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Modulation of Vestibular Evoked Reflexes in Postural Muscles During Self-Motion Experiences in Virtual Environments

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Introduction

Posture is defined as the biomechanical alignment of the body and organization of body segments in the environment with respect to the body's center of mass (COM) located over a smaller base of support (BOS) (Shumway-Cook & Woolacott, 2012; Masani, et al., 2007). The BOS refers to the ground contact points beneath a person's body where the feet make contact with a support surface (Shumway-Cook & Woolacott, 2012). Control of posture typically revolves around two key goals: orientation and stability of the body in space. Without proper control of posture, simple activities such as walking, running, and even standing would not be possible as posture provides the foundation for the production of more complex tasks. Development provides an example of how essential posture is to human movement. Infants must first be able to control chaotic head movement that interrupt balance before anymore movements resembling those of a mature infant can emerge (Woollacott & Shumway-Cook, 1990; Shumway-Cook & Woolacott, 2012). During the first year of infancy, several motor milestones are achieved such as crawling, sitting, and standing with assistance, that guide the way to independent control of posture, which can eventually lead to walking. Posture is therefore an integral component of human motor control that makes bipedal locomotion possible.

Underlying Mechanisms & Physical Demands of Postural Control

During standing, humans use small amounts of natural sway to reorient the body over the base of support when exposed to environmental perturbations. How the body reacts to perturbations in the environment is dependent on its initial position and alignment of segments. In standing, correct alignment refers to the position of the head directly over the trunk (spinal column), pelvis, and feet (Woodhull, Maltrud, & Mello, 1985). The slightest misalignment of these segments causes shifts in the distribution of gravitational forces exerted downward on the body, resulting in greater muscular effort to keep upright.

Postural tone, which refers to passive tension produced by antigravity muscles, counteracts the effects of gravity on the body, and allows the neck and limbs to remain stable, which is important in order to maintain stability (Shumway-Cook & Woolacott, 2012). Muscle tone, which refers to the force at which a muscle fiber resists stretching, is also an important component in maintaining posture (Basmajian & Deluca, 1985). Muscle tone creates rigidity in the segments of the body, which allows the body to remain upright and stable. During standing, muscle tone is present passively in healthy individuals. However, it is capable of being controlled actively, and is the primary mechanism that allows the ankle and hip strategies to maintain stability. Together, these mechanisms maintain the individual's center of mass directly above the BOS with minimal effort to preserve balance.

Ankle and hip strategies of postural control.

The ankle and hip strategies are the two primary means of postural control in upright standing. They are different from the mechanisms responsible for alignment as they are products of higher level planning, taking place in the central nervous system (CNS) and the motor cortex. The key roles of the ankle and hip strategies in the control of upright posture are to assist in anterior posterior and medial lateral stability (Winter, Patla, Ishac, & Gage, 2003). The two strategies are a specific set of muscle activations that work to correct the body when perturbed. The spontaneous sway observed in humans during stance is a direct result of ankle and hip strategies.

The ankle strategy controls posture when the body experiences small and low shifts in the forward or backward direction (Shumway-Cook & Woolacott, 2012; Horak & Nashner, 1986; Gatev, Thomas, Kepple, & Hallett, 1999). Activation of the Gastrocnemius, Soleus, and Tibialis Anterior muscles produces extension and flexion of the foot around the ankle joint, which causes a decrease in forward momentum, followed by a redirection of motion to the posterior position in a reverse pendulum-like manner and vice-versa. This is useful in many daily activities; standing in a bus as it takes off, for example. As the bus accelerates a posterior shift occurs in the body, which is corrected by actively flexing and extending the ankles muscles, resulting in a shift of momentum in the anterior direction.

In contrast, the hip strategy is responsible for rotations about the hip when experiencing large and sudden shifts in the support base (Gatev, Thomas, Kepple, & Hallett, 1999). This strategy contributes to stability of sway and center of mass in the

medial-lateral direction (Horak & Nashner, 1986). This is useful in cases where the BOS is narrow, such as standing on a narrow rail or walkway. In these conditions, ankle torque may not be sufficient, and may require large compensatory shifts in the hips and trunk to correct balance (Horak, 1987).

Some researchers previously accepted that posture was controlled solely by sway centered on the ankle joint (inverted pendulum) (Winter, Patla, Prince, Ishac, & Gielo-Perczak, 1998; Winter, Patla, Rietdyk, & Ishac, 2001; Creath et al., 2005). Although findings by Gatev, Thomas, Kepple, & Hallet (1999) revealed that in some instances ankle and hip torque were observed together, the majority of their results suggested that when sensory input was manipulated (i.e. eyes open or closed) the ankle strategy was dominant during quiet stance. Other investigators have claimed that the hip strategy is the sole contributor to stability during quiet stance. Findings from an investigation assessing the effects of surface perturbation on body sway indicated that the hip strategy was most often used when shifts in the BOS were large or sudden, and when the BOS was smaller than the feet (Horak & Nashner, 1986).

Recent findings have supported the notion that posture in quiet stance is more complex requiring synchronous movement about both the ankle and the hip (Creath, et al., 2005). A study by Runge, Shupert, Horak, & Zajak (1999) assessing ankle and hip torques during surface perturbations did not support the idea of a single mechanism (Horak & Nashner, 1986), but rather identified that both hip and ankle strategies were present when the shifts in the environment or BOS were extremely fast or when other sensory input was restricted. The findings by Runge, Shupert, Horak, & Zajak (1999)

indicated that mixed strategies are often utilized by healthy adults when experiencing increases in velocity and shifts in BOS on flat surfaces. The findings from this study revealed that even at higher perturbation velocities, which is when the hip strategy is expected to be the sole contributor to balance, ankle torques were also evident. These findings provide support for the claim made by Winter, Patla, Ishac, & Gage (2003) that control of posture in quiet stance can be modulated by altering and combining two separate and independent mechanisms (ankle and hip strategies) resulting from environmental changes.

Sensory motor integration in higher neural centers

The sensory systems play vital roles in controlling posture and increasing stability. Maintaining upright posture, anticipating changes in the environment, and adapting to these changes are key responsibilities of the sensory systems. Strong interactions are present between the vestibular, visual, and somatosensory systems, but this can vary depending on the condition or health of the sensory systems and the information that is available from the environment (Redfern, Yardley, & Bronstein, 2001). In most cases, the frequency and amplitude associated with a task, and even positioning of the body segments with respect to the environment, can lead to an increase in gain in one of the sensory systems at which point it is the dominant system of postural control (Creath, et al., 2005). For example, in order to utilize visual information properly, the head must be in alignment relative to the trunk, pelvis, and feet; even the slightest shift in the positioning of the head could result in a sudden shift in the BOS,

which produces a cross-over from reliance on visual input and vestibular input to somatosensory input (Kandel, Schwartz, & Jessell, 1991).

Little is known about how conflicting information from the three sensory systems is processed and combined to produce appropriate postural adjustments (i.e. body sway or corrective torque) (Peterka, 2002). However, Peterka (2002) suggested that each sensory system operates at an optimal frequency, which allows each system to control posture depending on the information available in the environment. The task properties, frequency and amplitude of any given task are situated at optimal frequencies. These frequencies dictate how the CNS uses the sensory information to produce corrective postural adjustments. The CNS must be able to translate the sensory information during standing to information that can be interpreted to maintain posture by the cerebellum; one of the areas in the brain responsible for motor processes. In healthy individuals with normal cerebellar function, sensory input is translated into adaptive changes in postural control (Nashner, 1976). However, research has indicated that patients with deficits (lesions) in cerebellar function lack the ability to produce adaptive changes in response to perturbations in sensory input, which leaves them prone to extreme shifts in equilibrium.

Humans with normal function constantly utilize several sources of sensory input to orient themselves in the environment and to maintain posture (van der Kooij, Jacobs, Koopman, & Helm, 2001). However, to better understand postural control, it must be understood how the sensory systems integrate during standing. Furthermore, it needs to be investigated how each system contributes individually to postural control and how any changes in these systems could potentially affect stability.

Feedback and Feed Forward Control of Posture

Research has indicated that maintaining upright posture during exposure to external stimuli requires sensory feedback and feed-forward control (Johansson & Magnusson, 1991 as cited in Maurer, Mergner, & Peterka, 2006). Feedback control refers to control which results from sensory feedback provided visual, vestibular or somatosensory information modulated by disturbances in the environment (Shumway-Cook & Woollacott, 2012). In comparison, feed-forward control refers to adjustments, which occur in anticipation for voluntary movements needed to maintain stability (Shumway-Cook & Woollacott, 2012). Utilization of the ankle and hip strategies mentioned earlier involves passive and active initiation of the postural muscles in the legs, which occurs as a direct result of feed-forward and feedback control. Both of these forms of control are key to maintaining postural stability and stem from integration of the CNS and sensory systems.

Visual sensory feedback.

One of the primary means of postural control in upright stance comes from information received by the visual sensory system. The role of visual input on the maintenance of posture is essential, and plays an important part in the preservation of balance during human stance. Visual cues in the environment provide essential information about specific features such as texture and contrast, which are key components that allow humans to produce accurate postural adjustments during stance (Redfern, Yardley, & Bronstein, 2001). Vision is typically present in control of posture

in healthy adults, but when vision is suppressed or completely removed its contributions become evident.

Shifts in the visual field evoke whole-body responses (leaning) in the direction that the visual shift occurs (Blümle, Maurer, Schweigart, & Mergner, 2006; Guerraz et al., 2001; & Merger, et al., 2005). Research has reported increased postural sway and sway velocity in individuals who experienced removal or perturbation of visual stimuli in the environment (Redfern, Yardley, & Bronstein, 2001). Guerraz et al., (2001) reported significant shifts in the position of the head in response to lateral shifts of the visual scene. In a study assessing the effects of virtual environments on movement responses, Reed-Jones & Vallis (2009) observed significant rotation of the head and trunk in the direction of the visual perturbation. Combined, these results support the dominance of visual input to the CNS's interpretation of body orientation during standing.

