 2014). Parameters such as overall duration, force, and muscles used can be scaled to produce changes in the task. This theory has received criticism because of the improbable capability of the brain to store multitudes of GMPs and schemas. This line of thought led to the development and utilization of internal models (Latash, 2008). In short, internal models are expected to predict the interactions within the body and its interactions with the environment (Latash, 2010). More specifically, inverse models compute descending commands based on outdated sensory information while direct models predict the effects of descending signals on the effector (Latash, 2008, 2012). The brain sends out two copies of the movement plan: one to the effector and another to itself (an efference copy). The efference copy contains both the movement plan and the expected sensory information which will result from the movement (Ives, 2014). This is used to compare the predicted with the actual information and alters commands for future movements. The presence of muscle activity which occurs in anticipation of an upcoming movement provides support for this area of research.

**Motor Abundance.** As mentioned previously, Bernstein’s work with blacksmiths suggested abundance over redundancy. Interestingly, the Russian term Bernstein used in his writings can be translated as either “redundancy” or “abundance” (Latash, 2000). Additionally, Gelfand and Tsetlin (1966) proposed the principle of non-individualized control. In this approach, the CNS no longer needs to control each individual element; rather elements are combined in task-specific structural units the controller uses for the purpose of synergies. This led to Gelfand and Latash’s (1998) proposal of the principle of abundance, which posits rather than a single solution, the CNS produces families of solutions that are able to accomplish the given motor task (Latash, 2008, 2010, 2012).

**Heterarchical Control.** Rather than the previously mentioned hierarchical control models, heterarchical control models provide a more realistic approach to the control of human movements. Heterarchical control refers to the idea that elements of a system(s) can be related in various ways rather than a straightforward top-down approach. In this regard, the systems model can be applied to understand motor behavior in humans (Ives, 2014). The systems model compiles ecological approaches, action theory, and dynamic systems theory (DST) to propose that the interaction of the individual, environment, and task produce movement.

The ecological approach to motor behavior holds there exists an "organism-environment" relationship rather than a purely cognitive approach (Araújo & Davids, 2011). This provides a perception-action relationship in that the organism has the opportunity to perceive its environment, which provides opportunities for movement and interaction. Further exploration of the environment affords additional opportunities for movement. Therefore, according to the ecological approach, postural sway serves an exploratory purpose in that it allows the ability to obtain more sensory information (Araújo & Davids, 2011; Haddad et al., 2013). This approach is also referred to as dynamic systems theory which states behavior results from the interaction of the individual, the task, and the environment (Figure 1; Colombo-Dougovito, 2017; Newell, 1986). Each of these components are identified as systems having further sub-systems which also interact (Ives, 2014). Each system provides constraints influencing the performance of a motor task.

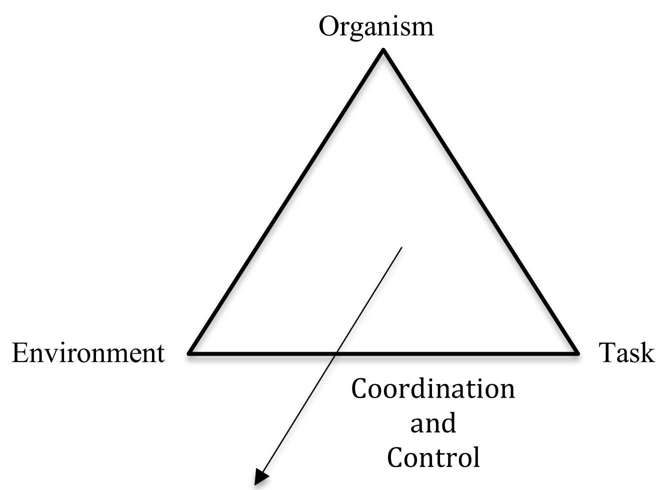



**Figure 1.** Schematic of constraint categories which influence coordination and control of a motor task (adapted from Newell, 1986).

**Solutions.** Regardless of the DOF perspective (MR or MA), system organization must occur. Proposed solutions include elimination, optimization, and synergies (Latash et al., 2007).

Briefly, elimination, or "freezing", of the DOF has been suggested as a solution to reduce the redundant DOF. While DOF cannot be physically eliminated without major surgery, researchers can attempt to induce freezing by constraining movement options (Latash, 2000). Freezing of the DOF is most often observed during the learning of a novel motor task. Additionally, due to the notion of a single, optimal solution for any given motor task, optimization approaches attempting to find a solution to either minimize or maximize some cost function are common (Latash, 2008, 2012; Latash et al., 2007). Examples of specific criterion include minimum time (bang-bang control), minimum impulse (bang-zero-bang control), minimum jerk, minimum fatigue, minimum effort, and maximum comfort. Finally, the presence of synergies has been suggested as a way to reduce the number of elements required to be independently controlled.

Motor control research has attempted to identify both kinematic and muscle synergies during upright standing. For example, as was discussed in the introduction, the single inverted pendulum (SIP), dual inverted pendulum (DIP), and multi-link models for postural control have revealed generic postural strategies during different balance tasks. Although the multi-link model has grown in popularity, the SIP and DIP models are still often used. The utilization of these models has allowed the identification of ankle and hip strategies regarding both AP and ML sway (Horak & Nashner, 1986; Winter, Prince, Frank, Powell, & Zabjek, 1996; Winter et al., 1993). Horak and Nashner (1986) identified ankle, hip, and combined postural strategies in regard to direction of muscle activation as a result of altered support surface and perturbation amplitude. Furthermore, Winter and colleagues (1996) associated AP movement with the ankle joint and ML movement with the hip joint. Moreover, it was found the relationship between direction and joint can change depending on stance type.

**Equilibrium Point Hypothesis.** In light of the SIP model, Zatsiorsky and Duarte (1999, 2000) proposed the idea of rambling (Rm) and trembling (Tr) to explain postural sway (Duarte & Zatsiorsky, 1999). In this approach, the COP is broken down into the two components and analyzed in both the AP and ML directions. The Rm component reflects the moving equilibrium point (EP) while the Tr component reflects fluctuations around the EP (Latash & Zatsiorsky, 2016). This idea is in line with the Equilibrium Point Hypothesis (EPH), proposed by Feldman and colleagues (1986) in attempts to explain the posture-movement paradox. This paradox occurs due to the physiological mechanisms (e.g. muscle spindles) responsible for maintaining joint equilibrium (Latash, 2008; Sainburg, 2015). In summary, the EPH states the controller changes the activation threshold of the tonic stretch reflex (λ), thus producing movement.

**Uncontrolled Manifold Hypothesis.** In maintaining balance, the many DOF must be properly coordinated. The question remains as to how they are coordinated and controlled. The uncontrolled manifold (UCM) hypothesis suggests rather than the controller being responsible for each possible DOF and solution, it is responsible for selecting a sub-space, or manifold (UCM), which allows for successful performance of the task (Scholz & Schöner, 1999). The elemental variables in the UCM, can vary ($V_{good}$), while those outside of the manifold should not ($V_{bad}$) (Krishnamoorthy, Latash, Scholz, & Zatsiorsky, 2003; Latash, 2008). Therefore, from this perspective, there is room for “good variability.”

## Variability

These problems and approaches are related to postural control in that sway, or variability, has been seen as both a positive and negative characteristic of the system (Van Emmerik & Van Wegen, 2002). Movement variability was often investigated using linear measures, which ignore the spatial and temporal characteristics of a signal (Stergiou et al., 2006). Therefore, these techniques only provide information regarding the amount, or magnitude, of variation over time. However, this view on movement variability has been challenged in the growing literature base. Rather variability is now viewed as a functional, beneficial process allowing for a more exploratory, flexible, and adaptable system (Cavanaugh et al., 2005; Duarte & Zatsiorsky, 1999; Haddad et al., 2013; Stergiou & Decker, 2011; Stergiou et al., 2006; Van Emmerik & Van Wegen, 2002). Given this new approach to movement variability, researchers have begun to use non-linear measures to analyze data rather than solely linear measures. Thus, the dynamic structure of various systems including postural sway and muscle activity can be investigated.

Traditional research used linear measures to evaluate the COP trajectory. As a result, sway was viewed as random noise needing to be eliminated or minimized; therefore it was removed during data analysis (Gatev et al., 1999). Examples of linear sway measures include the mean, standard deviation, coefficient of variation, length, amplitude, velocity, and area (Paillard & Noé, 2015). Given these techniques provide information on the amount of sway, it was long interpreted that increased values indicated reduced postural stability while lower values indicated better stability. Moreover, increased amounts of postural sway have been associated with an increased fall risk in elderly and sensorimotor disorder populations. However, other studies have found contrasting results suggesting reduced sway may not be indicative of improved postural stability (Latash & Zatsiorsky, 2016; Rocchi, Chiari, & Horak, 2002). Rather, sway could be used to explore the boundaries of stability.

