Fear of Falling, Proprioception and Spinal Reflex Modulation

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ABSTRACT

Clinical and experimental research has demonstrated that the emotional experience of fear impairs postural stability in humans. This is problematic considering that fear-related postural instability contributes to a greater likelihood of an individual suffering a fall that can result in devastating physical and financial consequences. For this reason, the research presented in this thesis was performed to clarify the current description of the postural behaviour observed among those who experience fear and/or anxiety and to investigate how human proprioceptive information is utilized by the central nervous system to explain anxiety-induced changes in postural control. Over a series of four consecutive studies, elevated surface heights were used to assess the within-subject effect of fear and anxiety on changes in static posturography, spinal reflex excitability as well as changes in mechanically (TEP) and electrically (SEP) evoked somatosensory potentials. The results of the first study demonstrated that the changes in postural control that occurred with increased surface height were dependent upon the degree of fear of falling experienced by the participants. The results of the second study demonstrated that soleus tendon reflex (STR) excitability could be facilitated during states of height-induced fear and anxiety, without any accompanying changes at the level of the somatosensory cortex. The results of the third study failed to demonstrate that descending pre-synaptic inhibition influences soleus Hoffmann reflex (SOL H-reflex) excitability during states of height-induced fear and anxiety. As such, the fourth study in this thesis was designed to test the effectiveness of using visual feedback to overcome the biomechanical confounds that limited the interpretation of changes in static posturography measures and SOL H-reflex excitability observed in the previous three studies. Taken together, the results of these four studies extend the current understanding of how posture changes during states of height-induced fear and anxiety and sheds new light on the mechanisms that facilitate the changes in spinal reflex excitability and cortical control of posture during such circumstances.

PREFACE

Chapter 2 of this thesis is a slightly modified version of a published manuscript. Davis, J.R., Campbell, A.D., Adkin, A.L. and Carpenter, M.G. The relationship between fear of falling and human postural control. (2009). *Gait and Posture.* 29(2):275-9. I was responsible for data collection, data analysis and manuscript preparation and publication.

Chapters 2-5 detail the experimental findings of studies conducted in the Neural Control of Posture and Movement Lab at UBC. All work was conducted under the supervision of Dr. Mark Carpenter and in collaboration with my fellow graduate student; Adam D. Campbell; Brian C. Horslen; and Chantelle D. Murnaghan. With respect to the work conducted, I was responsible for experimental design, data collection, and data analysis and manuscript preparation.

All of the experimental methods used to collect the data included in Chapters 2-5 were approved by the University of British Columbia's Clinical Research Ethics Board (UBC CREB Number: H06-70316. Please see (Appendix 1) for a detailed copy of the approved ethics certificate.

The order in which the chapters contained in this thesis are presented does not reflect the chronological order in which the data for each study was collected. Chapter 2 was collected first, followed by Chapter 5, Chapter 3 and Chapter 4.

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CHAPTER 1: GENERAL INTRODUCTION AND LITERATURE REVIEW

Bipedal standing balance is a complicated sensori-motor process that is essential for one to lead an independent lifestyle. The inability to maintain standing balance can leave one incapacitated and unable to engage in a vast majority of everyday activities. This is especially a concern for older adults considering that the inability to properly maintain balance can often lead to unfortunate injury, expensive hospitalization, rehabilitative therapy and possible death (Zijlstra et al., 2007; Stevens et al., 2006; Carroll et al., 2005; Englander et al., 1996).

Unfortunately, the research and medical communities lack a detailed understanding of the exact neural and biomechanical mechanisms that facilitate standing balance. For this reason, it is important that we improve our understanding of how standing balance is achieved. Improving the basic understanding of how the human central nervous system (CNS) controls standing balance is essential to understanding the mechanisms underlying postural instability associated with specific pathologies in order to develop effective treatment strategies and rehabilitative therapies. Additionally, the study of standing balance serves as an excellent model for basic researchers to study human neurophysiology and biomechanics.

1.1 Sensory Contributions to the Control of Standing Balance

Sensory information from three modalities, the visual system, the vestibular system and the proprioceptive system is required to maintain balance (Rothwell, 1995). The maintenance of stance is an ongoing process of sensory integration where information from these three modalities is constantly monitored in order to maintain balance against the forces of gravity and other forces that disturb postural stability during stance (Winter et al., 1990). Therefore, a constant stream of sensory information is required for the postural system to maintain a correct orientation and postural equilibrium within the three dimensional world. However, the process of integrating these three sources of sensory information is not well understood (Wade and Jones, 1997). Additionally, there is great debate over how exactly each modality contributes to the maintenance of posture (Fitzpatrick et al., 1994).

1.2 Visual Contributions to Standing Balance

During periods of postural sway, one of the most significant sensory contributions to the maintenance of standing balance comes from the visual system (Wade and Jones, 1997). The strongest argument for this statement comes from the observation that the amplitude of spontaneous postural sway increases by as much as 50% when humans stand with their eyes closed (Edwards, 1946; Travis, 1945; Mirka and Black, 1990; Kuo et al., 1998). It has been proposed that the visual system is particularly sensitive to low frequency stimulation and therefore detects low frequency oscillations that occur during postural sway (Warren, 1995). Therefore, vision has been suggested to facilitate aspects of postural sway occurring at less than 0.5Hz (Warren, 1995). A large body of evidence detailing the importance of vision in maintaining postural stability has come from the work of Paulus et al. (1984). In their work, they clearly identified that the visual acuity with which one views the world is proportional to ones postural stability. More specifically, as visual acuity decreases, postural sway increases (Paulus et al., 1984). Furthermore, the size of one's field of view (Paulus et al., 1984) and the distance from one's eye to the nearest visual reference point (Brandt et al., 1979; Bles et al., 1980) have also been identified as critical to maintaining postural stability.