In addition, research conducted by Ivanenko, Grasso, & Lacquiniti (1999) indicated that sway was oriented in the direction of vision when receiving neck vibration or stimulation to the vestibular system. The presented findings indicated that vision is a key component for directing the position of the body when exposed to changes in the environment or sensory systems, suggesting that vision takes primary control of postural control when altered sensory information is presented to the CNS.

The removal or suppression of visual information elicits specific postural adjustments in the body, which include shifts in center of mass/center of pressure and torque adjustments in the ankle and hip. Lack of visual input during the standing task typically results in an increase in sway in healthy adults, as well as an increase in sway

velocity. Considering this response, Adamcova & Hlavaka (2007) set out to assess the effects of visual and proprioceptive interaction during quiet stance control in humans. The aim of the study was to assess whether or not visual and proprioceptive feedback modulated in anyway the magnitude and velocity of postural reflexes in the lower limbs during muscle vibration. The findings of the study indicated that visual input played a role in the orientation of postural control based on the direction of the visual feedback (i.e. Center of pressure shifts in the anterior plane with forward feedback and vice-versa). In addition, as previously thought, the magnitude of these effects were increased during trials in which participants had their eyes closed (no visual input).

A similar investigation by Duarte & Zatsiorsky (2002) was conducted to assess balance in conditions with different states of leaning along with different visual information based on targets corresponding to BOS. The findings from the study revealed that deviations from center of pressure increased for all leaning conditions, regardless of the visual information. Ivankenko, Grasso, & Lacquaniti (1999) assessed the effects of eye orientation on postural responses elicited by neck vibration and like other studies assessing similar constructs, they found that body sway was directly associated with the visual information available in the environment (i.e. body sway shifted in alignment with the direction of vision). The findings from these studies indicate that visual information provided by the visual sensory system carries serious implications for postural control. Furthermore, these findings provide more insight on why clinical populations suffering from visual deficits are at greater risk for experiencing dramatic shifts in posture outside the limits of stability, increasing falls risks.

In spite of visual significance in postural control, a consideration must be made for conditions in which visual input is diminished or distorted. In such cases, control of posture is completely reliant on the somatosensory and vestibular sensory systems, but which system becomes the primary controller of postural adjustments is dependent on the nature of the activity taking place and the information that is available in the environment. It was stated that when visual information is removed, the gain of the other two systems is increased in order to compensate for the deficits. The reflexes produced by the removal of vision require the body to rely on the reweighting of the proprioceptive and vestibular sensory systems.

Somatosensory feedback.

Somatosensory feedback provides information about the environment, but unlike vision, the feedback is specific to physical changes sensed by specialized receptors in the skin and muscles. These receptors can detect the slightest changes in pressure, shifts in the BOS, and even provide characteristics about the type of surface in the environment. These properties make this type of feedback an important contributor to the control of balance during standing. Similar to visual feedback, somatosensory feedback also has an optimal range at which it is in primary control of stability (Redfern, Yardley, & Bronstein, 2001).

The feedback provided by the somatosensory system is essential to maintaining postural control and varies depending on task conditions. For example, standing on solid surfaces does not require much feedback from the mechanoreceptors to maintain stability in quiet stance. However, standing on an unstable surface such as a vibrating board,

would require all somatosensory information possible to maintain stability of quiet stance.

Simoneau, Ulbrecht, & Cavanagh (1995) assessed the effects of somatosensory deficits in patients with diabetic neuropathy on the control of posture in quiet stance. Investigators used a combination of sensory conditions to elicit postural responses, which involved tilting of the head and opening and closing of the eyes. The experiment revealed that patients with diabetic neuropathy in the distal limbs experienced a notable increase in the magnitude of the deviations in center of pressure when compared to the healthy participants in all conditions. The investigators attributed this directly to the loss of cutaneous sensation observed in these patients, but did note that an additive effect was likely present when altering the visual and vestibular sensory input (Simoneau, Ulbrecht, & Cavanagh, 1995). Nevertheless, the loss of stability during quiet stance experienced by patients with diabetic neuropathy serves as a model to better understand the somatosensory contributions to quiet stance.

Hlavacka & Horak (2006) conducted a similar study to assess how postural responses resulting from vestibular stimulation were affected by diabetic neuropathy during standing on a shifting support surface. The investigators observed that the loss of somatosensory information resulting from diabetic neuropathy and from standing on the translating support surface resulted in larger deviations in center of pressure. These findings provide further support for the findings presented in by Simoneau, Ulbrecht, & Cavanagh (1995) and indicate that the vestibulo-somatosensory interactions are highly dependent on accurate somatosensory information. The findings from this study suggest

that vestibular-evoked postural responses increase in sensitivity when somatosensory information is altered or manipulated (Hlavacka & Horak, 2006).

The importance of somatosensory information was once again observed in a study conducted by Peterka & Benolken (1995), in which they produced visually induced sway in healthy patients and patients with bilateral vestibular loss to assess the role of somatosensory input and vestibular information on postural control in environments with unreliable somatosensory cues (fixed support surface and sway referenced). Findings revealed that both normal and vestibular deficit patients produced larger amplitude sways in the sway-referenced condition when compared to the fixed support condition, regardless of the frequency and amplitude of the task stimulus. Also, normal subjects did not fall during any of fixed support trials and only occasionally in the sway-referenced trials. Patients with complete vestibular loss fell in both types of conditions, whereas patients with partial loss still fell, but more consistently in the sway-referenced condition (Peterka & Benolken, 1995).

The findings once again suggest that somatosensory information is vital to control posture, and although these behaviors were observed on an unstable surface, the same mechanisms of control still apply to quiet stance. The fact that healthy adults and partial vestibular loss patients fell in the sway-referenced trials suggests that inaccurate somatosensory information results in a decrease in postural stability, but based on these findings, vestibular function cannot be overlooked as an important contributor for control of posture and stability. Maintenance of posture on unstable surfaces requires more

integration from vestibular cues to process velocity sensitive cues resulting from body sway (Masani, et al., 2007).

Jeka, Kiemel, Creath, Horak & Peterka (2004) observed this relationship between vestibular and somatosensory cues in a study in which they tested sway behavior and whether or not it was indicative of deficits in velocity cues rather than cues provided by acceleration and position. Participants were required to stand on a platform that shifted positions in the anterior-posterior direction with feet oriented at shoulder width and eyes closed for three conditions (fixed surface, sway-reference surface, and foam surface). The results revealed that the amplitude of deviations from center of mass were much more pronounced in the sway and foam conditions when compared to the fixed surface condition, similar to results observed in previous studies (Jeka, Kiemel, Creath, Horak, & Peterka, 2004). This suggests that inaccurate somatosensory feedback coupled with velocity information from vestibular input is not sufficient to maintain complete stability on unstable surfaces.

Vestibular sensory feedback.

The vestibular system provides essential information about changes in velocity and acceleration of the body in space. This occurs primarily by the sensory system detecting motion of the head and feeding information back to the brain where the proper response can be organized and set into motion (Guerraz & Day, 2005). Vestibular contributions to posture typically occur at frequencies greater than 0.01Hz and sensory thresholds from the otolith organs are utilized below 0.1Hz. During standing, if a sudden perturbation is produced, which affects the position of the head; a strong postural

response can be produced to maintain stability. The magnitude of this response is dependent on task conditions or vestibular function. In healthy humans, the semicircular canals and otolith organs (utricle, macula, and saccule) found within the inner ear respond to angular and linear head acceleration (Cathers, Day, & Fitzpatrick, 2005). These structures respond to dynamic shifts in the body in a gravitational field, which makes the vestibular sensory system important for human bipedal control of posture in quiet stance.

Located at the end of each of each canal and within the otolith organs are thousands of crista or hair cells that move with the head (Fitzpatrick & Day, 2004). These hair cells detect gravitational acceleration resulting from motion of the head and bend due to inertial forces. The bending of these hair cells can result in a decrease or increase of the afferent fiber firing rates, which respond by sending signals to the CNS to reproduce a spatial representation of the body to control posture (Fitzpatrick & Day, 2004). In natural settings, the position and acceleration of the head change naturally due to dynamic movements produced during locomotion or quiet stance. Theses changes produce specific postural responses that work to maintain stability.

Horak, Nashner, & Diener (1990) conducted a study to assess the effects of vestibular loss on coordination of postural movements. The investigation compared normal and vestibular loss individuals while standing on a normal support surface (force plates) and a shortened support surface, which required participants to balance on a narrow beam positioned on top of the force plates. The findings revealed no differences between the two groups when standing on the normal support surface. However,

vestibular loss patients frequently lost balance on the shortened support surface compared to the control group. In addition, researchers identified that patients with vestibular loss were not utilizing a hip strategy (medial lateral stability) when surface information was available. Surprisingly, vestibular loss patients did not utilize a hip strategy even when it was vital to maintain balance on the shortened support surface (Horak, Nashner, & Diener, 1990). These findings suggest that vestibular sensory information plays an integral role in identifying task specific postural strategies. Furthermore, they suggest that a lack of vestibular sensory information might make patients with vestibular deficits less able to maintain balance during quiet stance and tasks requiring medial-lateral and anterior-posterior stability.