Recent investigations employ the use of non-linear measurement techniques to analyze the dynamic structure of the COP signal. These measures take into consideration the spatiotemporal characteristics of the data. Common measures such as approximate entropy (ApEn), sample entropy (SampEn), and detrended fluctuation analysis (DFA), are used as non-linear tools in postural studies (Caballero et al., 2015; Dutt-Mazumder et al., 2016; Murillo et al., 2012; Ramdani, Seigle, Lagarde, Bouchara, & Bernard, 2009; Stergiou et al., 2006). These measures have been shown to provide a more reliable and sensitive assessment allowing the identification of subtle changes in the COP signal. They have revealed discrepancies between various populations such as healthy and unhealthy, as well as young and elderly. Furthermore, entropy measures have also uncovered postural issues in concussed athletes (King, 2019; Stergiou et al., 2006).

Current motor control research utilizes both linear and non-linear measures to gain a holistic understanding of the underlying control mechanisms. Using both techniques is especially beneficial when attempting to discern differences during postural tasks of varying difficulty. For example, changing the support surface and the availability of vision are common manipulations used to perturb stability. Research shows an increase in task difficulty is associated with increased amounts of postural sway as well as reductions in system complexity, or increases in regularity (Dutt-Mazumder et al., 2016; Murillo et al., 2012). Furthermore, an increase in task difficulty induced by the removal of vision is associated with increased amounts of sway (Ferreira et al., 2011; Noé et al., 2009). However, the effects of vision vary amongst research conclusions (Ramdani et al., 2009).

While there are bountiful measures available to the postural control researcher, difficulty remains in associating the quantitative findings to the underlying system and processes (Latash & Zatsiorsky, 2016). Using additional levels of analysis, such as EMG, can improve upon this problem. As previously discussed, postural control studies using EMG have identified postural synergies and strategies occurring in the presence of a threat to stability (Gatev et al., 1999; Horak & Nashner, 1986). Multi-muscle synergies are required to maintain upright stance. Furthermore, both active and passive ankle torque are required to perform upright standing (Morasso & Schieppati, 1999). The finding that lateral gastrocnemius (LG) activity precedes forward movement of the COP supports this notion and suggests a feed-forward control aspect of the postural control system (Gatev et al., 1999; Masani et al., 2003).

Many of the postural control investigations utilizing EMG have attempted to quantify the timing and magnitude of muscle activation (Cimadoro et al., 2013; Murillo et al., 2012; Noé et al., 2009). Variability has been minimally investigated at the muscular level during postural tasks with few studies utilizing non-linear techniques. Morrison and colleagues (2007) found task requirements significantly change the structure of EMG signals. This finding was supported by a more recent study utilizing linear and non-linear measures to investigate COP and EMG during postural tasks of varying difficulty (Murillo et al., 2012). Specifically, reduced complexity as well as increased amounts of muscle activity were found. More investigations are needed to understand the dynamic structure of ankle muscle activity during various postural tasks.

# Chapter III: Methods

## Participants

Twelve individuals (21.67 ± 1.11 yrs., 170.18 ± 10.35 cm, 67.39 ± 11.58 kg, 9 females, 3 males) between 18 and 25 years of age were recruited to partake in the study for voluntary participation. Individuals were excluded if they reported to have one or more of the following: known balance, visual, or neuromuscular disorder or impairment; ankle, knee, or hip injury (such as a sprain) within the last two years; a history of lower extremity surgery of any sort; and/or an allergy to silver.

Recruitment occurred both on and off Texas Christian University (TCU) campus through word-of-mouth and mass email (e.g., department wide email). All recruitment methods informed individuals participation was completely voluntary and withdrawal from the study could occur at any time without penalty. No compensation was provided for participation in the study. All procedures were approved by the TCU departmental and institutional review boards prior to the start of data collection. All participants were required to sign an approved consent form prior to participation in the study.

## Materials

Self-reported demographic data including age, height, weight, and gender were collected from each participant. Additionally, the Waterloo Footedness Questionnaire (Elias, Bryden, & Bulman-Fleming, 1998; See Appendix A) was used to determine each participant's dominant foot, which was then used to record muscle activity. A Trigno Wireless Biofeedback system (Delsys, Natick, MA) collected the EMG signals from the tibialis anterior (TA), peroneus longus (PL), soleus (Sol), and gastrocnemius medialis (MG) muscles at a sampling frequency of 2000 Hz. One Trigno Avanti sensor (SP-W06) was assigned to each muscle and synced with Qualisys

Track Manager (QTM, Göteborg, Sweden) which was used for data collection integration. Each sensor was applied to each muscle belly with hypo-allergenic adhesive interfaces. A strain-gauge force plate (AMTI OR6-7, Advanced Mechanical Technology, Inc., Watertown, MA) was used to obtain force and moment data in x, y, and z directions with a sampling frequency of 100 Hz. The EMG base station was connected to the Trigger Module (Delsys SP-U02, Natick, MA) in order to simultaneously collect the force and EMG data. Additionally, a prefabricated angled platform was used to induce an ankle constraint in the sagittal plane.

**Procedures**

Prior to participant arrival researchers checked all connections between the EMG base, Qualisys system, and computer. Each electrode was wirelessly paired to the Trigno base and prepared for placement on the participant. Finally, a test trial was conducted to ensure all data were collected properly.

Participation in the study included one 45-minute visit to TCU’s motor control laboratory. Screening for inclusion and exclusion criteria occurred upon each individual’s arrival. If individuals did not report any exclusion criteria and desired to continue with participation, they were provided time to read through the consent form and freely ask questions (see Appendix C). Once written, informed consent was provided, all demographic data (age, height, weight, gender, and dominant foot) was collected. The Waterloo footedness questionnaire, which determined dominant foot, was given to the participant to complete. A researcher read the instructions to each participant and informed them they could act out each prompt as necessary and ask questions if needed. Once the dominant foot was determined, participants were asked to be seated and remove socks and shoes. Then, researchers measured and marked locations for electrode placement according to the SENIAM guidelines for the TA, PL, Sol, and MG muscles (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000; see appendix B). After muscle bellies were marked, manual muscle testing was performed to ensure proper sensor placement. Once locations were verified, researchers shaved and cleaned sites to ensure reliable recordings. Finally, the electrodes were placed onto their respective muscle sites and checked a final time to ensure proper readings.

Once electrodes were placed, researchers instructed participants on the experimental protocol. Participants were instructed to stand on the platform with their arms at their sides, as upright and still as possible, with feet approximately shoulder width apart, and maintain their gaze at a visual target two meters in front of them at eye level. Maintaining upright posture as still as possible during the 30 second tasks was emphasized to each participant. Researchers visually inspected performance throughout testing to ensure no excess movement occurred. If a participant was deemed to have leaned (excessively forward or backward), performed a voluntary movement (such as scratching their nose), or fell off the platform, the condition was performed again with a maximum of three attempts per trial. Between each trial, researchers reminded participants to stand as still and upright as possible and to keep their gaze on or toward the visual target.

Participants performed a total of 14 task conditions including flat (0º), inclined (10º, 20º, and 25º), and declined (10º, 20º, and 30º) angles. Additionally, each angle was performed with eyes open (EO) and eyes closed (EC). A practice trial of less than 20 seconds was given for the 25º incline and 30º decline conditions. Trial order was randomized to minimize the risk of an order effect. Each trial lasted 30 seconds, and participants were provided a minimum of 30 seconds of rest between each trial while a researcher changed the platform condition. Postural difficulty was defined by orientation and degree of slope (see Table 1).

**Table 1.** Task condition with corresponding postural difficulty rating.

| Condition | Postural Difficulty |
|---|---|
| 30 Down | -3 |
| 20 Down | -2 |
| 10 Down | -1 |
| Flat | 0 |
| 10 Up | 1 |
| 20 Up | 2 |
| 25 Up | 3 |

**Data Processing**

All data were exported from Qualisys to MATLAB (Mathworks, v. 2019b) where filtering occurred, and dependent variables were computed. The collected force and moment data were used to compute the COP position trajectory. The first three and last two seconds were cropped from the raw data to ensure the participant was standing firm on the platform. The COP signals were smoothed with a low pass, second order Butterworth filter at a 10-Hz cut-off frequency. Linear COP dependent variables included the coefficient of variation in the ML and AP directions ($CV_{ML}$ and $CV_{AP}$), length ($COP_{length}$) and area ($COP_{area}$).

Similar to the COP data, the first three and last two seconds were removed from the raw EMG data. The raw EMG data were filtered with a band-pass Butterworth filter between 30 and 400 Hz. The mean RMS amplitude was calculated using a 125 ms window with 50% overlap (Cimadoro et al., 2013) for each individual muscle ($RMS_{TA,\ PL,\ Sol,\ MG}$). Finally, a coupling measurement between the COPAP displacement and each muscle was calculated (COPAP_TA, COPAP_PL, COPAP_Sol, COPAP_MG).