More recent work has characterized the importance of the visual system in detecting movement related to self-motion versus motion of the three dimensional world (Guerraz et al., 2000). Displacement of an observer in relation to the three dimensional world generates a spatio-temporal pattern of stimulation on the retina specific to that observer. Therefore, when multiple visual targets at varying distances move across the retina during sway, they generate what is known as motion parallax (Guerraz et al., 2000). The detection of motion parallax has been identified as an important contributor to the control of upright stance (Bronstein and Buckwell, 1997; Guerraz et al., 1999; 2000).

1.3 Vestibular Contributions to Standing Balance

The second sensory modality that contributes to the control of static posture is the vestibular system. The vestibular system is a bilateral sensory organ located in the inner ears comprised of fluid filled semi-circular canals that detect angular accelerations in the horizontal, sagittal and frontal planes. Additionally, the vestibular system consists of bony otolith structures that detect linear accelerations in the horizontal and frontal planes (Kandel et al., 2004).

There has been some contradictory evidence regarding the involvement of the vestibular system in the maintenance of standing balance. For instance, Winter et al. (1995) argued that the theoretical angular acceleration of the head that occurs during spontaneous sway is insufficient to stimulate vestibular pathways and therefore, vestibular information does not

contribute to the active maintenance of static balance. However, when mild perturbations, at intensities within the normal bounds of postural sway were applied to study participants in the absence of visual and proprioceptive cues, participants were able to detect these perturbations (Fitzpatrick et al., 1994). Given that participants in the Fitzpatrick et al. (1994) study lacked visual and proprioceptive inputs, the only modality through which they could have been able to detect the perturbation was through the vestibular system. The role of the vestibular system in the maintenance of static posture is further supported by the work of Lackie and Loram (2006). In their experiments, participants were able to maintain upright posture when balancing an inverted-pendulum like apparatus in the absence of visual and proprioceptive cues (Lackie and Loram, 2006). Therefore, it has been argued that vestibular information can be re-weighted in order to maintain balance in the absence of visual and proprioceptive cues.

Studies of spontaneous postural sway among bilateral vestibular loss patients has shown that the amplitude of postural sway observed among this clinical group is not significantly different than that of otherwise healthy control participants so long as both visual and proprioceptive cues are available (Nashner et al., 1982). However, when either visual or somatosensory information is perturbed, bilateral vestibular patients suddenly lose the ability to maintain postural equilibrium (Nashner et al., 1982; Horak et al., 1989).

Given these observations, it is likely that the vestibular system provides redundant sensory information to the central nervous system during quiet stance. More specifically, it is plausible that the CNS relies on vision and proprioception as first line sensory modalities, but in situations when either one or both of these modalities are absent, vestibular information can serve as a second line sensory modality for the control of standing balance (Horak and Hlavaka, 2001).

1.4 Proprioceptive Contributions to Standing Balance

In addition to visual and vestibular contributions to the control of standing balance, proprioceptive contributions from cutaneous sensory receptors in the skin, sensory receptors within the skeletal musculature and gravioceptors throughout the body have all been identified to contribute to the control of standing balance. The strongest evidence supporting the involvement of proprioceptive inputs to the control of standing balance comes from case studies involving an individual completely lacking proprioceptive sense; I.W. Due to an unfortunate viral infection, the entire compliment of large diameter peripheral afferent innervation of cutaneous and muscle proprioceptors of I.W. were destroyed rendering him completely unable to sense touch and the position of his limbs. Consequently, I.W. was initially unable to move let alone stand. With time and training, I.W. eventually learned how to overcome his lost proprioceptive

sense by re-weighting visual input (Cole, 1992). The observation that turning off the lights, thereby removing I.W.'s access to visual information, results in compete loss of postural stability strongly implicates the necessity of proprioceptive information for maintaining standing balance in otherwise healthy individuals.

Individual case studies of complete deafferentation are quite rare, making it difficult to study the influence of total proprioceptive loss on standing balance in a comprehensive manner. However, it is possible to perform experimental deafferentation studies in animals to gain understanding of the proprioceptive contributions to standing balance. For example, pyridoxine (Vitamin B_6) administered in high doses results in the destruction of large diameter Ia afferents (Schaumburg et al., 1983) and complete deafferentation of the animal model while leaving descending motor neurons intact (Windebank et al., 1985). Pyridoxine induced deafferentation of the cat model has demonstrated that the proprioceptive information carried along large diameter Ia afferents is critical to the maintenance of standing balance (Hulliger et al., 2000; Allum et al., 1998) and spinal reflex activity related to locomotion (Hulliger et al., 2000) despite the fact that the exact mechanism of pyridoxine induced Ia deafferentation is unknown.