Similar findings were presented in Peterka & Benolken, (1995). However, they observed that individuals with vestibular deficits had a more difficult time maintaining balance on both fixed surface trials and trials in which the visual surround was manipulated. One of the findings from this study provides some degree of support for the importance of vestibular contribution to posture. In one of the patients who displayed vestibular loss with preservation of vestibular function, they identified a resistance to falling during both trial conditions when compared to two other patients with no evidence of vestibular function. Findings from other investigations suggest that the direction of body tilt resulting from loss of vestibular sensory information is significantly controlled by gaze deviation, regardless of the support surface (Ivanenko, Grasso, & Lacquaniti, 1999). It is to say, that direction of visual stimuli may elicit deviations in center of

pressure (COP) as a result of increased muscle activation on the side oriented towards the stimuli (i.e. right or left).

Typically, researchers have altered vestibular function by manipulating the visual scene in the environment or by using perturbation platforms to provoke shifts in the BOS (Horak, Nashner, & Diener, 1990; Perterka & Benolken, 1995). However, a method known as galvanic vestibular stimulation (GVS) has proven to be a more effective and direct means of stimulating the primary vestibular afferents, which is valuable for researchers to better understand vestibular contribution to posture in quiet stance. This method is valuable for assessing posture because it does not require the participant to produce gross dynamic movements for the sake of changing the gravitational acceleration of the head. Instead, GVS simulates gravitational acceleration of the head through electrical stimulation. Furthermore, GVS provides an apt tool to isolate vestibular inputs from other sensory systems without completely disturbing posture (Cathers, Day, & Fitzpatrick, 2005).

Galvanic Vestibular Stimulation

Galvanic vestibular stimulation (GVS) is a method often used by researchers to assess posture, postural stability, and vestibular function (Fitzpatrick & Day, 2004; Johansson, Magnusson, & Fransson, 1995). This method can mimic vestibular deficits, such as those seen in people with concussions and severe head trauma. When introducing electrical current to the vestibular system via GVS, the system perceives this stimulation as an unexpected movement of the body and accordingly alters the position of the head and trunk (Guerraz & Day, 2005). This serves as an important protective

mechanism, which may serve to prevent falls and possibly other bodily harm. In spite of this, the counteracting response is incorrect, since in reality, the position of the head is not changing, therefore leading to further loss of stability when experiencing GVS (Fitzpatrick & Day, 2004).

Typically, currents of no more than .20 mA are required to elicit a visible deviation from the center of the subject's head and trunk and currents above 5 mA could cause irregular sensations of the skin and might even cause physical burns (Britton et al., 1993). The deviation observed from center is a direct result of the electrical current altering the firing rate of vestibular afferent nerves. In addition to the visible sway that is produced while administering GVS, it also elicits an oculomotor response, which occurs due to the rapid repositioning of the head (Fitzpatrick & Day, 2004). These responses have been quantitatively analyzed by assessing COP, ground reaction forces, and also by assessing the activity of vestibular evoked postural reflexes of the muscles in the lower limbs (Welgampola & Colebatch, 2002).

Effects of GVS on semicircular canals and otolith organs.

The effects of GVS are very pronounced and they are a direct result of the electrical stimulation interacting with specialized structures of the inner ear. When GVS is administered, the body senses a tilt in the BOS; as a result, the body tries to compensate and readjusts the position of the head to control balance. The readjustment of the head causes changes in both angular and linear acceleration. The change in acceleration is detected by the otolith structures and the semicircular canals, two structures that have fixed coordinates and are key to controlling human bipedal upright

posture and stability (Cathers, Day, & Fitzpatrick, 2005). Vestibular stimulation results in an increase of firing rates of the primary vestibular afferents on the side of the cathode, and a decrease on the anodal side, which causes a tilt to the side of the anode (Wardman, Taylor, & Fitzpatrick, 2003). The magnitude of these responses are maximized when the subject's feet are together during quiet stance and can be detected by assessing postural muscle activity in certain muscles of the legs (Welgampola & Colebatch, 2002).

Cathers, Day, & Fitzpatrick (2005) suggest that the semicircular canals and the otolith organs should be considered separate sensory systems, altogether. This was after conducting a study that was used to assess the latency or timing of vestibular reflexes. In the study, researchers utilized GVS to separate the contributions of the canals and otolith organs to human balance control. The findings from the study revealed that by changing the position of the head during vestibular stimulation, signals transmitting through the vestibular system would travel through different pathways; the head up position resulted in balance responses by the semicircular canals (medium-latency 90-100ms) and the head down position resulted in short latency (64ms) otolith responses. These responses were detected by assessing muscle activity of the postural muscles in the lower limbs, which provides a suitable means of identifying vestibular signal pathways (Cathers, Day, & Fitzpatrick, 2005; Britton et al., 1993).

Effects of galvanic vestibular stimulation on center of pressure and EMG.

The effects of GVS vary between subjects, but regardless of the response, two things are certain; muscles in the lower limbs (i.e. gastrocnemius, soleus, and tibialis anterior) responsible for controlling and maintaining postural stability are activated at the

onset of stimulation (Welgampola & Colebatch, 2002), and this results in a shift in center of pressure. The timing of these responses varies, but typically they occur in set frames of time, which have been categorized simply as short-latency (60 ms), medium latency (100 ms), and long-latency periods (> 100 ms), respectively (Britton et al., 1993). The timing of these muscle responses are directly associated with the descending pathway of the signals received by the vestibular system (Cathers, Day, & Fitzpatrick, 2005; Britton et al., 1993). Short latency signals are routed from the vestibular system directly to receptors in the spinal chord, and thus, the reflexes that result are considered vestibulospinal reflexes. Medium and long latency signals are routed through a longer pathway stretching from the vestibular system, to the reticuli located in the midbrain, and finally to receptors in the spinal chord; the reflexes that are produced via this interaction are aptly named reticulospinal reflexes (Britton et al., 1993; Watson & Colebatch, 1997).

Several studies have investigated the interactions between vestibular stimulation and muscle responses during quiet stance and have determined that several factors have the potential to affect reflex latencies and amplitude. A study by Welgampola & Colebatch (2002) assessed quiet stance and the effects of ageing on vestibular-dependent lower limb responses following GVS. The findings revealed that out of 70 participants, 60 presented with a normal short-latency (60 ms) muscle reflex in the soleus. The 10 participants who did not present the reflex were 61-85 years of age. Investigators also observed that short-latency responses reduced in amplitude after age 30. Another finding revealed an increase in the amplitude of medium-latency responses from the third to the eight-decade.

These findings indicate that ageing has a significant effect on vestibular signal processing and thus the timing of muscle reflexes, which is likely due to degeneration of the hair cells in the inner ear. In healthy adults this would likely not pose a threat to the control of posture during quiet stance, but older adults or individuals with vestibular deficits might struggle to control posture and maintain equilibrium when exposed to changes in the environment. This is especially the case due to the fact that galvanic evoked reflexes are greatly influenced by the sensory information that is available through the postural task (Fitzpatrick, Burke, & Gandevia, 1994).

Aside from ageing, another factor that has been shown to affect how galvanic vestibular stimulation modulates muscle reflexes is the orientation of the semicircular canals and the otolith organs. A study discussed previously by Cathers, Day, & Fitzpatrick (2005) determined that when the head was turned upwards during vestibular stimulation, short-latency reflexes occurred as expected at 64 ms and medium-latency (opposite polarity) reflexes followed after 124 ms. The researchers observed however, that when the head was oriented downwards, short latency reflexes were still present, but medium-latency reflexes were completely abolished. This suggested that the short-latency response lasted longer and did not dissipate when the medium-latency reflex was expected to occur. In all, these findings suggested that GVS does not stimulate all vestibular structures equally, unless positioned accordingly, therefore affecting signal pathways that produce postural adjustments in the lower limbs. During quiet stance the head is in a neutral position, which might be why the effects of GVS are more

pronounced, assuming that the position of the head does in fact change how the stimulus affects the vestibular structures.

When dealing with healthy adults, research has provided evidence to support that the change in muscle reflexes associated with GVS creates a postural shift and thus affects stability during standing (COP) (Fitzpatrick & Day, 2004; Coates, 1973 as cited in Fitzpatrick, Burke, & Gandevia, 1994). Johannson, Magnusson, & Fransson (1995) reported that participants who were exposed to GVS produced an obvious sway in the direction of the stimulation. Along with this response, investigators also noted a shift in center of pressure in the BOS that was associated with the shift seen in the lateral plane. Another study identified similar patterns and noted that participants who were exposed to GVS elicited significant directional postural responses (i.e. medio-lateral center of pressure) (Pavlik, Inglis, Lauk, Oddson, & Colins, 1999). These postural shifts occur as a result of interplay between the vestibular, somatosensory, and visual sensory systems, but how this feedback is organized to produce postural adjustments still requires further investigation.

Purpose

How conflicting information from the three sensory systems is processed and utilized to generate correct postural adjustments is still not fully understood (Peterka, 2002). Furthermore, we currently do not know how vestibular information is weighted during postural control. Electromyography (EMG) may be used to examine this and may serve as an assessment tool to predict how motor recruitment patterns are responsible for the onset of postural control during vestibular stimulation. This might also allow insight into the neural reflexes of the vestibular system which could be used to determine vestibular contributions to control of posture (Welgampola & Colebatch, 2002). Furthermore, an assessment of posture by means of center of pressure analysis could provide a better idea of what strategies humans implement to stabilize balance during visual manipulations. With this in mind, the purpose of this investigation was to determine if screen-simulated visual stimuli alter central vestibular function, resulting in longer muscle onset latencies and modified postural control.