**Statistical Analysis**

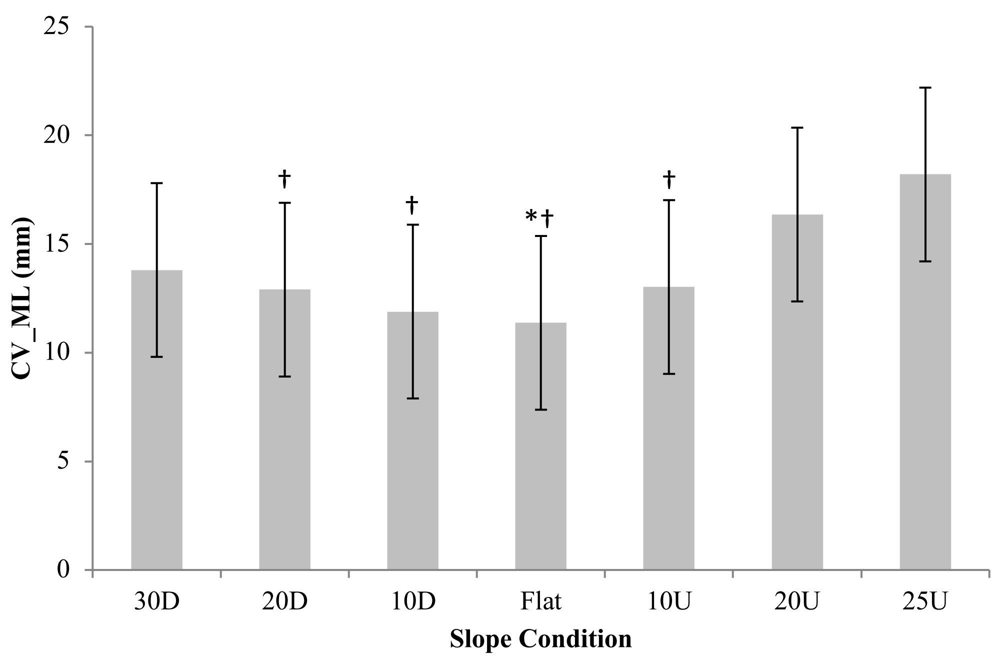
All dependent variables were analyzed in SPSS (Statistical Package for Social Sciences; International Business Machines, IBM). Each dependent variable was evaluated using a general linear model with vision (two factors: eyes open – EO; and closed – EC) and postural difficulty (seven factors: -3, -2, -1, 0, 1, 2, 3) as fixed factors. When significant main effects were found a Tukey post hoc test was conducted to determine where differences occurred. The alpha value was set at .05 to define statistical significance.

# Chapter IV: Results

## COP

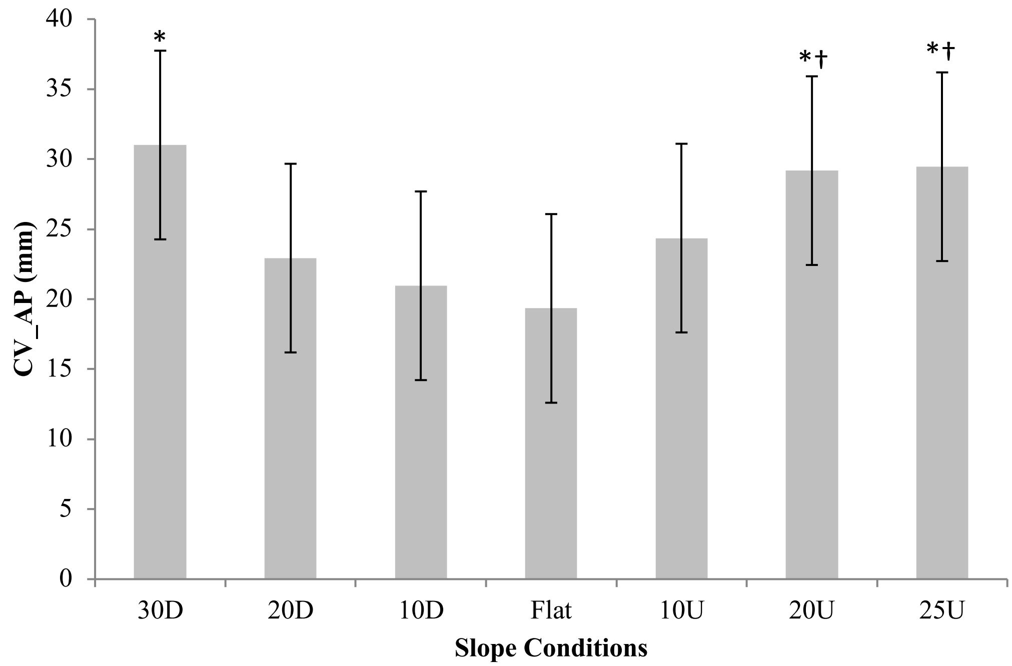
Univariate analysis showed significant main effects of postural difficulty and vision for all COP measures ($CV_{ML}$, $CV_{AP}$, $COP_{length}$, and $COP_{area}$; Table 2). Furthermore, no significant interaction effects were found. Tukey post hoc analyses revealed a general "U" shaped curve in all COP measures in that as slope increased in both the inclined and declined directions the amount of sway increased. Pairwise comparisons can be seen in figures 2 through 5. Data is presented as the mean and standard deviation.

**Figure 2.** Effects of postural difficulty on $CV_{ML}$.



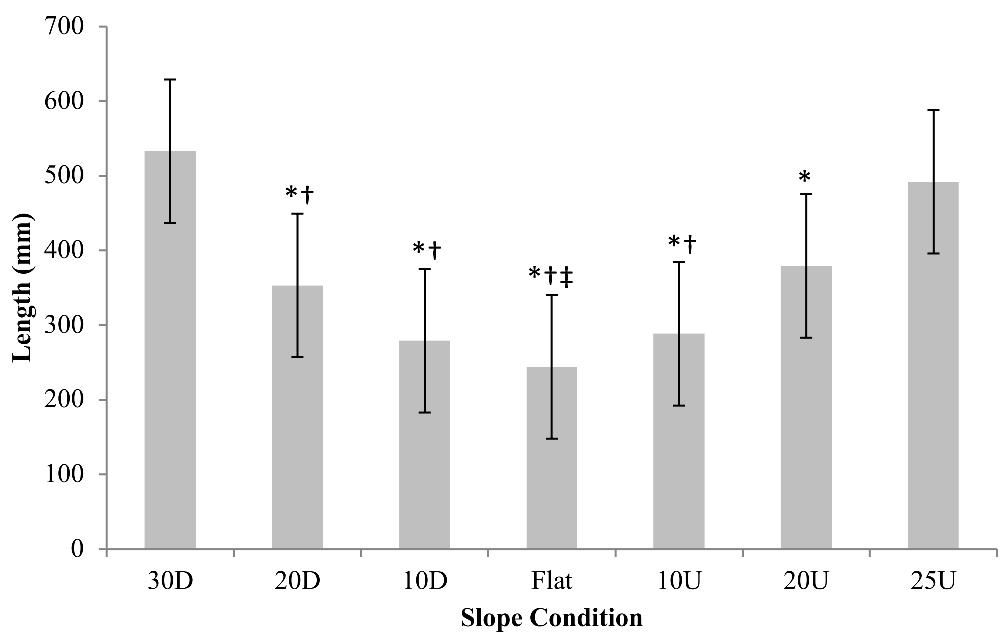

* significantly different from 20Up; † significantly different from 25Up

**Figure 3.** Effects of postural difficulty on $CV_{AP}$.



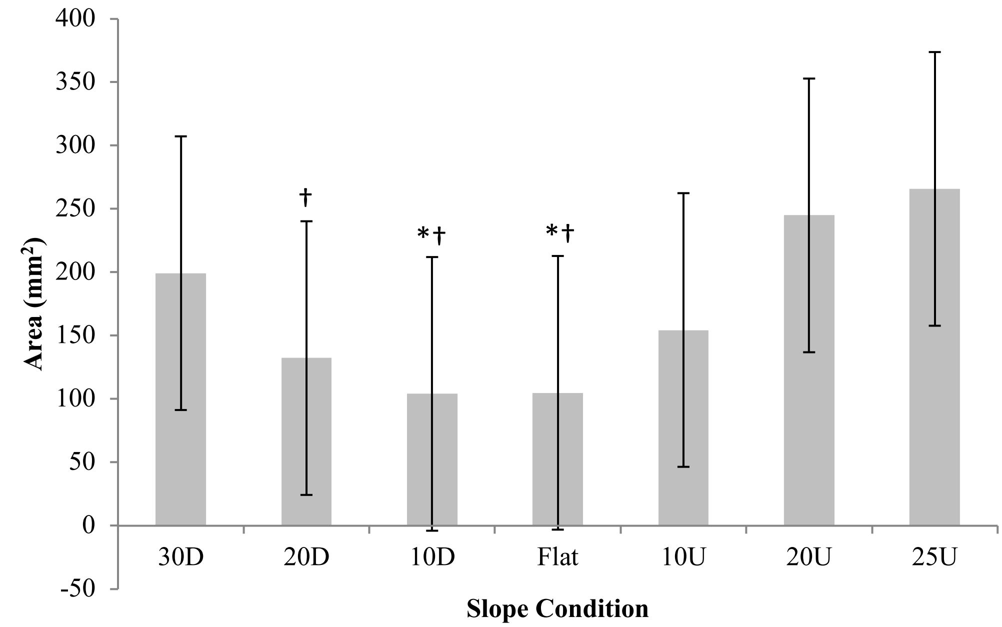

* significantly different from 10Down; † significantly different from Flat

**Figure 4.** Effects of postural difficulty on $COP_{Length}$.




* significantly different from 30Down; ‡ significantly different from 20Up; † significantly different from 25Up