In addition to completely deafferented human and animal models, individuals suffering from sensory neuropathy and degraded proprioceptive efficacy provide a clinical group that can be studied in order to understand how compromised proprioceptive efficacy can lead to postural instability. For instance, when comparing the sway amplitude of otherwise healthy young individuals to a group of age-matched individuals suffering from systemic peripheral neuropathy secondary to diabetes, it has been shown that sufferers of peripheral neuropathy have significantly broader ranges of postural sway than otherwise healthy controls (Geurts et al., 1992; Bergin et al., 1995; Simoneau, 1995). Moreover, the magnitude of peripheral sensory loss is correlated with the magnitude of postural instability as measured by the absolute range of postural sway (Bergin et al., 1995). This correlation has been identified in not only peripheral neuropathy patients, but also in older adults suffering from age related proprioceptive decline (Bergin et al., 1995). These observations support the hypothesis that the postural deficits observed among older adults may be associated with proprioceptive decline (Bergin et al., 1995). Studies involving peripheral neuropathy patients have also made a significant impact on our understanding of the relative weighting of different sensory contributions to the maintenance of upright stance. For instance, it has been shown that removing vision (closing the eyes) and impairing vestibular function (titling the head backward) do not result in a further challenge to standing balance among peripheral neuropathy sufferers but does so for otherwise healthy controls (Simoneau et al., 1995). The interpretation of this observation is that visual and vestibular functions cannot fully compensate for the compromised proprioceptive function in terms of their contribution to the control of standing balance. Furthermore, the fact that

balance testing is required for the diagnoses of peripheral neuropathy (Mauritz et al., 1980) highlights the robust contributions from the proprioceptive system to the control of upright stance.

Unfortunately, studies involving select patient groups suffering from sensory neuropathies can be confounded by the co-morbidities of muscular atrophy and weakness associated with the disorder (Geurts et al., 1992) as well as other unidentified deficits associated with the neuropathy. Therefore, it is difficult to translate the findings made in these patient groups to understand the proprioceptive contributions to standing balance in otherwise healthy populations.

To overcome this limitation, researchers have been able to apply temporary lesions to normal proprioceptive efficacy. For instance, placing pressure cuffs around the lower limbs and cooling distal limbs substantially creates an ischemic blockade of ascending proprioceptive information from cutaneous, muscle and joint sensory organs. Studies involving ischemic block placed just above the knee demonstrated that removing proprioceptive inputs from the lower limb musculature resulted in larger amplitude postural sway even when vision is available. This suggests that proprioceptive sensory organs embedded within the lower limb musculature, muscle spindles and golgi tendon organs (GTOs), provide the primary proprioceptive information used to control standing balance (Mauritz and Dietz, 1980). It has also been demonstrated that removing cutaneous proprioceptive input from the feet by applying an ischemic block at the ankle results in larger amplitude postural sway when visual inputs are removed suggesting that cutaneous receptors on the sole of the foot provide critical proprioceptive input that is used to control standing balance (Diener et al., 1984). Results from these studies are important to our understanding of proprioceptive contributions to the control of posture. However, it is still not clear whether proprioceptive contributions from the receptors embedded in the muscle or cutaneous receptors on the bottom of the feet, or both, provide the primary afferent input required to control standing balance. Despite the existing debate within the literature over the exact origin of the critical somatosensory input, it is clear that proprioceptive contributions are essential to the maintenance of standing balance.

In addition to studies investigating the effects of removing proprioceptive inputs on the control of posture, a number of studies have investigated how providing additional proprioceptive inputs can improve postural stability. For instance, when individuals lightly touch a haptic cue that is insufficient to provide postural stability, the amplitude of postural sway is reduced (Jeka et al., 1994; Jeka et al., 1998). Furthermore, when standing in the absence of visual input, providing individual with haptic cues can reduce the amplitude and velocity of postural sway and stabilize the individual to the same degree as if visual input were available. This same stabilizing effect is observed when individuals with vestibular loss and peripheral

neuropathy of the lower limbs are provided with haptic cues (Lackner et al., 1999; Dickstein et al., 2001). Taken together these observations demonstrate that increasing the relative contributions of proprioceptive inputs can facilitate postural stability. Additionally, these findings reinforce previous work demonstrating the redundant nature of the sensory contributions to the control of standing balance (Horak and Hlavaka, 2001).

1.5 Emotional Influences on the Control of Standing Balance

In addition to sensory contributions, there is a great deal of evidence suggesting that cognitive factors (Maki and McIlroy, 1996), physiological changes (Hunter and Kearney, 1981; Jeong, 1991) and emotional influences (Yardley et al., 2004) can modulate the control of standing balance. For example, the emotional influence of fear and anxiety on the control of standing balance has been studied in many different experimental paradigms and experimental models.

In the most extreme case, it has been demonstrated that individuals suffering from clinical panic disorder and moderate to severe agoraphobia report more significant feelings of dizziness and unsteadiness than otherwise healthy controls (Jacob et al., 1997). It has been reported that not only do sufferers of clinical panic disorder and agoraphobia feel less stable, these patients also demonstrate postural deficits as reflected by increased velocity and amplitude of body sway in comparison to otherwise healthy controls (Perna et al., 2001). However, co-morbidities such as vestibular dysfunction that are commonly observed among panic disorder sufferers may ultimately underlie the balance abnormalities (Jacob et al., 1997; Perna et al., 2001).