Hypotheses

Given what is known about the relationship between visual and vestibular to postural control, it was hypothesized that when exposed to dynamic visual cues while receiving GVS, participants would increase COP adjustments more so than when exposed to static visual cues only. This was expected because under dynamic visual conditions and visual conditions with GVS the visual and vestibular sensory systems relay information to the CNS indicating that incorrect or irregular information is being received, leaving only somatosensory information to interpret the correct

position/orientation in the environment (see Table 1). It was also hypothesized that participants would increase COP adjustments to a greater extent when performing standing trials with no visual cues (eyes closed) when compared to trials in which only static visual cues were available. This observation was expected because in this condition visual input is suppressed, which leaves only vestibular and somatosensory information to control posture (Table 1). Finally, it was hypothesized that activation of postural muscles that results from GVS would be reduced when individuals were exposed to simulated, dynamic visual activities, resulting in an increased muscle response latency stemming possibly from a greater contribution of vision and a reduction of the CNS weight of vestibular information during postural control. This was expected due to the fact that the additional sensory information from the dynamic visual stimulus would increase the amount of time needed to process the incoming vestibular information leading to an increased latency.

Table 1. Breakdown of sensory system contributions for trials in present study.

Trial Type:	**Sensory System Contributions**		
Eyes Closed only		Vestibular	Somatosensory
Static Visual Only	Visual	Vestibular	Somatosensory
Dynamic Visual Only		Vestibular	Somatosensory
Eyes Closed + GVS			Somatosensory
Static Visual + GVS	Visual		Somatosensory
Dynamic Visual + GVS			Somatosensory

Methods

Participants

For this experiment, 15 healthy young adults (individuals ranging in age from 18-30 years) were recruited primarily from an undergraduate participant pool at the University of Texas at El Paso. Participants reported no history of vestibular deficits (i.e. concussions) and no history of motor or visual impairments. Prior to the laboratory visit, participants were instructed to wear comfortable clothing (i.e. shorts and t-shirt) to allow for mobility and attachment of other experimental components. The study was approved by the University of Texas at El Paso Institutional Review Board (IRB).

Apparatus and Materials

Questionnaire. The general health questionnaire (Appendix A) was administered in this study to each participant prior to inclusion to ensure volunteers were healthy and free of any neurological disorders (e.g. vertigo and hearing disorders), as well as any medical conditions that could have put them at increased risk by participating in the study (e.g. heart conditions).

Measurement tools for participant responses. To monitor and assess postural control of COM, one force platform recording at (60 Hz) and operating through Vicon Workstation version 5.2.9 (Vicon Motion Systems, Oxford, United Kingdom) was utilized. The force platform was used specifically to record COP and deviations from BOS. Participants were asked to stand on one strain gauge force plate (AMTI, Watertown, Massachusetts) with a narrow stance as they interacted with the visual

stimulus on the screen to assess COPx and COPy (medio-lateral deviations and anterio-posterior deviations).

To acquire muscle responses during standing, participants were outfitted with six wireless lower-limb surface EMG electrodes from the Trigno Wireless System (DELSYS, Boston, Massachusetts). The surface electrodes were placed bilaterally on the soleus, gastrocnemius, and tibialis anterior muscles. Additionally, two wireless surface electrodes were placed bilaterally on the upper trapezius (L/R) to detect onset of galvanic vestibular stimulation. This technique involved placing electrodes over the muscle bellies of the measured muscles and recording the electrical activity from the neural activation of these muscles. EMG data were collected at 2000 Hz for 60s for all the trials.

Tools to elicit postural responses. Participants were outfitted with two bilateral EMG electrodes placed on the mastoids behind the ears. The skin was swabbed with alcohol to clear any excess residue. Vestibular Stimulation Threshold testing was then initiated following the procedure of (Bent, McFayden, & Inglis, 2002), which involved administering a small current starting at 0.20 mA on the mastoid bones and increasing the stimulation by 0.05 mA increments until the investigator observed an obvious head tilt. The head tilt was an indication that the threshold stimulation level had been reached in the subject. For testing purposes, this threshold was multiplied by a factor of 3. Typical thresholds can range from 0.2 mA to 0.8 mA; therefore testing stimulus did not exceed 2.5 mA. Application of a single stimulus did not exceed a 30s time period to ensure comfort and safety of the participant. Stimulation was administered using the A395 Linear Stimulus Isolator (World Precision Instruments, Sarasota, Florida).

Participants engaged with a virtual environment in the form of a video projection on a seven by six feet projection screen. The 60s video depicted movement through space and gave the participant the impression of moving towards the screen or having the screen move towards them.

Figure 1. Starfield visual encountered by participants during visual trials.

Procedure

This study involved one testing session of approximately two-hours, which took place at the Stanley E. Fulton Biomechanics and Motor Behavior Laboratory at the University of Texas El Paso. Each session included a series of 45 randomized trials consisting of 6 conditions (10 EYES CLOSED+GVS, 10 VISUAL+GVS, 10 EYES OPEN+GVS, 5 EYES CLOSED*, 5 STATIC VISUAL*, 5 DYNAMIC VISUAL*) each one-minute in duration. Refer to Table 1 for a summary of the sensory manipulations for each of these conditions. Control trials (*) consisted of the individual standing in front of the screen with the eyes open with a static frame from the original video, the dynamic video, and eyes closed. The experimental trials consisted of visual conditions with GVS.

In the DYNAMIC VISUAL+GVS condition, the participants experienced vestibular stimulation (forward GVSf or backward GVSb) while a visual stimulus was presented on the screen. In the STATIC VISUAL+GVS condition, the participants experienced galvanic stimulation (forward or backward) as a static frame from the original video was presented. Finally, in the EYES CLOSED+GVS condition, the participant only received vestibular stimulation (forward or backward) as the eyes remained closed and the head still positioned at 90 degrees relative to the sagittal plane. The order of all trials was randomized within three visual blocks (eyes closed, dynamic visual, and static visual).

Prior to data collection, each participant read and signed an informed consent form and then proceeded to complete the general health questionnaire (Appendix A). Upon completion of both forms, the participants were asked to change into the required attire (shorts and t-shirt).

Participants were instructed to remain in a relaxed position for each trial with their head turned at 90-degree relative to the sagittal plane while facing a projection screen located about one meter to the right. An assistant began recording force plate and EMG data in Vicon as the investigator simultaneously triggered the visual stimulus or GVS depending on the trial. GVS was administered for 30s during the one-minute trials. Application of a single stimulus (GVS) did not exceed a 30s time period to ensure comfort and safety of the participant. Additionally, a one-minute rest period was given to all participants in between each trial to avoid fatigue or residual effects. Once all trials were completed, each participant was required to sit for ten minutes to avoid the

possibility of residual effects of GVS, which have been documented to include mild itching or tingling (Utz et al., 2011).

Data and Statistical Analysis

Control trials (*) were used to compare the effects of visual stimuli (eyes closed, dynamic visual, static visual) and GVS on vestibular dependent muscle responses and COP. Force plate data were used to identify COP excursions in the x/y direction (A-P M-L movement). A custom, in house program designed in MATLAB (MATHWORKS, Natick, Massachusetts) was used to calculate deviations, and velocity shifts in COP over the trials. Stimulus dependent muscle responses were band-pass, fully rectified, and low-pass (Butterworth 4^{th} order) (cut-off 20-450 Hz) filtered using EMGworks Analysis (DELSYS, Boston, Massachusetts). EMG data were analyzed to determine short (60 ms) and medium reflex latencies (> 60 ms) (onset) during activity using an in house MATLAB program (MATHWORKS, Natick, Massachusetts). Analysis involved a two way repeated measure ANOVA conducted for each muscle response and COP measure (dependent variables). T-tests were performed to determine significant differences between GVS forward and GVS backward conditions on COP. For all analyses, a critical alpha level of .05 was used to determine statistical significance and post-hoc Bonferroni corrected pair-wise comparisons were performed on significant effects.

Results

Participant Measures

Fifteen (n=15) healthy (8 males 7 females), college aged males and females (23.07 ± 3.06 years) participated in the investigation. Table 2 below provides additional information, such as height (173 ± 10.35 cm), mass (75.34 ± 17.37 kg), and vestibular stimulation amplitude (1.01 ± 0.32 mA).

Table 2. Descriptive statistics for research participants.

	Age (yrs.)	**Height (cm)**	**Mass (kg)**	**GVS Stimulation (mA)***
Mean	23.07	173.08	75.43	1.01
SD	3.06	10.35	17.37	0.32
Min	19.00	157.48	46.27	0.60
Max	30.00	193.04	104.32	1.65

**Note: GVS stimulation represents the value (mA) at which GVS was administered during trials.*

Center of Pressure Anterior-Posterior Displacement

Center of pressure data from 15 participants were used in the displacement/RMS velocity analysis. T-tests revealed no significant differences between GVS forward and backward conditions and were therefore combined for analysis. A significant main effect was found for the three visual blocks (eyes closed, static visual, dynamic visual) for mean anterior-posterior center of pressure displacement ($F\ (1, 14) = 16.125$, $p < 0.05$, $\eta^2 = 0.712$). Post-hoc Bonferroni pair-wise comparisons revealed that the dynamic visual only condition yielded greater anterior-posterior displacement when compared to the static visual only condition ($p < 0.05$, 95% CI_{Δ} -2.874 to -0.311) (see Figure 2). In addition, comparisons revealed that the eyes closed only condition produced greater anterior-posterior displacement when compared to the static visual only condition ($p < 0.05$, 95%

CI_{Δ} 0.661 to 2.869) (see Figure 2). A significant main effect was also found for GVS for mean anterior-posterior center of pressure displacement (F (1, 14) = 6.294, $p < 0.05$, $\eta^2 = 0.310$). The pair-wise comparisons revealed a significant difference (p =0.025) between GVS trials and no GVS trials regardless of the visual stimulus presented (see Figure 3).