**Figure 5.** Effects of postural difficulty on $COP_{Area}$.

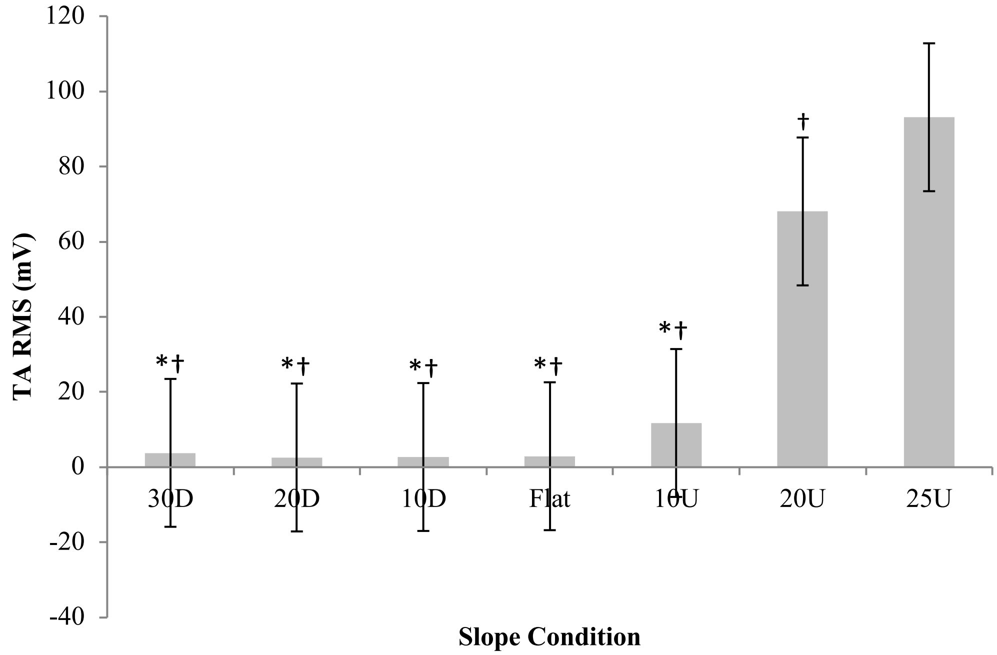



* significantly different from 20Up; † significantly different from 25Up

## EMG

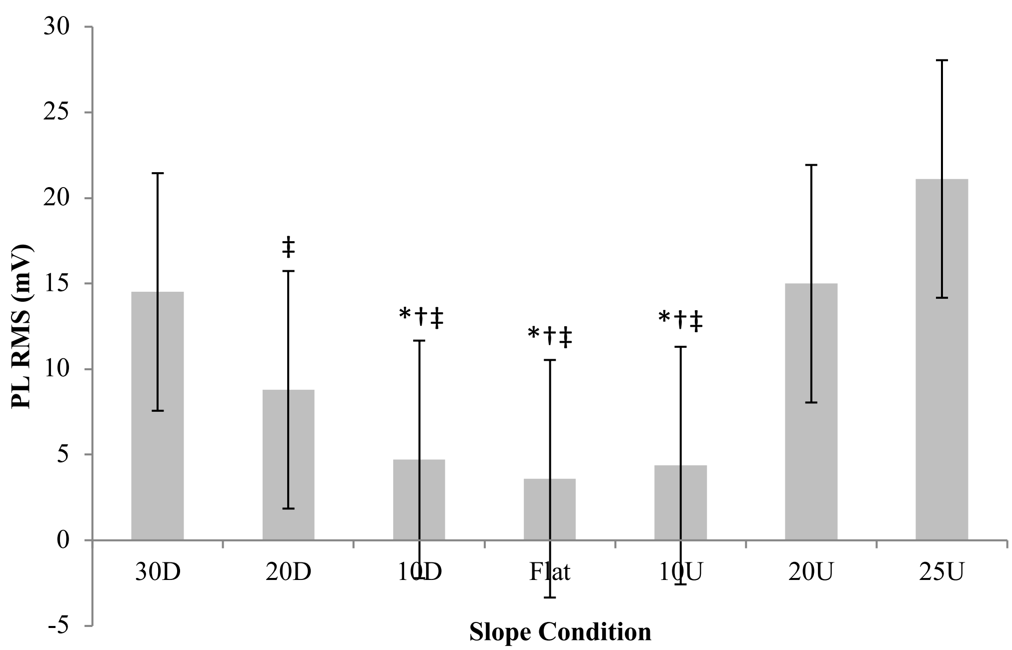
Univariate analysis showed a significant main effect of postural difficulty for all RMS values (Table 2). No significant vision effects or interaction effects were found. Tukey post hoc analyses revealed increased TA activity with inclined conditions and increased MG activity with declined conditions (Fig. 6 and 9). Additionally, post hoc analyses revealed a general "U" shaped curve for PL and Sol muscles (Fig. 7 and 8). Pairwise comparisons can be seen in figures 6 through 9. Data is presented as the mean and standard deviation.

**Figure 6.** Effects of postural difficulty on mean RMS amplitude of TA activity.



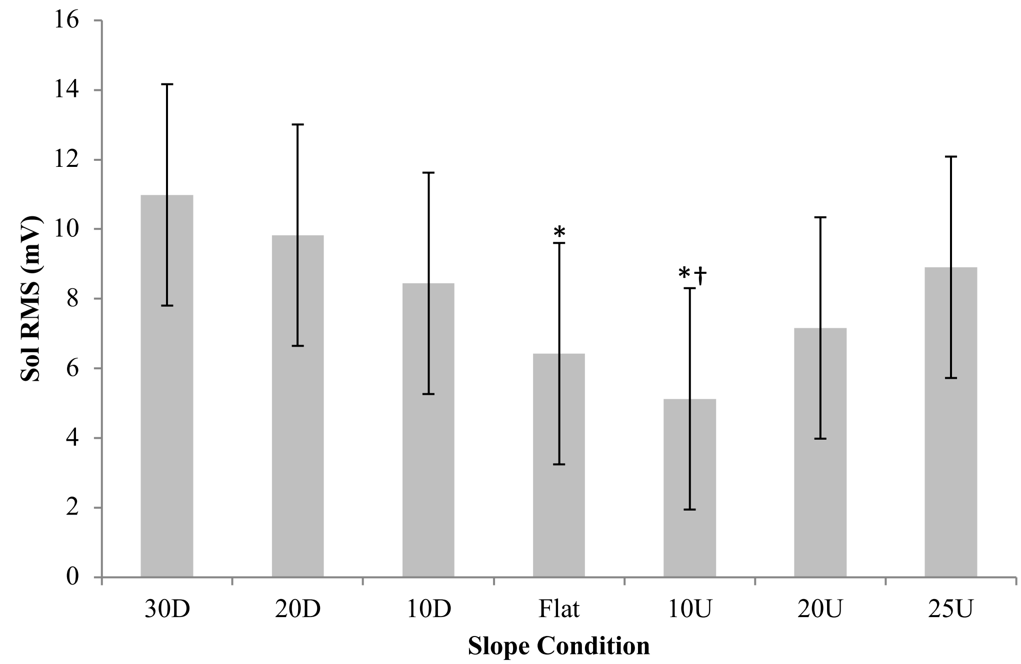

* significantly different from 20Up; † significantly different from 25Up

**Figure 7.** Effects of postural difficulty on mean RMS amplitude of PL activity.



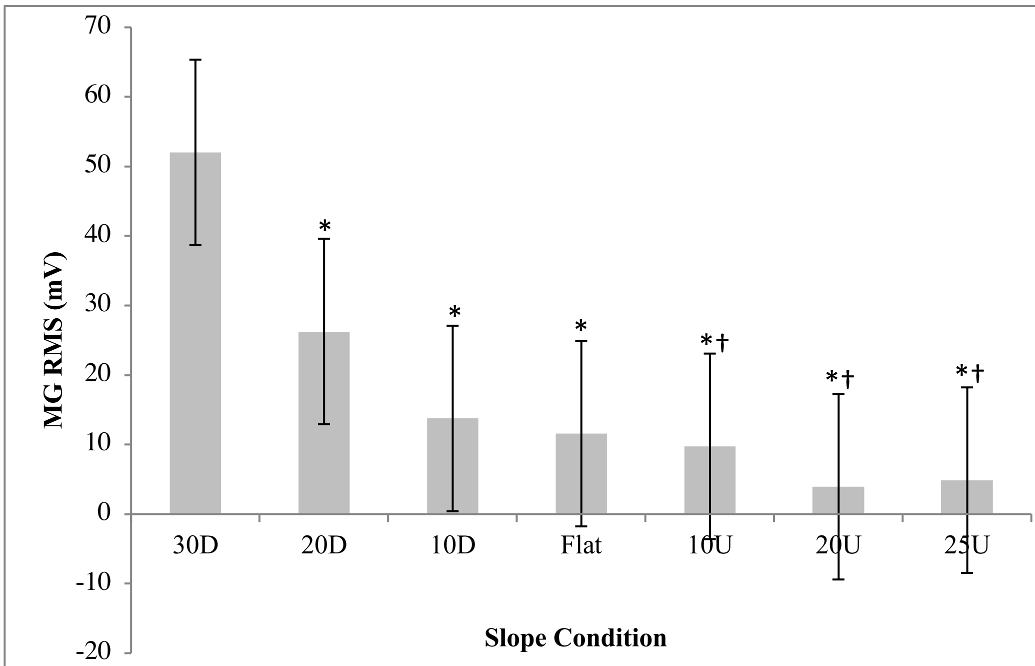

* significantly different from 30Down; † significantly different from 20Up; ‡ significantly different from 25Up

**Figure 8.** Effects of postural difficulty on mean RMS amplitude of Sol activity.




* significantly different from 30Down; † significantly different from 20Down

**Figure 9.** Effects of postural difficulty on mean RMS amplitude of MG activity.




* significantly different from 30Down; † significantly different from 20Down

**Coupling**

Univariate analysis showed a significant main effect of postural difficulty for all COP-EMG coupling pairs (Table 2). Additionally, a significant main effect of vision was found for the COP-Sol and -MG pairings (Table 2). No significant interaction effects were found. When significant main effects were found, Tukey post hoc analyses were conducted. Pairwise comparisons can be seen in figures 10 through 13. Data is presented as the mean and standard deviation.