A similar relationship has also been demonstrated in clinical studies among populations suffering from more specific anxiety disorders rather than clinical panic disorder. For instance, sufferers of postural phobic vertigo, an anxiety disorder characterized by feelings of dizziness and instability despite normal balance testing scores, demonstrated larger amplitude ankle torque, greater ankle torque variance and larger total sway area than otherwise healthy controls during quiet stance (Holmberg et al., 2003). This increase in ankle torque variance likely explains previous findings in a separate study among postural phobic vertigo sufferers who demonstrated increased frequencies of sway in the 3-8.5Hz bandwidth compared to otherwise healthy controls during quiet stance (Krafczyk et al., 1999).

Studies involving participants suffering from sub-clinical levels of anxiety have also established a relationship between balance performance and non-pathological levels of anxiety. For instance, in a study involving university aged women who were parsed into two groups (high anxiety and low anxiety) based on their self-reported state anxiety, those in the high anxiety

group were found to have higher frequencies of body sway in the 0.02-0.21Hz bandwidth and lower frequencies of body sway in the 2.02-10.0Hz bandwidth compared to those in the low anxiety group (Wada et al., 2001). This study highlights the potential differences that can exist between groups depending on reported levels of state anxiety. A similar finding has been reported in a within-groups study investigating the relationship between anxiety and balance among males (Bolmont et al., 2002). When standing balance efficacy was measured and related to mood and anxiety levels assessed over a 12-day period, a significant negative correlation was observed between mood and balance performance. During periods of low mood and anxiety, participants were found to demonstrate poorer balance performance (Bolmont et al., 2002). The findings of these two studies highlight three important factors that must be considered: 1) the effects of anxiety on balance control are not gender specific, 2) the level of anxiety that can hinder balance performance can be sub-clinical and 3) the influence of anxiety on balance control can be transient and not necessarily related to a prolonged bout of anxiety. These considerations are important when interpreting the data from studies investigating the influence of anxiety on the postural stability of older adults.

It has been documented that 25% of all older adults over the age of 69 will experience a fall each year (Tinetti and Speechley, 1989). A multitude of research has identified that the exact etiology of falls among the elderly can be due to any single or combination of age related deficits including reduced proprioceptive sensitivity, reduced muscle strength as well as impaired visual, neurological, cognitive or musculoskeletal function (Tinetti and Speechley, 1989; Lord et al., 1991; Gerson et al., 1989). In addition to the age related decline in balance efficacy, more recent studies have highlighted the contribution that the anxiety associated with a specific fear of falling has on balance performance in older adults (Maki et al., 1991; Yardley, 2004; Brown et al., 2006). It has been proposed that fear of falling may impair balance control in three possible ways. First, balance is thought to be impaired due to direct impairment of motor function causing increased stiffness and rigidity. Secondly, balance may be impaired through the indirect sympathetic nervous system activation that occurs secondary to the arousal associated with fear and anxiety. Thirdly, balance may also be impaired due to the cognitive change associated with anxiety interfering with normal balance control (Yardley, 2004; Huffman et al., 2009).

In a study comparing the magnitude of spontaneous sway between older adults with and without a fear of falling, it was demonstrated that those with a fear of falling had significantly larger ranges of spontaneous sway than those without a fear of falling (Maki et al., 1991). In contrast, when fear of falling is experimentally manipulated by increasing the surface height and postural threat-associated with standing, older adults adopt a stiffer posture characterized by smaller ranges of spontaneous sway and higher frequency postural adjustments (Brown et al.,

2006). The discrepancy between these two studies may be associated with underlying neurological difference between older adults with a chronic fear of falling (Maki et al., 1991) and older adults subjected to an acute fearful stimulus (Brown et al., 2006). Irrespective of the cause of this discrepancy between the findings of these two studies, a great deal of understanding has yet to be achieved with respect to the influence of fear and anxiety on the postural control of both younger and older adults.

1.6 Elevated Postural Threat via Elevated Surface Height

In addition to studying how emotion influences balance control among those experiencing pathological and non-pathological anxiety, a great deal of research has been conducted using experimental exposure to fear evoking stimuli in otherwise healthy young adults. In these situations, it is possible to test how fear and anxiety alone impair balance control in the absence of potentially confounding co-morbidities such as vestibular impairment (Jacob, 1997; Perna et al., 2001) and age-related musculoskeletal and neurological decline (Yardley, 2004). One way to temporarily evoke a sensation of fear and anxiety in a population of healthy young adults is to have them stand at elevated surface heights. It is reasoned that the increased consequences of falling in terms of injury potential creates a temporary experience of fear and anxiety in these situations. When young adults stand at the edge of an elevated platform raised 1.6m into the air, they adopt stiffer control of their posture characterized by an increase in the mean power frequency (frequency) of postural sway and a decrease in the root mean square (amplitude) of postural sway when they stand with their eyes open, but not with their eyes closed (Carpenter et al., 1999). This observation has since been corroborated in both otherwise healthy younger and older adults (Brown et al., 2006; Carpenter et al., 2006). In addition to the effects of height on the control of quiet stance, standing at the edge of a 1.6m high platform has also been demonstrated to impair anticipatory postural control by slowing and reducing the amplitude of anticipatory movements prior to engaging in planned movements (Adkin et al., 2002). The fear and anxiety inducing effects of elevated surface heights have also been demonstrated to alter dynamic balance control. For example, when participants are forced to respond to an unexpected balance perturbation when standing at the edge of the 1.6m high platform, the compensatory postural response to the perturbation was observed to be larger in magnitude compared to when standing on the ground (Carpenter et al., 2004). In summary, elevated surface heights have been demonstrated to alter the control of standing balance (Carpenter et al., 1999; Brown et al., 2006), anticipatory postural control (Adkin et al., 2002) and dynamic postural control (Carpenter et al., 2004). These studies suggest that the fear and anxiety inducing effects of elevated surface heights influence a

central mechanism involved in balance control due to the consistent pattern of postural changes associated with height-induced fear and anxiety.