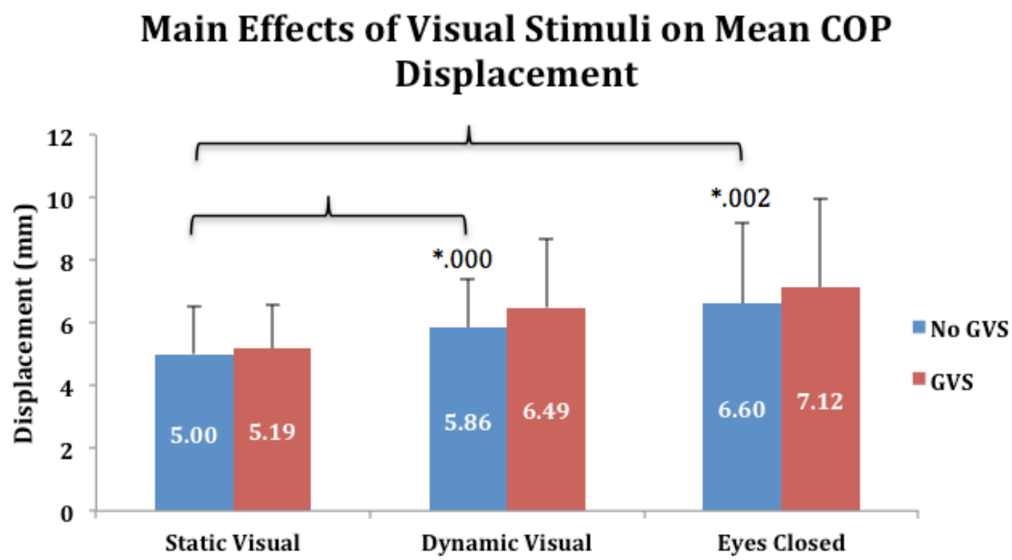

Figure 2. Comparisons of mean A/P COP displacement (mm) for the three visual conditions. The dynamic visual condition and eyes closed condition produced significantly greater displacement when compared to the static visual condition.

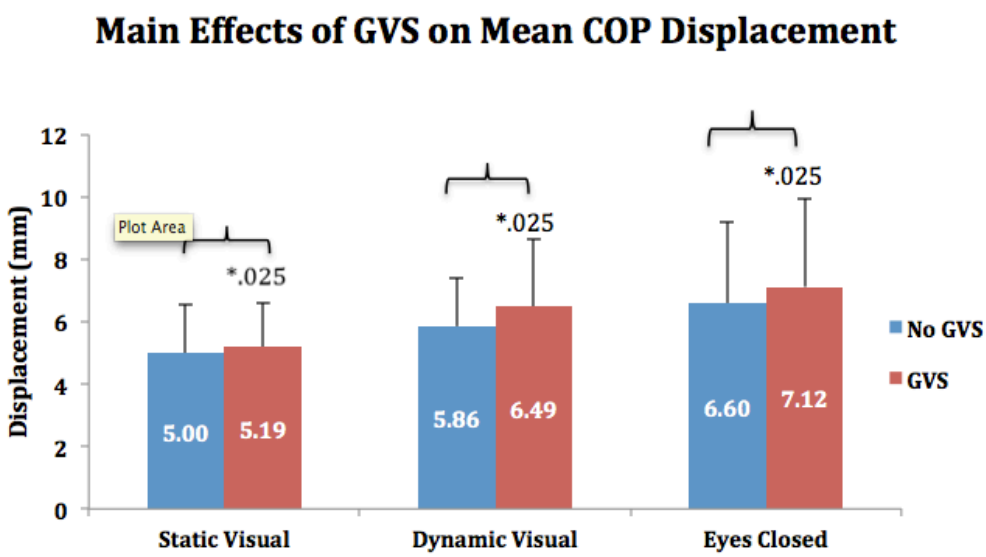

Figure 3. A main effect was found for GVS. GVS trials produced significantly greater displacement than no GVS trials regardless of which visual stimulus was presented.

Root Mean Square COP Velocity

A significant main effect was found for the three visual blocks (eyes closed, static visual, dynamic visual) for mean anterior-posterior RMS velocity (F (1, 14) = 280.487, $p < 0.05$, $\eta^2 = 0.952$). Post-hoc Bonferroni pair-wise comparisons revealed a significant increase for RMS velocity in the dynamic visual only condition when compared to the static visual only condition ($p < 0.05$, 95% CI_{Δ} 1.263 to 4.285) (see figure 4). In addition, comparisons revealed that the eyes closed only condition produced a greater degree anterior-posterior RMS velocity when compared to the static visual only condition ($p < 0.05$, 95% CI_{Δ} 0.146 to 5.927) (see figure 4). A significant main effect was also found for GVS for mean anterior-posterior RMS velocity (F (1, 14) = 10.969, $p < 0.05$, $\eta^2 = 0.439$). The pair-wise comparisons revealed a significant difference (p =0.005) between GVS trials and no GVS trials regardless of the visual stimulus presented (see Figure 5).

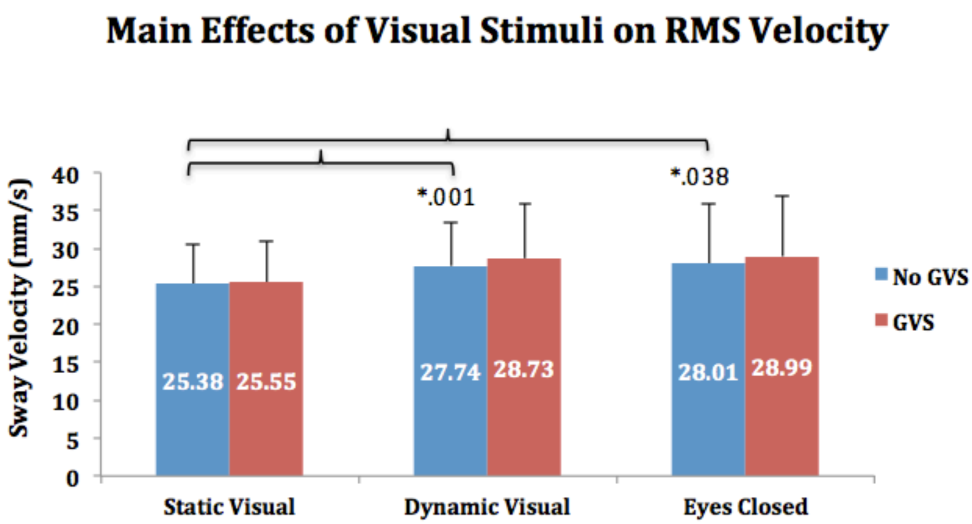

Figure 4. Comparisons of mean A/P RMS velocity (mm/s) for the three visual conditions. The dynamic visual condition and eyes closed condition produced a significantly greater degree of RMS velocity when compared to the static visual condition.

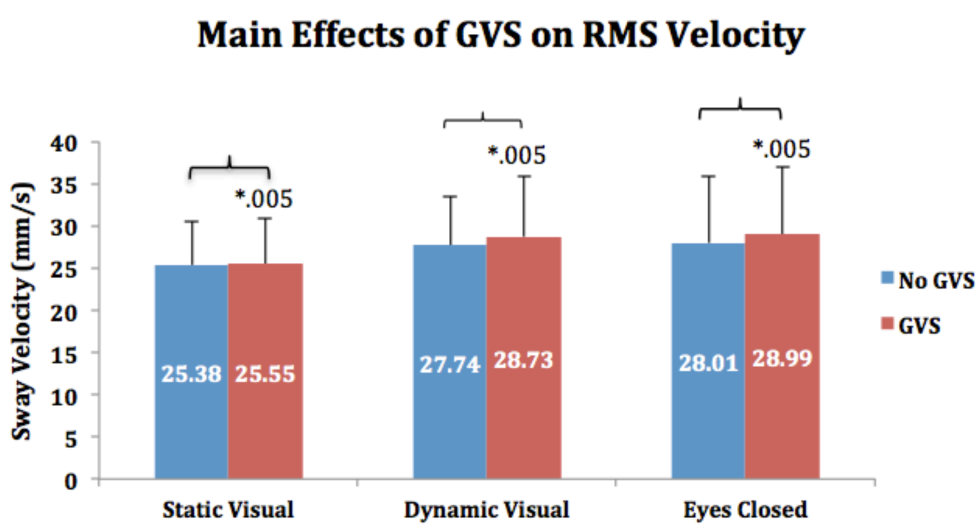

Figure 5. A main effect was found for GVS. GVS trials produced a significantly greater degree of RMS velocity than no GVS trials regardless of which visual stimulus was presented.

Muscle Activation Latency

EMG from 11 participants was used in the analysis of muscle activation latency. Four of the original participants had to be excluded from the EMG analysis due to corrupted data files. No significant main effects were found for vestibular dependent muscle activation as measured by muscle response onset. Right and left sides on the soleus (RSOL: (F (1, 10) = 21.449, $p > 0.05$, $\eta^2 = 0.682$), (LSOL: F (1, 10) = 20.324, $p > 0.05$, $\eta^2 = 0.670$) (Figure 6), gastrocnemius (RGAS: (F (1, 10) = 19.208, $p > 0.05$, $\eta^2 = 0.658$), (LGAS: (F (1, 10) = 21.384, $p > 0.05$, $\eta^2 = 0.681$) (Figure 7), and tibialis anterior (RTA: (F (1, 10) = 16.812, $p > 0.05$, $\eta^2 = 0.627$), (LTA: (F (1, 10) = 124.381, $p > 0.05$, $\eta^2 = 0.926$) (see Figure 8). Post-hoc Bonferroni pair-wise comparisons revealed no significant changes ($p > 0.05$) in the response latency of the RSOL and LSOL when comparing the eyes closed + GVSf, static visual + GVSf, and dynamic visual + GVSf conditions. Furthermore, no significant changes ($p > 0.05$) were observed in the response latency of the RGAS and LGAS when comparing the eyes closed + GVSf, static visual + GVSf, and dynamic visual + GVSf conditions. Finally, no significant changes ($p > 0.05$) were observed in the response latency of the RTA and LTA when comparing the eyes closed + GVSb, static visual + GVSb, and dynamic visual + GVSb conditions.