**Figure 10.** Effects of postural difficulty on COPAP_TA coupling.

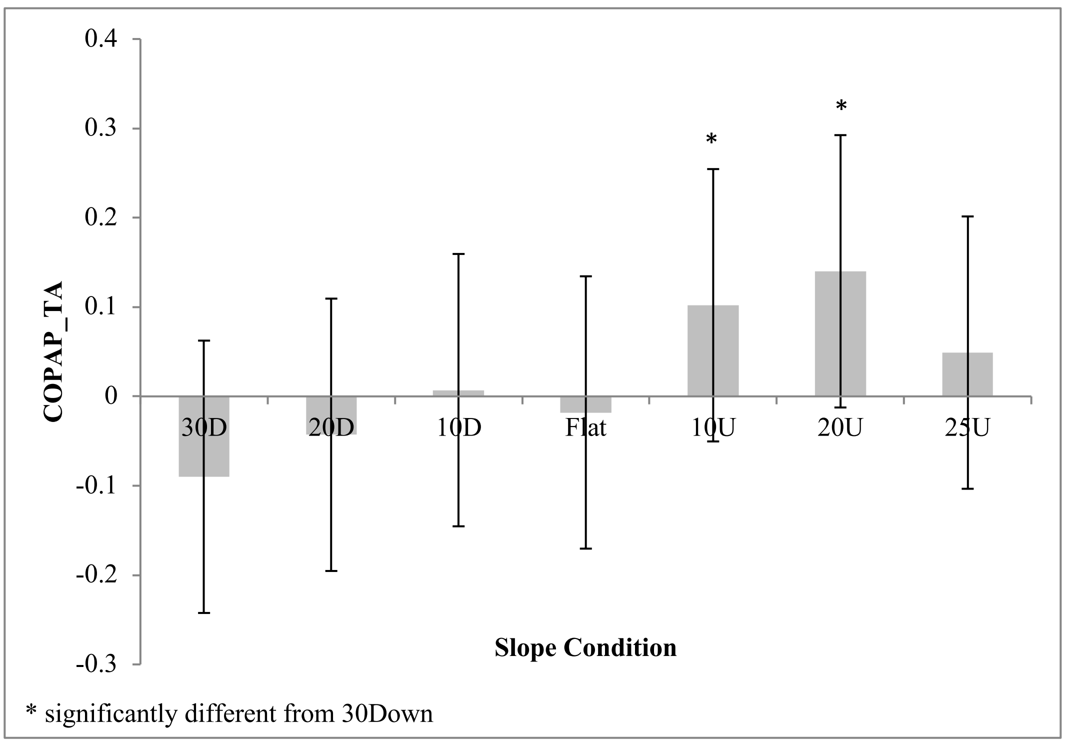
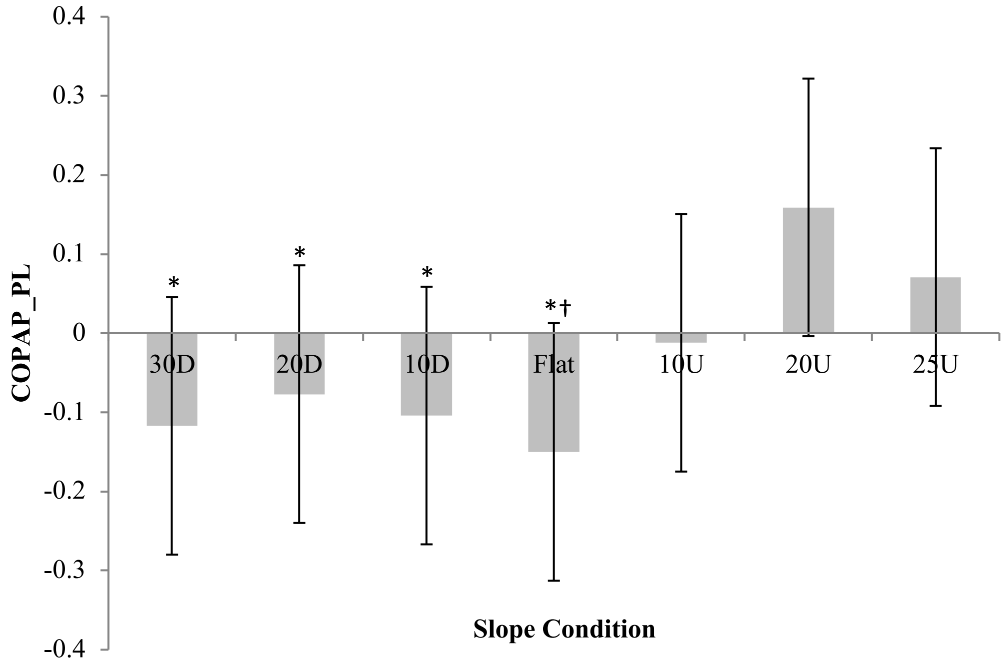
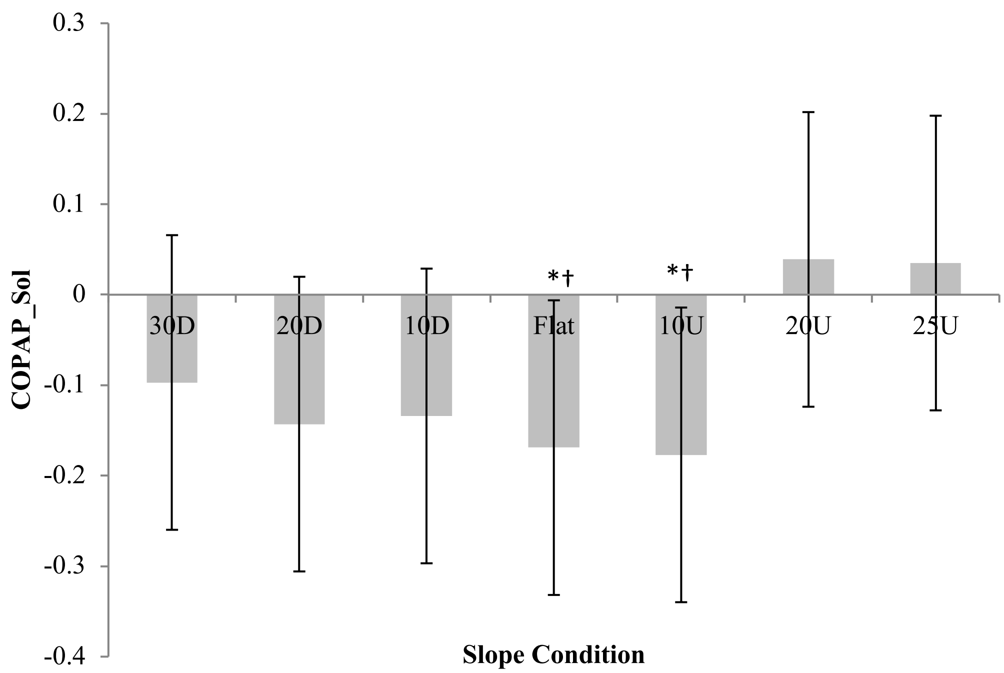