A second important finding regarding the effectiveness of elevated surface height as an experimental tool to manipulate fear is that the magnitude of postural response observed among healthy adults is scaled to the magnitude of threat to which they are exposed to (Adkin et al., 2000). In this situation, the higher one is raised in the air, the stiffer their posture becomes (Adkin et al., 2000). One question that arises from this work is the possibility that the change in the visual field of view associated with standing at high heights may be the causal factor in mediating the balance changes observed, as opposed to an increase in state anxiety (Brandt et al., 1979; Bles et al., 1980). This is not a likely case considering that elevated surface heights have been validated as an effective tool for inducing a state of anxiety and compromising one's sense of self-efficacy (Hauck et al., 2008). Additionally, the work reported in this thesis (See Chapter #2) has demonstrated that the postural changes observed when standing under conditions of height-induced fear and anxiety occur independent of whether or not visual information is available.

One noteworthy limitation of the current literature relying on elevated surface heights to impose threat is the fact that the observed postural changes (stiffer posture) fail to model the postural changes observed among older adults with a self-reported fear of falling (Maki et al., 1991). This discrepancy limits the effectiveness of elevated surface heights as a tool to model the fear of falling experienced by older adults in otherwise healthy young adults. One possible explanation that has been proposed to reconcile the postural differences observed between these two groups is that the level of postural threat imposed by surface heights of 1.6m is not sufficient to elicit a sensation of fear among healthy young adults that is comparable to that experienced by older adults with a fear of falling (Brown et al., 2006). This explanation is somewhat supported by studies that have investigated the effect of more extreme surface heights on postural control. When participants were raised to a height of 10.2m, they demonstrated larger amplitude spontaneous sway comparable to that observed among older adults with a fear of falling (Nakahara et al., 2000). However, this study was limited by the fact that it was conducted outdoors on a rooftop where the influences of external forces such as wind may have influenced their measures of sway. In a separate study, in which participants were raised to a height of 9m, a similar observation was documented whereby participants demonstrated larger amplitude sway when standing at 9m compared to standing on the ground (Simeonov and Hsiao, 2001). However, this study is limited by fact that the eye to target distance was not controlled for between heights, thereby introducing a potential confound to the visual control of balance between heights. Also, the study was conducted among experienced high steel construction workers, not a randomly selected participant population. In summary

there is some evidence to suggest that the explanation put forth by Brown et al. (2006) is correct in that surface heights of 1.6m may not be sufficient to evoke a sensation of fear among healthy young adults that is comparable to that experienced by older adults with a fear of falling. However, the work that does support this claim is substantially confounded by poor experimental design (Nakahara et al., 2000) and sampling bias (Simeonov and Hsiao, 2001). For this reason it is essential that more prudent studies be conducted at surface heights higher than 1.6m in order to validate elevated surface heights as an effective tool for modelling the fear and anxiety experienced by older adults in an otherwise healthy population of young adults.

1.7 Evidence to Suggest That Fear Leads to a Functional Proprioceptive Adaptation

Although the effects of height-induced fear and anxiety on postural performance are well documented, the underlying sensori-motor processes responsible for mediating those changes remain unknown. There is some evidence to suggest that height-induced fear and anxiety change how proprioceptive mechanisms influence the spinal reflexes involved in postural control. One such spinal reflex that has been investigated is the electrically evoked soleous Hoffmann Reflex (SOL H-reflex). Experimentally, it has been demonstrated that the peak-peak amplitude of the SOL H-reflex decreases when participants stand under conditions of elevated postural threat (Sibley et al., 2007). One possible mechanism proposed to attenuate SOL H-reflex excitability in high threat situations is descending pre-synaptic inhibition (PSI) of the Ia afferents originating from SOL muscle spindles that form mono-synaptic connections with the lower motor neurons innervating SOL (Sibley et al., 2007, Capaday and Stein, 1986). This neurophysiological mechanism is thought to be a means for the system to gain supra-spinal control over posture while standing under conditions of elevated postural threat (Sibley et al., 2007). An alternative mechanism that may attenuate SOL H-reflex amplitude during high postural threat situations is homosynaptic post-activation depression (HPAD) (Lewellyn et al., 1990; Pinniger et al., 2001; Tokuno et al., 2008). In this situation it is reasoned that elevated postural threat results in increased muscle spindle sensitivity and tonic Ia afferent firing on the lower motor neuron pool innervating SOL thereby depleting the excitatory neurotransmitter stores and subsequent magnitude of the excitatory post-synaptic potential (EPSP) generated in response to phasic Ia afferent stimulation (Hultborn et al., 1996; Nordlund et al., 2004; Tokuno et al., 2008).