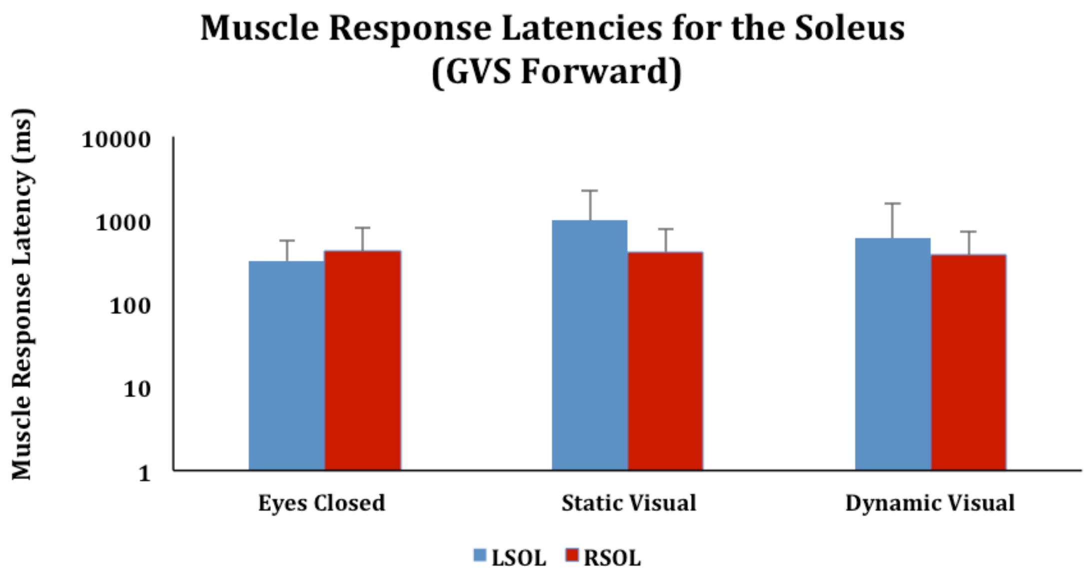

Figure 6. Comparison muscle latencies (ms) for the left and right soleus for the eyes closed + GVSf, static visual + GVSf, and dynamic visual + GVSf conditions. There were no significant effects of visual stimulus or GVS on muscle response latencies.

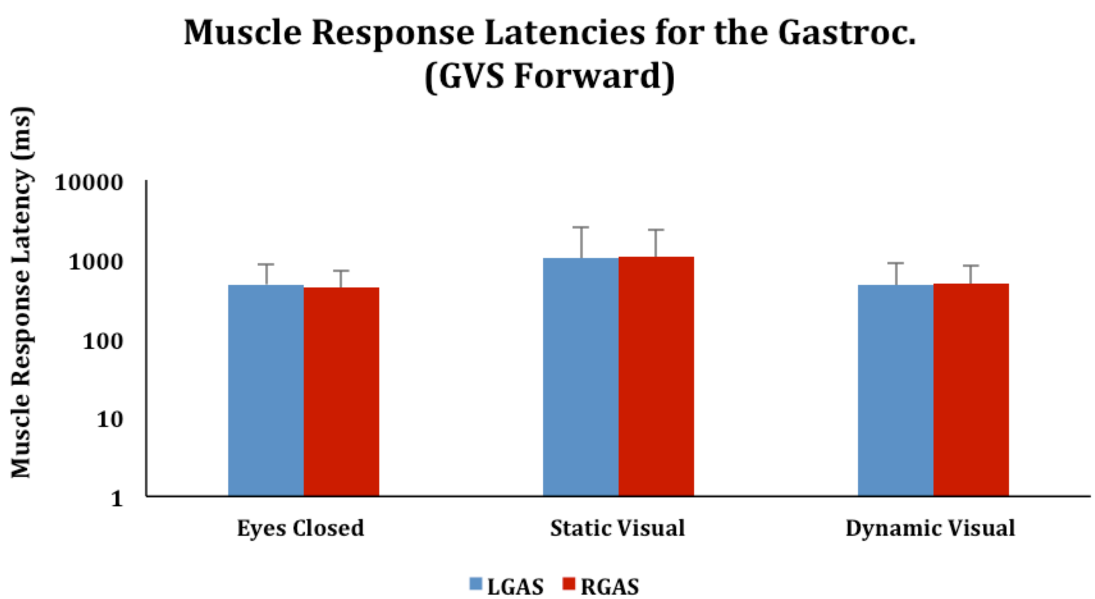

Figure 7. Comparison of muscle latencies (ms) for the left and right gastrocnemius for the eyes closed + GVSf, static visual + GVSf, and dynamic visual + GVSf conditions. There were no significant effects of visual stimulus or GVS on muscle response latencies.

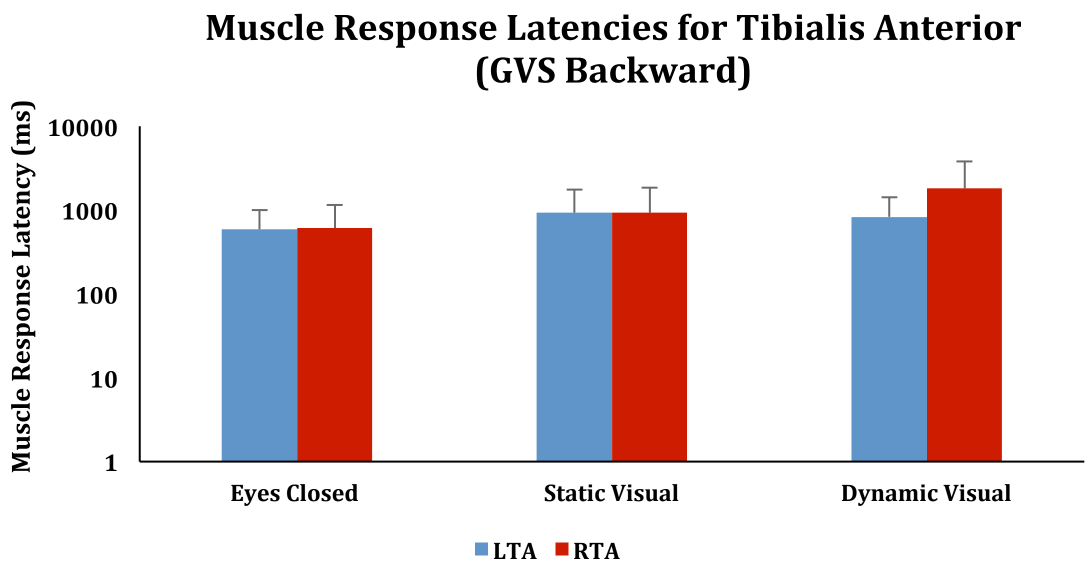

Figure 8. Comparison of muscle latencies for the left and right tibialis anterior for the eyes closed + GVSb, static visual + GVSb, and dynamic visual + GVSb conditions. There were no significant effects of visual stimulus or GVS on muscle response latencies.

Discussion

Fixed (static) visual environments have been shown to increase stability during standing (Borger, Whitney, Redfurn, & Furman, 1999; Redfurn, Yardley, & Bronstein, 2001). There is evidence to suggest that focusing vision on a stationary or fixed targets such as the static visual stimulus in the present study helps minimize body sway and increases stability during standing (Ustinova & Perkins, 2011; Paulus, Straube, Krafczyk, & Brandt, 1989). This serves as a compensation mechanism during situations in which there exists conflicting sensory information (i.e. GVS) and is facilitated in part by information received by the retina. In the presence of moving visual environments the retina detects motion and provides people with information on self-motion or motion of objects in the environment (Sheldon, 1963**).** These visual cues typically lead to dynamic shifts in COP, but are utilized by the (CNS) to derive orientation and position of the body for postural control by activating the optokinetic reflex. The visual feedback helps stabilize the image of the visual surround by producing reflexive eye movements in response to dynamic changes in the environment, although responses often take the form of dynamic shifts, typically in the direction of the visual stimulus (Zupan, Merfeld, & Darlot, 2002).

Certain situations can provide sensory conflict and require the individual to decide whether actual movement of the body is taking place or movement in the environment (Lee & Lishman, 1975). Previous studies have determined that feedback provided by a static reference point allows individuals to create more accurate perceptions about the position of the body in physical space by reducing the degree of

eye pursuit or excess head tracking (reducing retinal slip), thus leading to increased stability (Glasauer, Schneider, Jahn, Strupp, & Brandt, 2005; Ivanenko, Grasso, & Lacquiniti, 1999; Jahn et al., 2002). Assuming the participants in the present study followed protocol, the static visual condition would have provided the configuration needed to maximize stability (i.e. reduced head tracking, eye pursuit, dynamic visual cues) regardless of whether or not vestibular sensory inputs were altered.

The purpose of this study was to determine the effects of visual stimuli on central vestibular function and vestibular dependent muscle reflexes during standing as measured by center of pressure (COP) and electromyography (EMG), respectively. Healthy college-aged males and females performed standing trials with three visual blocks (eyes closed, static visual, and dynamic visual) coupled with vestibular stimulation (GVS) or no stimulation. These conditions were chosen to determine primarily how the vestibular, and visual sensory systems are weighted during standing tasks in the presence of a virtual stimulus.