**Figure 11.** Effects of postural difficulty on COPAP_PL coupling.




* significantly different from 20Up; † significantly different from 25Up

**Figure 12.** Effects of postural difficulty on COPAP_Sol coupling.




* significantly different from 20Up; † significantly different from 25Up

**Figure 13.** Effects of postural difficulty on COPAP_MG coupling.

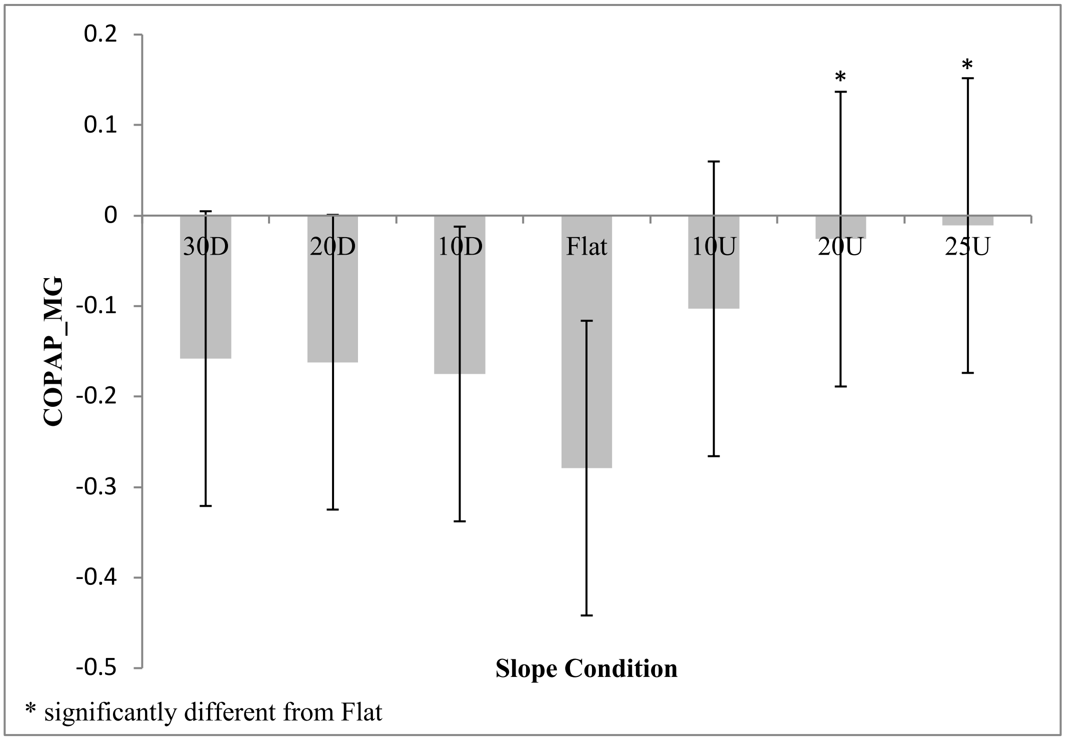



**Table 2.** Main effect results for all dependent variables. Gray highlight indicates $p>0.05$.

| **Dependent Variable** | | |
|---|---|---|
| COP | Postural Difficulty | Vision |
| *CV_ML* | $F(6, 154) = 4.595, p = 0.000$ | $F(1, 154) = 6.929, p = 0.009$ |
| *CV_AP* | $F(6, 154) = 5.540, p = 0.000$ | $F(1, 154) = 6.969, p = 0.009$ |
| *Length* | $F(6, 154) = 15.715, p = 0.000$ | $F(1, 154) = 22.953, p = 0.000$ |
| *Area* | $F(6, 154) = 4.436, p = 0.000$ | $F(1, 154) = 5.669, p = 0.018$ |
| EMG | | |
| *TA* | $F(6, 154) = 44.381, p = 0.000$ | $F(1, 154) = 0.064, p = 0.800$ |
| *PL* | $F(6, 154) = 11.213, p = 0.000$ | $F(1, 154) = 0.700, p = 0.404$ |
| *Sol* | $F(6, 154) = 4.863, p = 0.000$ | $F(1, 154) = 3.046, p = 0.083$ |
| *MG* | $F(6, 154) = 19.334, p = 0.000$ | $F(1, 154) = 3.805, p = 0.053$ |
| Coupling | | |
| *COPAP_TA* | $F(6, 154) = 3.359, p = 0.004$ | $F(1, 154) = 0.000, p = 0.983$ |
| *COPAP_PL* | $F(6, 154) = 5.768, p = 0.000$ | $F(1, 154) = 1.978, p = 0.162$ |
| *COPAP_Sol* | $F(6, 154) = 3.851, p = 0.001$ | $F(1, 154) = 4.517, p = 0.035$ |
| *COPAP_MG* | $F(6, 154) = 3.971, p{=}0.001$ | $F(1, 154) = 7.731, p{=}0.006$ |

## Chapter V: Discussion

This study aimed to investigate how standing at various degrees of ankle plantarflexion and dorsiflexion influences postural strategies through investigating the COP and muscle activity. Standing on inclined and declined surfaces is a common task people must perform but has not been adequately studied in the current postural control literature. The angled platform design provides a continuous task constraint which must be used to solve the motor problem of maintaining upright posture. Each slope condition provided a different postural difficulty, which was shown to significantly influence COP and EMG.

The primary purpose of this study was to investigate how standing at different degrees of incline and decline influences postural strategies through examining postural sway and muscle activity. Regarding postural sway, as hypothesized, the results showed a significant effect of postural difficulty on all COP variables. Results also revealed a general "U" shaped curve supporting the hypothesis as slope deviated from the flat condition the amount of postural sway would increase. Regarding muscle activity, the results partially confirmed our hypothesis. Findings demonstrated a significant increase in TA and MG activity during inclined and declined conditions, respectively. However, Sol and PL activity increased as the slope deviated from the flat condition generating the "U" shaped curve. The secondary purpose of this study was to determine the relationship between muscle activity and postural sway during upright standing on sloped surfaces. Postural difficulty significantly influenced the COP-EMG coupling relationship; however, correlations were low, indicating no relationship occurred. The tertiary, and final, purpose of this study was to investigate the influence of vision on postural sway and muscle activity while standing at various degrees of incline and decline. As hypothesized, removing vision significantly increased postural sway. However, removing vision did not significantly influence muscle activity, thus rejecting the sixth hypothesis.

The finding of increased postural sway, as measured by linear COP variables, associated with postural difficulty is consistent with previous findings. Dutt-Mazumder and colleagues (2016) conducted a similar study with an angled platform design. In support of the present findings, they found increased postural sway measured by COP length and area. Similarly, Kirchner and colleagues (2013) found increased amounts of postural sway as a result of altered stance including inclines and declines. Other investigations have also found increased amounts of postural sway as a result of various altered surface conditions (e.g., foam, wobble boards, trampolines; Cimadoro et al., 2013; Ferreira et al., 2011; Murillo et al., 2012; Noé et al., 2009). These findings are often interpreted as reduced stability; however, this may not be the case. Rather, increased postural sway could represent a flexible system more adaptable to change. The dynamic structure should be investigated to determine the influence of sloped surfaces on postural sway and muscle activity complexity.

The present findings of increased TA and MG muscle activity during inclined and declined conditions, respectively, are supported by previous research (Mezzarane & Kohn, 2007; Sasagawa, Ushiyama, Masani, Kouzaki, & Kanehisa, 2009). Yet, Sasagawa and colleagues (2009) found TA activity to stay the same or slightly increase during declined conditions. Similarly, in the present study, during the 30° decline, TA activity increased in relation to the flat condition; however, the increase was minor and not significant. Few studies have specifically investigated muscle activity during altered slope conditions. Nonetheless, previous results have demonstrated an increase in the amount of muscle activity as a result of increased task difficulty (Cimadoro et al., 2013; Ferreira et al., 2011; Murillo et al., 2012). This could also support the unexpected finding of increased Sol and PL activity as the slope deviated from the flat condition. Previous studies have reported the Sol muscle is constantly active during upright standing (Alrowayeh, Sabbahi, & Etnyre, 2011; Ferreira et al., 2011; Tucker & Türker, 2004). Therefore, in the present study, a general demand for increased muscle activity as postural difficulty increased could be the reason for the Sol behavior. Moreover, it has been reported the Sol muscle is most active during dorsiflexion as a stabilizer (Tucker & Türker, 2004).

The increase in PL activity during the inclined conditions was more peculiar due to its role as a plantarflexor. It was hypothesized PL would increase during declined conditions and decrease during inclined conditions based on the task constraints. While the results partially confirmed this hypothesis, the contradictory finding of increased PL activity in inclined conditions presented a problem. Given the significant increase in ML sway, as measured by the $CV_{ML}$, in the extreme inclined conditions (20° and 25° incline), a reasonable suggestion is the PL produced significantly more eversion activity to adapt to the ankle constraint. More studies should be conducted to either support or refute this interpretation. Investigating the relationship between the ML sway and PL activity, similar to the present COPAP coupling pairs, would provide insight into this proposed connection.

While a significant effect of postural difficulty was found for the COP-EMG coupling pairs, the correlation values were low, indicating no relationship. These findings were reasonably unexpected. Previous research has found changes in task and stance width can reduce these correlations (Carpenter, Frank, Silcher, & Peysar, 2001; Lemos, Rodrigues, & Vargas, 2014). However, given correlation values were low even in the flat condition, this was unlikely. EMG data should be re-processed and analyzed to better understand the relationship between these systems. Moreover, this study did not investigate the time shift between muscle activation and

COP changes. Previous studies have demonstrated the COP lags behind muscle activity (Gatev et al., 1999; Masani et al., 2003). More specifically, Gatev and colleagues (1999) investigated the relationship between lower limb postural muscles and shifts of the COP during normal and Romberg stance conditions. A low, but significant correlation was found between lateral gastrocnemius (LG) activity and the AP component of the COP. In addition, the COP position change lagged behind LG activity between 240 and 270 ms. A few years later, Masani and colleagues (2003) performed a similar experiment and found comparable results. Dorsiflexors (MG, LG, and Sol) were significantly correlated with COP in the AP direction. Furthermore, similar to Gatev's results (1999), increased EMG activity preceded the COP shift (COP lagged behind muscle activity). These findings have been interpreted as anticipatory muscle activation in attempts to keep the COM within the BOS.