Decreased SOL H-Reflex excitability has also been observed in situations where postural control is either threatened (McIlroy et al., 2003) or challenged (Lewellyn et al., 1990) by means other than changes in support surface elevation. For instance, McIlroy et al. (2003) observed a decrease in SOL H-reflex excitability when participants were threatened with a

perturbation to the stability of an inverted pendulum they were instructed to balance with their feet while seated. Likewise, Lewellyn et al. (1990), observed a decrease in SOL H-reflex excitability when participants stood on an elevated narrow beam. However, in both these studies, it is unclear whether the novelty associated with the balance task, or the potential anxiety/threat imposed during the task caused the observed SOL H-reflex attenuation. Independent of the exact cause, Lewellyn et al. (1990) proposed that SOL H-reflex attenuation occurs during beam walking as a result of the novelty/threat-associated with the task causing increased spindle sensitivity and HPAD. In addition to the evidence suggesting that HPAD occurs during both these situations, there is evidence to suggest that there is a simultaneous increase in the cortical sensitivity to incoming afferent information. More specifically, a concomitant decrease in SOL H-reflex excitability and increase in the amplitude of the somatosensory evoked potential (SEP), reflecting the cortical reception of the afferent volley evoked by the SOL H-reflex stimulation, is observed when participants were threatened with a perturbation to the stability of an inverted pendulum (McIlroy et al., 2003).

The observation of a decrease in the spinal (SOL H-reflex) contribution to the control of balance and the increase in the cortical (SEP) control or monitoring of balance in these two studies (Lewellyn et al., 1990; McIlroy et al., 2003) has led to the development of a debatable working hypothesis with respect to the control of standing balance. Specifically, it has been proposed by Lewellyn et al. (1990) and McIlroy et al. (2003) that during periods of balance challenge, there is a shift from primarily spinal control over standing balance to an increased involvement of cortical inputs that do not normally play a dominant role in the control of standing balance.

1.8 The Spinal Processing of Proprioceptive Information

In order to fully understand how changes in proprioceptive sense may be involved in mediating the postural changes that are observed during states of height-induced fear and anxiety, it is critical to understand the anatomy and physiology of the proprioceptive system. During static stance, proprioceptive information from a variety of afferent sources is involved in sensing the biomechanical changes that occur during postural sway. For instance, the muscles of the lower limbs and trunk are constantly changing in length during sway (Loram et al., 2005) and the proprioceptive system relies on muscle spindle sensory receptors that are embedded in parallel with the extrafusal fibres of the muscle. These muscle spindles detect dynamic changes in muscle length (Kandel et al., 2004). Additionally, information pertaining to the force of active muscle contractions made during sway is detected by GTO receptors found at the muscle-tendon junction. And finally, cutaneous sensory receptors embedded in the glaborous

skin of the foot sole serve as mechanoreceptors relaying information about the body's pressure distribution beneath the feet (Mauritz and Dietz, 1980).

Information pertaining to the velocity of muscle stretch is largely relayed via large diameter Ia afferents and information pertaining to the absolute length of the muscle stretch is carried via a combination of Ia and smaller diameter type II afferents from the muscle spindle to spinal cord (Kandel et al., 2004; Pierrot-Deseilligny and Burke, 2005). The afferent signals created by the stimulation of these receptors enter the spinal cord via the dorsal horn and form monosynaptic connections onto the alpha motor neurons of the motor units of the same muscle from which the afferent originated. This monosynaptic circuit facilitates stretch reflex activity during spontaneous postural sway. Essentially, the stretch of a given agonist muscle (e.g. SOL) causes a proportional contractile force to be generated by its motor units in order to bring the agonist back to its original length (Kandel et al., 2004). Simultaneously, the Ia afferent bifurcates as it enters the dorsal horn and monosynaptically synapses onto Ia inhibitory interneurons. Excitation of Ia inhibitory interneurons in response to agonist stretch results in a GABA mediated inhibition of the antagonist muscle (e.g. tibialis anterior). This process is known as reciprocal inhibition and functions to prevent the force of the antagonist muscle contraction from interfering with the agonist contracting back to its original length (Rothwell 1995) following a phasic stretch.

Two other spinal reflexes compliment the monosynaptic stretch reflex and reciprocal inhibition. In response to a voluntary motor command to move, the alpha motor neuron of a given agonist muscle fires to contract the agonist but also bifurcates within the spinal cord to excite inhibitory Renshaw cells. Once excited, the Renshaw cell fires to achieve two functions: 1) inhibit a secondary firing of the agonist and 2) dis-inhibit the effects of reciprocal inhibition on the antagonist through a process called recurrent inhibition (Rothwell, 1995). Additionally, contraction of the agonist following the monosynaptic stretch reflex causes the tendinous fibres of the muscle to stimulate the GTO of the agonist. This contractile signal ascends to the lower motor neuron pool innervating the agonist via large diameter Ib afferents that synapse onto Ib inhibitory interneurons. Once stimulated, Ib inhibitory interneurons inhibit secondary agonist firing in a process called autogenic inhibition (Rothwell, 1995).

1.9 Cortical Processing of Proprioceptive Information

In addition to facilitating the spinal reflexes, proprioceptive information related to balance control ascends to sub-cortical and cortical centres of the brain via the posterior column-medial lemniscal (PCML) pathway. Once at the level of the medulla, primary sensory afferents within the PCML carrying proprioceptive information from the legs synapse onto second order

neurons within the Graciles nucleus and afferents within the PCML originating from the trunk and arms synapse onto neurons within the Cuneate nucleus. At this junction, the axons from second order sensory neurons decussate and carry this information to the contralateral Ventro-posterior lateral (VPL) nucleus of the thalamus (Kandel et al., 2004; Rothwell et al., 1995; Blumenfeld, 2002).