It was hypothesized that participants would produce greater COP displacement when exposed to dynamic visual trials and eyes closed trials when compared to the static visual trials. This is to say that the greatest degree of stability was expected in the trials with static visual stimuli. This was expected because under dynamic visual conditions and eyes closed conditions, only somatosensory information is left to control posture. Individual COP responses were expected to increase when the visual blocks were coupled with GVS. Previous literature (Adamcova & Hlavacka, 2007) has shown the importance of visual feedback in human locomotion and standing, but one of the goals of this study

was to take a closer look at how visual and vestibular inputs integrate to control posture when exposed to different visual conditions (i.e. dynamic stimulus, static stimulus, no stimulus). Results of COP measures supported our hypotheses and support results of previous research (Adamcova & Hlavacka, 2007; Bronstein, 2004).

Studies have shown that stability decreases by 200%-300% in both healthy and clinical research participants when visual cues are suppressed or removed by closing the eyes (Madeleine, Prietzel, Svarrer, & Arendt-Nielson, 2004; Kelly, Riecke, Loomis, & Beall, 2008). Even moderate suppression of visual input in the moving environment can have a notable influence on postural stability (Streepey, Kenyon, & Keshner, 2007). The visual sensory system provides vital information about the environment, which can be utilized to derive spatial orientation and can be used as a reference to coordinate movements (Wade & Jones, 1997). By suppressing or removing vision altogether, as in the case of the eyes closed condition, the reliance of postural control is placed on the vestibular or proprioceptive sensory systems, which then have to be re-weighted to compensate for the lack of visual information. Sensory reweighting occurs during specific tasks (e.g. standing) and enables the body to source and prioritize useful information from the three primary sensory systems based on the physical cues available in the environment (Allison, Kiemel, & Jeka, 2006). This process is thought to occur as a compensation mechanism, which contributes to postural stability during scenarios in which sensory conflict occurs (Bair, Kiemel, Jeka, & Clark, 2007; Reed-Jones, Vallis, Reed-Jones, & Trick, 2008).

When visual suppression was coupled with the disruption of the vestibular afferents produced by GVS, an increase in displacement and sway was observed when compared to the static visual conditions (coupled with GVS). The lack of visual and vestibular sensory feedback left only the proprioceptive system to manage posture, and could have been the contributing factor for the increased sway and decrease in stability for the eyes closed conditions. Previous research studies have found similar results, but have not directly examined the coupling effect of visual suppression (eyes closed) and GVS. For instance, a number of studies have been performed on older adults assessing the effects of loss of vision on postural stability, which have indicated that stability can be significantly affected when lacking sensory feedback from the system (Wade & Jones, 1997; Stoffregen, 1986). Studies have revealed that removing vision altogether eliminates peripheral field of view and optic flow, which are essential to navigating or maintaining the position of the body in space (Stoffregen, 1986). These two components allow humans to distinguish textures and features of the physical environment that aid in controlling stability. Findings from other studies also suggest that removing vision during the standing task, specifically the Romberg test (similar to the present study), significantly affects static balance.

A study by (Bohannon, Larkin, Cook, Gear, & Singer, 1984) testing the effects of vision on standing balance revealed that stability was significantly impacted during the eyes closed condition when compared to the eyes open condition. These patterns were observed in all age groups spanning five decades (20-70 years). Coupling these effects with the destabilizing effects that have been reported when using GVS provides support

for the current findings. When lacking information from the visual system, humans lose the ability to track the position of the body in space, which ultimately results in the inability to stabilize the head (e.g. when the body moved the head moved). When the head moves the vestibular system typically detects angular acceleration and produces the necessary postural adjustments, but in the presence of GVS only the proprioceptive system is left to control posture.

Dynamic visual conditions led to decreased stability and increased sway when coupled with GVS. These responses were expected in the GVS trials due to the fact that disruption of the vestibular afferents leads to increased sway in the direction of the anode (i.e. GVS anode right leads to sway to right or in the posterior direction when the head is turned 90 degrees to the right). In addition, participants can also experience GVS-induced nystagmus, which can make it difficult to detect visual cues in the environment that can be used to produce postural adjustments (Curthoys & MacDougall, 2012). However, a notable decrease in stability was also observed during dynamic visual trials without GVS. Several findings from previous studies suggest that large-visual-field motion (dynamic alterations of stimuli) leads to postural deviation in the direction of the visual stimulus (Bronstein, 1986; Adamcova & Hlavacka, 2007). This occurs due to a perception of self- motion or vection produced by the stimulus. Self- motion is mistaken as displacement of the body and results in a compensatory postural response to maintain stability (Bronstein, 1986; Bardy, Warren, & Kay, 1996).

When exposed to dynamic visual stimuli, healthy humans respond by leaning in the direction of the stimulus. This displacement results in a tilt of the head, which causes

the vestibular system to lose the ability to accurately detect orientation in space (Paloski et al., 2006). As a result, somatosensory afferents are re-weighted to produce the necessary postural adjustments to compensate for erroneous vestibular and visual feedback. Evidence has also shown that moving visual environments can cause disequilibrium and motion sickness in healthy adults (Redfurn, Yardley, & Bronstein, 2001). Exposure to moving visual environments can produce sensory conflict by feeding erroneous visual cues to an individual; since vision is in primary control of posture, incorrect visual feedback could lead to motion sickness or sense of loss of balance.

Overall, the results of the current study fully support our original hypothesis for postural measures. It was expected that alterations to the visual conditions would affect COP readings, specifically when comparing the dynamic and eyes closed conditions to the static visual condition with GVS and without GVS. The observations made in the patterns of COP changes are in line with those presented in previous literature and based on the small responses suggests that participants relied more on the ankle mechanism to control posture than the hip strategy during dynamic visual trials. These findings also suggest that vision plays a significant role in how posture is controlled during the standing task and during instances in which sensory feedback is altered.

Dynamic visual cues elicit a postural response in the direction of the stimulus (Blümle, Maurer, Schweigart, & Mergner, 2006). Therefore, alterations to the visual cues were expected to have a significant effect on vestibular dependent muscle reflexes in the lower legs. With this in mind, the second hypothesis stated that GVS dependent muscle activation would decrease during trials in which participants experienced dynamic visual

stimuli, which would lead to delayed muscle onset and modified postural responses. However, no significant effects or distinct patterns were observed in the EMG signals when comparing the (GVS forward and GVS backward) conditions for the eyes closed, static visual, and dynamic visual conditions. Without external stimuli, these postural EMG responses should have occurred in two phases, a short (60ms) and medium (100ms) latency (Welgampola & Colebatch, 2002; Fitzpatrick & Day, 2004; Nashner, 1977). Research findings by (Welgampola & Colebatch, 2001) reported that vestibulospinal associated muscle latencies did not occur earlier or later than expected when performing standings trials when visual sensory information was available in a narrow stance configuration. Medium latency responses were observed earlier however, when a wide stance configuration was implemented with external support.

Some evidence suggests that vestibulospinal reflexes are greatest (e.g. quick latency) during conditions in which visual information is absent or misleading (eyes closed or dynamic visual) (Nashner, Black, & Wall 1982). One could then infer that standing in a dynamic, virtual environment provides the participant with erroneous visual cues, which should be identifiable by observing a short latency (60ms) response in the EMG signals for the respective muscles during GVS forward or GVS backward conditions. According to evidence provided by (Nashner, Black, & Wall, 1982) the same idea should be applicable to standing with the eyes closed. This was not the case however for the present findings. Not only was there not a clear indication of a normal short latency response, there were no indications of even a normal long latency response.

The dynamic (GVSf and GVSb) conditions resulted in irregular latencies that were not distinguishable in terms of postural responses and did not support the original hypothesis or what has been reported in previous studies. Similar results were observed for the eyes closed and static conditions with latencies exceeding 1000ms in some cases. Son, Blouin, & Inglis (2008) reported normal patterns (40-120 ms) in the Soleus and Tibialis Anterior during GVS. They observed a decrease in the latency of the Soleus and an increased response in the Tibialis Anterior as the participants shifted back onto the heels (GVS backward) and vice-versa. The findings in our study might suggest that something may be occurring in the descending pathways down the spinal tract and thus might affect how the vestibular signal gets transmitted and processed, but once again the EMG were not distinguishable nor were they similar to previous findings. This factor prevents us from making a strong case for issues with the descending pathways resulting in increased muscle response latencies.

Previous studies have indicated that somatosensory loss resulting from neuropathy can produce vestibulospinal sensitivity, which can affect muscle activity and result in decreased muscle activation latency (Nashner & Wolfson, 1974 as cited in Welgampola & Colebatch, 2002). However, none of the participants who were recruited reported any health issues, much less peripheral neuropathy. Evidence has been presented, which suggests that short latency muscle responses are preserved in the majority of participants under the age of 60 (Welgampola & Colebatch 2002). However, nothing was observed in the latency analysis that suggested any preservation or presence

of normal latency timing (60-10ms). Once eliminating health factors and ageing, the visual stimulus was then examined as a catalyst for the irregular signals.

Britton et al., (1993) reported that visual stimuli could result in the elimination of the medium latency responses without affecting the short latency response. However, given that the visual stimulus was identical for the visual trials for all participants this does not provide an explanation for the lack of short latency muscle responses. Some research has indicated that differences in vestibular dependent EMG signals can result from differences in skull anatomy between males and females (Krogman, 1962; Welgampola & Colebatch, 2002). Female participants can present with larger EMG amplitudes and quicker reflex latencies as a result of greater current flow through a thinner and lighter skull (Keen, 1950). However, the irregularities were observed for both male and female participants, which suggests that the anatomical differences were not responsible for the irregular EMG signals.