As expected, the removal of vision significantly increased postural sway as measured by all COP variables. These findings confirmed various results from past studies and further provided support for the visual system's role in maintaining upright posture (Braun Ferreira et al., 2011; Gatev et al., 1999; Noé et al., 2009). Vision also significantly influenced the COPAP_Sol and COPAP_MG pairings. As mentioned previously, Gatev and colleagues (1999) investigated similar relationships and the effects of vision on postural control. Their findings also demonstrated the importance of vision during upright standing. In contrast to previous studies, the removal of vision did not produce increased muscle activity. For instance, Ferreira and colleagues (2011) found increased muscle activity as a result of eye closure during flat conditions as well as various unstable surface conditions. Given those results, the lack of interaction effects in the present investigation demands researchers adopt this methodology and conduct replica studies.

**Conclusion**

In conclusion, findings showed varying the degree of incline and decline and removing vision altered postural sway. While these results, along with those of previous studies, demonstrate increased postural difficulty results in increased postural sway, the underlying mechanism responsible for the changes remains unknown. Findings also showed increased postural difficulty produced increased muscle activity; however, not as expected. Finally, results demonstrated postural difficulty, induced by varying the degree of incline and decline, significantly influenced the association between the COP and muscle activity. However, correlations indicated no relationships existed.

Given these findings, future studies should aim to identify the mechanisms responsible for changes in postural sway. In addition, more research is needed to understand how sloped surfaces influence the activity of ankle plantarflexors and dorsiflexors. Also, future research should examine the relationship between COP and plantarflexor and dorsiflexor activity to better understand the control system for upright posture.

Standing at inclines and declines of varying degrees is a common task individuals experience on a regular basis. Additionally, this type of constraint could be easily implemented into a clinical setting. The present results combined with those from previous studies suggest sloped conditions, especially inclined conditions, can be more dangerous for individuals with fall-risk. Therefore, understanding the mechanisms responsible for changes in postural strategies is necessary to aid in the development of rehabilitative techniques for injured and at-risk individuals.

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# APPENDIX A

**Appendix: Waterloo Footedness Questionnaire—Revised**

**Instructions**: Answer each of the following questions as best you can. If you *always* use one foot to perform the described activity, circle **Ra** or **La** (for **right always** or **left always**). If you **usually** use one foot circle **Ru** or **Lu**, as appropriate. If you use **both** feet **equally often**, circle **Eq**.

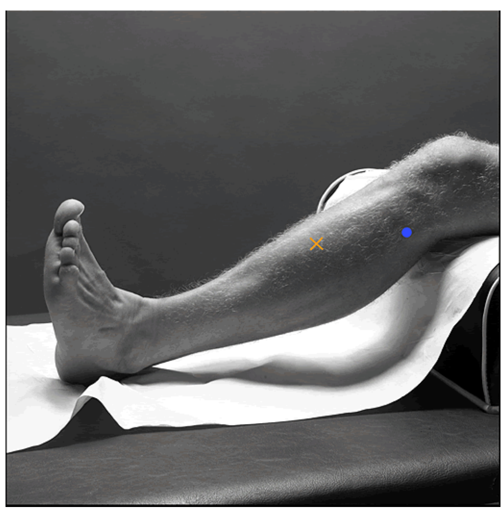
Please do not simply circle one answer for all questions, but imagine yourself performing each activity in turn, and then mark the appropriate answer. If necessary, stop and pantomime the activity.

| | | | | | | |
|---|---|---|---|---|---|---|
| 1. | Which foot would you use to kick a stationary ball at a target straight in front of you? | La | Lu | Eq | Ru | Ra |
| 2. | If you had to stand on one foot, which foot would it be? | La | Lu | Eq | Ru | Ra |
| 3. | Which foot would you use to smooth sand at the beach? | La | Lu | Eq | Ru | Ra |
| 4. | If you had to step up onto a chair, which foot would you place on the chair first? | La | Lu | Eq | Ru | Ra |
| 5. | Which foot would you use to stomp on a fast-moving bug? | La | Lu | Eq | Ru | Ra |
| 6. | If you were to balance on one foot on a railway track, which foot would you use? | La | Lu | Eq | Ru | Ra |
| 7. | If you wanted to pick up a marble with your toes, which foot would you use? | La | Lu | Eq | Ru | Ra |
| 8. | If you had to hop on one foot, which foot would you use? | La | Lu | Eq | Ru | Ra |
| 9. | Which foot would you use to help push a shovel into the ground? | La | Lu | Eq | Ru | Ra |
| 10. | During relaxed standing, people initially put most of their weight on one foot, leaving the other leg slightly bent. Which foot do you put most of your weight on first? | La | Lu | Eq | Ru | Ra |
| 11. | Is there any reason (i.e. injury) why you have changed your foot preference for any of the above activities? | **YES** | **NO** | (circle one) | | |
| 12. | Have you ever been given special training or encouragement to use a particular foot for certain activities? | **YES** | **NO** | (circle one) | | |
| 13. | If you have answered **YES** for either question 11 or 12, please explain: | | | | | |

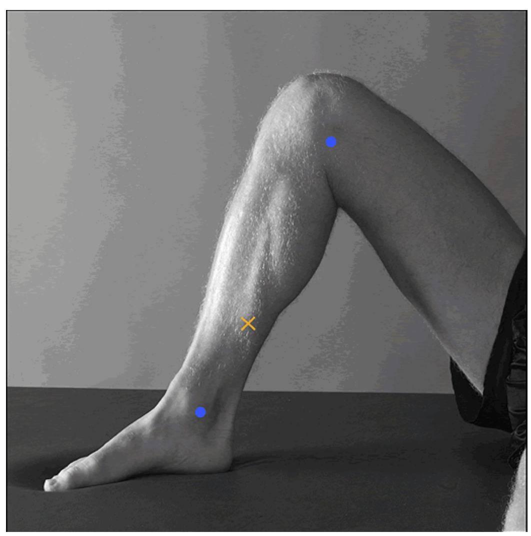
# APPENDIX B

## SENIAM Guidelines for Electromyography Electrode Placements

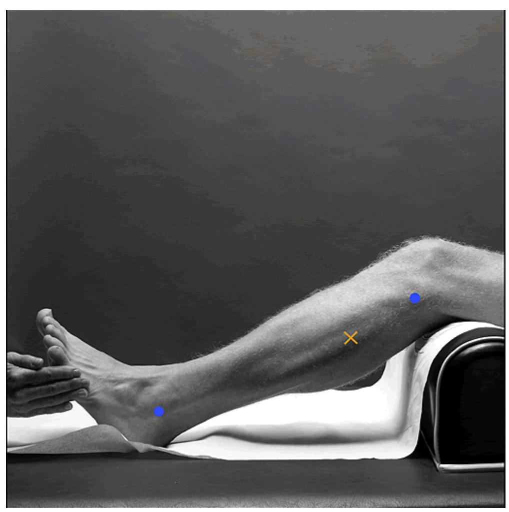
| Name | Tibialis anterior |
|---|---|
| Subdivision | |
| | |
| Origin | Lateral condyle and proximal 1/2 of lateral surface of tibia, interosseus membrane, deep fascia and lateral intermuscular septum. |
| Insertion | Medial and plantar surface of medial cuneiform bone, base of first metatarsal bone. |
| Function | Dorsiflexion of the ankle joint and assistance in inversion of the foot. |
| **Starting posture** | **Supine or sitting.** |
| Electrode size | Maximum size in the direction of the muscle fibres: 10 mm. |
| Electrode distance | 20 mm. |
| Electrode placement | |
| - location | **The electrodes need to be placed at 1/3 on the line between the tip of the fibula and the tip of the medial malleolus.** |
| - orientation | In the direction of the line between the tip of the fibula and the tip of the medial malleolus. |
| - fixation on the skin | (Double sided) tape / rings or elastic band. |
| - reference electrode | On / around the ankle or the proc. spin. of C7. |
| Clinical test | Support the leg just above the ankle joint with the ankle joint in dorsiflexion and the foot in inversion without extension of the great toe. Apply pressure against the medial side, dorsal surface of the foot in the direction of plantar flexion of the ankle joint and eversion of the foot. |



| **Name** | **Soleus** |
|---|---|
| Subdivision | |
| | |
| Origin | Posterior surfaces of the head of the fibula and proximal 1/3 of its body, soleal line and middle 1/3 of medial border of tibia and tendinous arch between tibia and fibula. |
| Insertion | With tendon of gastrocnemius into posterior surface of calcaneus. |
| Function | Plantar flexion of the ankle joint. |
| | |
| **Starting posture** | **Sitting with the knee approximately 90 degrees flexed and the heel / foot of the investigated leg on the floor.** |
| Electrode size | Maximum size in the direction of muscle fibres: 10 mm. |
| Electrode distance | 20 mm. |
| Electrode placement | |
| - location | **The electrodes need to be placed at 2/3 of the line between the medial condylis of the femur to the medial malleolus.** |
| - orientation | In the direction of the line between the medial condylis to the medial malleolus. |
| - fixation on the skin | (Double sided) tape / rings or elastic band. |
| - reference electrode | On / around the ankle or the proc. spin. of C7. |
| Clinical test | Put a hand on the knee and keep / push the knee downward while asking the subject / patient to lift the heel from the floor. |