The thalamus is a relay nucleus/gateway that sends third order neurons carrying this proprioceptive information to the necessary neurological centres including the somatosensory cortex. Once at the somatosensory cortex, individual nuances about lower limb and trunk proprioception including forces and lengths of the muscle stretch and skin afferent input from the sole of the foot are integrated by this unimodal cortical centre. From the somatosensory cortex proprioceptive information is sent to the posterior parietal cortex (association cortex) where it is integrated with sensory information from all other sensory modalities (Kandel et al., 2004; Blumenfeld 2002). This sensory integration is necessary so that the posterior parietal cortex can keep prefrontal and motor-planning areas of the brain constantly updated with the current state of proprioceptive affairs so that voluntary movement can be planned and prepared accordingly while postural equilibrium is maintained.

1.10 Scope and Aims of Thesis Research

The following chapters of this thesis will detail the experimental methods and findings of four studies designed to investigate the effects of height-induced fear and anxiety on static postural control and underlying proprioceptive mechanisms. The first study is designed to determine whether the changes in postural control that occur with increased surface height depend on the degree of fear of falling experienced by participants as well as the availability of visual information. The second study focuses on the investigation of how spinal reflexes and the cortical perception of proprioceptive information adapt during states of height-induced fear and anxiety. The third study investigates the possible neurophysiological mechanisms that have been suggested to facilitate proprioceptive adaptation during states of height-induced fear and anxiety. And finally, the fourth study in this thesis is designed to test the effectiveness of manipulating the control of postural sway using visual feedback to overcome the biomechanical confounds that limit the interpretation of static posturography measures and spinal reflex measures during states of height-induced fear and anxiety. Together, the results from these four studies will achieve the primary aims of this thesis:

1) To understand how fear and anxiety impair static postural control.

2) To determine whether proprioceptive adaptation and altered reflex sensitivity contribute to the posturographic changes that occur during states of height-induced fear and anxiety.

CHAPTER 2: A DIFFERENTIAL EFFECT OF FEAR AND ANXIETY ON POSTURAL CONTROL

2.1 Introduction

Studies have highlighted the importance of understanding the interaction between emotion and balance control (Maki et al., 1991; Jacob et al., 1997; Krafszyk et al., 1999; Carpenter et al., 1999; 2001; 2004; 2006; Adkin et al., 2000; 2002; Nakahara et al., 2000; Balaban, 2002; Yardley, 2004; Brown et al., 2006; Simeonov and Hsiao., 2006). For example, older adults with a self-reported fear of falling have been observed to make larger amplitude centre of pressure (COP) displacements during spontaneous sway compared to those without a fear of falling (Maki et al., 1991). However, the results of the study by Maki et al. (1991) could not be used to discern whether, participants were fearful because of an underlying balance deficit, or whether changes in balance were a result of an individual's fear of falling. To address this limitation, elevated surface heights have been used to manipulate the level of fear experienced by healthy adults in order to investigate its effect on balance control (Carpenter et al., 1999; 2001; Adkin et al., 2000; Brown et al., 2006). Individuals standing at surface heights of up to 1.6m have been observed to engage in a postural strategy characterized by smaller amplitude and higher frequency COP displacements compared to when standing on the ground (Carpenter et al., 1999; 2001; Adkin et al., 2000; Brown et al., 2006).

There are at least two possible explanations for why the postural differences observed when standing at elevated surface heights (Carpenter et al., 1999; 2001; Adkin et al., 2000; Brown et al., 2006) do not corroborate results observed among fearful individuals standing on the ground (Maki et al., 1991). It has been argued that while surface heights of 1.6m are effective for inducing anxiety, they may not be high enough to elicit a robust fear response (Brown et al., 2006). Fear and anxiety are known to have different neuroanatomical substrates and physiological outcomes (Davis, 1998; Rosen and Schulkin, 1998; Chua et al., 1999; Masaoka et al., 2003; Cravo et al., 2003) and may lead to differences in behaviour or action tendencies (Rosen and Schulkin, 1998) related to postural control (Jeong, 1991; Balaban and Thayer, 2001; Lepicard et al., 2003).

A second explanation for why elevated surface heights are associated with different postural behaviours than those observed between individuals with or without a fear of falling may be that the postural changes observed are related to differences within the visual field of

view that occur at high heights. For example, when standing at elevated surface heights, the eye to horizon distance may increase. Consequently, the inability to focus on close focal visual cues may contribute to postural height vertigo and increased postural sway (Brandt et al., 1979; Bles et al., 1980). To address this possibility, previous studies have controlled for the visual perturbation by providing a visual target at a constant eye to target distance between heights (Carpenter et al., 1999; 2001). However, despite this control, a vision by height interaction has been reported whereby characteristics of decreased postural sway were observed between heights when standing with eyes open, but not with eyes closed (Carpenter et al., 1999). Additionally, the eye to ground distance increases when standing at high heights thereby causing a change in the proximity of peripheral visual cues. It has been demonstrated that peripheral visual cues are used to reference self-motion and are important for maintaining postural equilibrium (Amblard et al., 1980; Berensci et al., 2005). Therefore, it is possible that changes in peripheral visual input that occur at high heights may contribute to the postural changes previously observed (Carpenter et al., 1999; 2001; 2006; Adkin et al., 2000; 2002; Nakahara et al., 2000; Brown et al., 2006; Simeonov and Hsiao, 2006) however this possibility has not yet been investigated.