Since the inconsistent response latencies were observed in both male and females, the issue may have been associated with the strength of the galvanic current. Perhaps stimulus amplitude was not sufficient to elicit the desirable and appropriate muscle response. While the majority of research has shown that increasing stimulus amplitude increases postural sway, very few have reported in regards to the effects of stimulus amplitude on EMG. Fitzpatrick & Day (2004) expressed that larger stimulus amplitude is needed to observe a short latency response, in some cases even up to 5 mA. This experiment implemented the protocol established by (Bent, McFayden, & Inglis, 2002), which used a maximum of 2.5mA for stimulus amplitude. The point at which the

participants responded to the stimulus may have been underestimated and could have therefore resulted in lower than ideal stimulus strength, contributing to irregular muscle activation patterns.

Within the present study, there were four primary limitations that could have affected the accuracy and overall outcomes of the postural measures and EMG measures. The first limitation is tied directly to the resolution of the visual stimulus that was used during the standing trials. Rendering of the original video affected the video resolution, which resulted in a slightly pixelated image. Previous research has indicated that dynamic visual stimuli in the digital realm provide the visual sensory system with ambiguous or inaccurate visual cues, which could lead to an exaggerated postural response or no response at all (Redfern, Yardley, & Bronstein, 2001). Such events would make it difficult to identify if the postural responses that occurred during the standing trials were actually associated with the video itself or a result of random postural adjustments produced by the participant.

A second group of limitations, which could have affected both COP and EMG reflex latencies, is electrode placement and GVS stimulus amplitude. As previous research has suggested, GVS results in a postural tilt in the direction of the stimulation (Britton et al., 1993). Therefore, if the electrodes were not placed properly over the mastoids the stimulus current may not have stimulated the vestibular afferents as intended, resulting in weak amplitude or poor transmission of the galvanic stimulus and thus, less dynamic COP responses and inaccurate or absent EMG latencies.

The final limitation that could have potentially affected the outcomes of this study is the use detection algorithms to identify COP and EMG measures. Previous studies have indicated that using algorithms to detect fine motor and neural responses, such as those in the present study, can be reasonably accurate (Micera, Sabtini, & Dario, 1998; Farina & Merletti, 2000). However, investigators from the same studies have indicated that at times fine responses such as EMG onset latencies can occur later than expected due to the manner in which the operating systems detect baseline activity, typically determined by a set number of standard deviations.

Future aims for this research will focus on identifying the proper short and medium latency responses that are associated with GVS during the standing task, which will involve refinement of the detection algorithm previously discussed, more specifically, refinement of the algorithm that detects baseline activity. In addition, future investigations will attempt to use a higher resolution video to provide accurate and more reliable visual cues in hopes of producing more consistent postural responses. Finally, future studies will aim at identifying optimal and safe GVS amplitudes in the attempt of obtaining better signal transmission through the vestibular afferents and thus, more pronounced muscle activation patterns, which should lead to better detection of the finer, short and medium latency muscles responses.

Conclusion

The purpose of this investigation was to determine if screen-simulated visual stimuli alter central vestibular function, resulting in modified motor recruitment patterns and modified postural control. The primary findings of the study revealed two key

conclusions. First, when engaging with a screen-simulated dynamic visual stimulus during the standing task, there was a significant increase in sway with a decrease observed in overall stability. The second conclusion revealed similar patterns when performing the standing task with no visual stimulus (eyes closed). Once again the findings revealed a significant increase in postural sway and a decrease in stability during the dynamic visual trials and eyes closed trials. These findings occurred regardless of whether or not GVS was administered during the trial. These primary findings suggest that vision plays an essential role in the control of posture and based on the postural responses suggest that the ankle strategy is likely dominant during conditions in which alterations of sensory information result in slower postural shifts. They also suggest that the condition of the visual stimulus also plays an integral role in how humans use vision to produce accurate postural responses.

Based on these primary findings, one would have expected to identify a dependent change (increase) in muscle reflex latencies directly associated with the visual stimuli and more exclusively GVS. However, no such pattern was detected. Despite the fact that muscle reflex latencies did not link with postural measures as anticipated, these findings are important because they provide further support for the existing body of knowledge revealing the importance of vision and visual cues during human stance. Future research may strive to replicate these findings with the primary goal of identifying a link between vestibular dependent muscle responses and modified posture observed during the different visual conditions.

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Appendix A

Health Status Questionnaire

Please complete the following questions as accurately as possible.

Date of Birth: ______/______/______ Age:________yr.

Weight: __________________ Height: ________________

Average number of hours worked per week:

☐ Less than 20 ☐ 20-40 ☐ 41-60 ☐ over 60

More than 25% of time spent at work/school is: (mark all that apply)

☐ Sitting at a desk ☐ Lifting or carrying loads ☐ Standing
☐ Walking ☐ Driving

Medical History

Please mark any who have died of heart attack before age 50 years:

☐ Father ☐ Mother ☐ Grandparent ☐ Brother ☐ Sister

Date of last physical exam: ______/______/______

Date of last physical fitness test: ______/______/______

Date of last menstrual cycle: ______/______/______

Is there any possibility that you are pregnant? Yes ☐

No ☐

Please mark and date all surgeries you have had:

☐ Back	______/______	☐ Heart	______/______
☐ Kidney	______/______	☐ Eyes	______/______
☐ Joint	______/______	☐ Neck	______/______
☐ Ears	______/______	☐ Hernia	______/______
☐ Lung	______/______	☐ Hysterectomy	______/______
☐ Other	______________________________		______/______

Please mark all of the following for which you have been diagnosed or treated by a physician or health professional:

- ☐ Alcoholism
- ☐ Anemia, sickle cell
- ☐ Anemia, other
- ☐ Asthma
- ☐ AIDS
- ☐ Back Strain
- ☐ Bleeding trait
- ☐ Bronchitis, chronic
- ☐ Cancer
- ☐ Cirrhosis, liver
- ☐ Concussion
- ☐ Congenital defect
- ☐ Diabetes
- ☐ Emphysema
- ☐ Epilepsy
- ☐ Eye problems
- ☐ Gout
- ☐ Hearing loss
- ☐ Heart problem
- ☐ Heart murmur
- ☐ Hepatitis
- ☐ High blood pressure
- ☐ Hypoglycemia
- ☐ High Cholesterol
- ☐ Infectious mononucleosis
- ☐ Joint problems
- ☐ Kidney problems
- ☐ Liver disease
- ☐ Lung disease
- ☐ Mental illness
- ☐ Neck strain
- ☐ Obesity
- ☐ Phlebitis
- ☐ Rheumatoid arthritis
- ☐ Stroke
- ☐ Thyroid problem
- ☐ Ulcer
- ☐ Other___________
- ☐ Neuromuscular disorders (multiple sclerosis, vertigo, cong. myasthenia, etc.)
- ☐ Multiple concussions

Please mark all medications/supplements taken during the past 6 months:

- ☐ Blood thinner
- ☐ Diabetic
- ☐ Diuretic
- ☐ Insulin
- ☐ Epilepsy medication
- ☐ Heart medication
- ☐ High blood pressure medication
- ☐ Hormones
- ☐ Other___________
- ☐ Other___________
- ☐ Other___________
- ☐ Other___________

Please mark any of the following symptoms you have had recently:

- ☐ Abdominal pain
- ☐ Arm or shoulder pain
- ☐ Breathless with slight exertion
- ☐ Blurred vision
- ☐ Blood in urine
- ☐ Burning sensations
- ☐ Chest pain
- ☐ Cough up blood
- ☐ Difficulty walking
- ☐ Dizziness
- ☐ Feel faint
- ☐ Frequent urination
- ☐ Leg pain/numbness
- ☐ Low blood sugar
- ☐ Low-back pain
- ☐ Palpitation or fast heart beat
- ☐ Shortness of breath
- ☐ Significant emotional problem
- ☐ Swollen joints
- ☐ Unusual fatigue with normal activity
- ☐ Weakness in arms

Have you experienced any bouts of vertigo, dizziness, or false sense of motion?

☐ Yes ☐ No

If so, how recent? ___________________

Do you ever feel lightheaded or feel the sensation of being disconnected from the physical environment?

☐ Yes ☐ No

If so, how often? ___________________

Do you ever feel off-balance or wobbly while standing or walking?

☐ Yes ☐ No

Do you or have you ever, experienced motion sickness? ☐ Yes ☐ No

Have you recently suffered from any severe head trauma/injuries (i.e. concussions, inner ear damage)?

☐ Yes ☐ No

Do you experience regular migraines? ☐ Yes ☐ No

If so, how often and how severe? ___________________

Have you recently suffered from an ear infection of a cold? ☐ Yes ☐ No

If so, how recent? ___________________

Curriculum Vitae

Fabricio Saucedo, Jr. earned a Bachelor's degree in Kinesiology with a minor in Psychology from the University of Texas at El Paso in December 2011. Throughout his undergraduate career Fabricio gained research experience by working as a research assistant in the Stanley E. Fulton Biomechanics and Motor Behavior Laboratory. Fabricio assisted with several studies, which dealt with walking and turning in older adults, young adults, and patients with Parkinson's disease. Fabricio enrolled in the Master of Kinesiology program at the University of Texas at El Paso in January 2012 and focused on Biomechanics. His work was mainly centered on vestibular dependent muscle responses in virtual environments, but also had the opportunity to work with concussed athletes. Throughout Fabricio's career as a master's student, he has given several presentations at national and international scientific meetings. In April 2012 he received an award for best master's presentation at the annual meeting for the South Central chapter of the American Society of Biomechanics. Fabricio also has several published works in peer-reviewed journals and will graduate in May 2014.

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