| Name | Peroneus longus |
|---|---|
| Subdivision | |
| Origin | Lateral condyle of tibia, head and proximal 2/3 of lateral surface of fibula, intermuscular septa, and adjacent deep fascia. |
| Insertion | Lateral side of base of first metatarsal and of medial cuneiform bone. |
| Function | Eversion of the foot and assistance in plantar flexion of the ankle joint. |
| **Starting posture** | **Sitting with extremity medially rotated.** |
| Electrode size | Maximum size in the direction of the muscle fibres: 10 mm. |
| Electrode distance | 20 mm. |
| Electrode placement | |
| - location | **Electrodes need to be placed at 25% on the line between the tip of the head of the fibula to the tip of the lateral malleolus.** |
| - orientation | In the direction of the line between the tip of the head of the fibula to the tip of the lateral malleolus. |
| - fixation on the skin | (Double sided) tape / rings or elastic band. |
| - reference electrode | On / around the ankle or the proc. spin. of C7. |
| Clinical test | Support the leg above the ankle joint. Everse the foot with plantar flexion of the ankle joint while applying pressure against the lateral border and sole of the foot, in the direction of inversion of the foot and dorsiflexion of the ankle joint. |



| **Name** | **Gastrocnemius** |
|---|---|
| Subdivision | Medialis |
| Origin | Proximal and posterior part of medial condyle and adjacent part of the femur, capsule of the knee joint. |
| Insertion | Middle part of posterior surface of calcaneus. |
| Function | Flexion of the ankle joint and assist in flexion of the knee joint. |
| **Starting posture** | **Lying on the belly with the face down, the knee extended and the foot projecting over the end of the table.** |
| Electrode size | Maximum size in the direction of the muscle fibres: 10 mm. |
| Electrode distance | 20 mm. |
| Electrode placement | |
| - location | **Electrodes need to be placed on the most prominent bulge of the muscle.** |
| - orientation | In the direction of the leg (see picture). |
| - fixation on the skin | (Double sided) tape / rings or elastic band. |
| - reference electrode | On / around the ankle or the proc. spin. of C7. |
| Clinical test | Plantar flexion of the foot with emphasis on pulling the heel upward more than pushing the forefoot downward. For maximum pressure in this position it is necessary to apply pressure against the forefoot as well as against the calcaneus. |

**APPENDIX C**

**Texas Christian University**
**Fort Worth, Texas**

# CONSENT TO PARTICIPATE IN RESEARCH

**Title of Research:** The Effect of Sloped Surfaces on Lower Leg EMG and Postural Control

**Principal Investigator:** Dr. Adam King (Co-PI); Jacelyn Patton-Baldridge (Co-PI)

**Co-investigators:** Sara Harris, Jayne Kernodle, Max Power

You are invited to participate in a research study. In order to participate, you must be between the ages of 18 and 25, free from lower extremity injury for the last two years, have no lower extremity surgical history, have no known balance, visual, or neuromuscular disorders, and not be allergic to silver. Taking part in this research study is voluntary.

**What is the purpose of the research?**
The purpose of this study is to investigate how sloped surfaces influence balance through observing ankle muscle activity and postural sway.

**How many people will participate in this study?**
If you decide to be in this study, you will be one of 40 participants in this research study.

**What is my involvement for participating in this study?**
If you agree to be in the study, you will participate in one study session in the TCU Motor Control Laboratory located in the Rickel building. Once you sign the consent form, we will collect your gender, age, height, and weight. You will also fill out a questionnaire to determine your dominant foot. Before testing begins, we will prepare your skin for muscle activity recordings in your lower leg. This will involve shaving and cleaning the skin over four muscles in your lower leg (tibialis anterior, peroneus longus, soleus, and gastrocnemius medialis). Electrodes will be placed over these muscles which will allow us to measure the muscle activity around your ankles. You will perform a total of 14 different balance tasks on an angled platform while barefoot. The force plate located underneath the angled platform will record forces that tell us information about your balance. Your ankle muscle activity will also be recorded during each trial. Testing may take 45- 60 minutes.

**How long am I expected to be in this study for and how much of my time is required?**
Your participation in this study will involve one visit to the motor control lab that is expected to take 45-60 minutes.

**What are the risks to me for participating in this study and how will they be minimized?**
There are some risks you might experience from being in this study. They include the following: receiving a scratch during shaving; skin irritation from preparation, placement, and removal of

electrodes; and muscular fatigue and falling from standing at inclined and declined conditions. In order to minimize risk of skin irritation during electrode placement and removal, hair will be shaved prior to electrode placement. Additionally, if you have an allergy to silver, you will not be allowed to participate. In order to minimize risk of fatigue and falling, at least 30 seconds will be given for rest between trials. If you feel like you are going to fall, open your eyes and step off the platform. In order to keep your information private, it will be stored securely in locked cabinets and password protected computers.

**What are the benefits for participating in this study?**
Although you will not directly benefit from being in this study, other researchers and professionals may benefit from the results of this study. Understanding how balance changes on different inclined and declined surfaces may help in the development of rehabilitative and training techniques.

**Will I be compensated for participating in this study?**
No compensation will be provided for your participation in this study.

**What is an alternative procedure(s) that I can choose instead of participating in this study?**
There are no known alternatives available to you other than not taking part in this study. If any significant new findings develop which may relate to your willingness to continue participation, they will be provided to you.

**How will my confidentiality be protected?**
We plan to publish the results of this study. Efforts will be made to limit the use and disclosure of your personal information. Each participant will be assigned an identification number once participation is established. All consent forms and demographic data will be locked in a filing cabinet in the Motor Control Lab. All electronic data will only be associated with identification numbers and will be stored on a password-protected computer in the Motor Control Lab with restricted access. Data will be stored for a minimum of three years.

The following individuals and organizations may engage in Data Processing of Your Data Records:

- *the study team, including other people who, and organizations that, assist the study team:*
    - *Jacelyn Patton-Baldridge*
    - *Adam King*
    - *Sara Harris*
    - *Jayne Kernodle*
    - *Max Power*
- *the TCU institutional review board (IRB)*

**Is my participation voluntary?**
It is totally up to you to decide to be in this research study. Participating in this study is voluntary. Even if you decide to be part of the study now, you may change your mind and stop at any time without penalty. You do not have to answer any questions you do not want to

answer. If you decide to withdraw before this study is completed*, you must inform the Principal Investigator, Jacelyn Patton-Baldridge at (817)773-1700 or j.c.patton@tcu.edu.*

**Who should I contact if I have questions regarding the study?**
You can contact Jacelyn Patton-Baldridge, principal investigator, at (817)773-1700 or j.c.patton@tcu.edu with any questions that you have about the study. Additionally, you may contact Dr. Adam King, supervising advisor, at (817)257-6869 or a.king@tcu.edu.

**Who should I contact if I have concerns regarding my rights as a study participant?**
Dr. Dru Riddle, Chair, TCU Institutional Review Board, (817) 257-6811, d.riddle@tcu.edu; or Ms. Lorrie Branson, JD, TCU Research Integrity Officer, (817) 257-4266, l.branson@tcu.edu.

By signing this document, you are agreeing to be in this study. Make sure you understand what the study is about before you sign. You will be given a copy of this document for your records. A copy also will be kept with the study records. If you have any questions about the study after you sign this document, you can contact the study team using the information provided above.

I understand what the study is about and my questions so far have been answered. I agree to take part in this study.

______________________________________________
Printed Subject Name

______________________________________________
Signature                                                  Date

______________________________________________
Printed Name of person obtaining consent

______________________________________________
Signature                                                  Date

**ABSTRACT**

POSTURAL SWAY AND MUSCLE ACTIVITY DYNAMICS
OF STANDING ON SLOPED SURFACES

by Jacelyn Cybill Patton-Baldridge M.S., 2020
Department of Kinesiology
Texas Christian University

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The purpose of this study was to investigate how standing at different degrees of plantarflexion and dorsiflexion influence (1) postural sway and muscle activity and (2) the relationship between muscle activity and postural sway. An additional purpose was to investigate the effects of vision on postural sway and muscle activity while standing on sloped surfaces. Participants (N=12) stood on an angled platform, which provided a continuous inclined or declined perturbation to their stance at varying difficulty. The angled platform was situated atop a force plate, which allowed for center of pressure (COP) evaluation. Electrodes were placed on the dominant leg for electromyography (EMG) measurements of plantarflexor and dorsiflexor muscles. Results showed the amount of postural sway increased as a result of increased difficulty and the removal of vision. Additionally, muscle activity was influenced by postural difficulty, but not as hypothesized. Finally, postural difficulty altered the relationship between COP and EMG.