The purpose of this study was to determine whether the changes in postural control that occur with increased surface height depend on the degree of fear of falling experienced by participants as well as the availability of visual information. It was hypothesized that the observed changes in COP would be: 1) dependent on surface height but independent of participant's reported fear of falling and 2) dependent on the availability of focal vision but not influenced by the availability of peripheral visual cues.

2.2 Methods

2.2.1 Participants

Thirty-six healthy young adults (21 females, mean ± SE; age 26.0 ± 3.5 years; height 169.0 ± 3.2cm; and weight 69.4 ± 3.2kg) volunteered to participate. Each participant completed a medical history survey and provided written informed consent prior to testing. Participants were excluded if they had existing medical conditions or took medications that could affect their balance. All experimental procedures were approved by the UBC Clinical Research Ethics Board.

2.2.2 Experimental Procedure

Participants stood as still as possible for 60s on a forceplate (#K00407, Bertec, USA) placed at the edge of a hydraulic platform at four different heights (ground level, 0.8m, 1.6m and 3.2m). At each height, participants stood with their eyes open, eyes closed and while wearing blinders designed to occlude both horizontal and vertical peripheral vision in order to maintain a consistent visual field size between heights. The blinders consisted of an open ended cardboard box (17cm wide x 7cm high x 17cm long) attached to a pair of generic lab safety goggles. Practice trials lasting 60s were performed at ground level under each of the three visual conditions to familiarize participants with the protocol and minimize any potential first trial effects (Adkin et al., 2000). Participant's feet were placed at the edge of the forceplate and stance width was equal to their foot length. The area of their foot position was kept constant for all standing trials. During each standing trial, participants focused on a visual target placed at eye level on the wall 3.87m away in order to prevent the potential effects of postural height vertigo (Brandt et al., 1979; Bles et al., 1980). A hydraulic lift with a 2.13m x 1.52m surface area (M419-207B10H01D, Penta-lift, Canada) was raised in ascending order to optimize the fear inducing effects of height (Adkin et al., 2000). The measured vertical distance from the floor to the forceplate surface was 8cm when at ground level and 0.8, 1.6 and 3.2m for each subsequent surface height. Participants were raised to each height while seated with their eyes open. For each trial, participants stepped to the edge of the platform and adopted the appropriate visual condition once stable. Throughout the study, participants were securely harnessed to the ceiling in case of a fall.

2.2.3 Measurements

To estimate physiological arousal, changes in Electrodermal Activity (EDA) were recorded from 28 participants using disposable surface Ag/AgCl electrodes placed on the thenar and hypothenar eminences (model 2502, CED, UK) and sampled at 1000Hz (Power 1401, CED, UK). There were 8 participants (1 fearful, 7 non-fearful) in the study for whom no EDA data was collected because the necessary equipment was not available at the beginning of the study. Mean EDA was calculated offline during the first 30s of each standing trial and referenced to baseline measures collected during the corresponding practice trial.

It has been reported that psychological measures of self-efficacy and anxiety as they relate to balance are separate constructs and that independent evaluation tools are necessary for measuring confidence, anxiety and fear (Hauck et al., 2008). Therefore, prior to each standing trial, participants rated their confidence in maintaining their balance to avoid a fall on an incremental scale between 0% (not at all) to 100% (completely) at each height. Following

each trial, participants rated their fear of falling (0-100%) and perceived state anxiety (1-9 on a 16 item survey) on incremental scales (Adkin et al., 2000).

Ground reaction forces and moments were sampled at 100Hz and low-pass filtered offline using a 5Hz dual-pass Butterworth filter before calculating COP in the anterior-posterior (A-P) direction. Three summary measures were recorded to characterize different aspects of postural sway. Mean position of the COP during each trial was calculated in the A-P direction to quantify the magnitude of lean toward or away from the edge of the platform. The mean position of A-P COP was subtracted from the raw A-P COP signal to create an unbiased signal from which the Root Mean Square (RMS) and Mean Power Frequency (MPF) of COP displacements were calculated in the A-P direction in order to quantify the amplitude and frequency of postural displacements, respectively.

2.2.4 Statistical Analysis

The potential interaction between group (fearful, non-fearful), height (ground, 0.8m, 1.6m and 3.2m) and vision (eyes open, eyes closed, peripheral vision occluded) was examined using a 2x4x3 mixed design ANOVA (SPSS, IBM, USA) for all dependent measures. The criteria for statistical significance was set to $p<0.05$. Bonferroni corrected pair-wise comparisons were used to compare the effects of vision and contrast analyses were used to determine the effects of height on all dependent measures. All correlation analyses were completed using a Pearson's corrected correlation analysis.

2.3 Results

2.3.1 Fear of Falling Response

The relative change in participants' reported fear of falling scores between the ground and 3.2m were not normally distributed. Therefore, participants were classified into two separate groups; participants who reported a change in fear of falling between ground and 3.2m of 50% or more were designated as 'fearful' (n=10), and those with a change in fear less than 50% were designated as 'non-fearful' (n=26). A change of 50% was chosen to parse the participant pool as it distinctly divided the bi-modally distributed fear of falling scores reported by participants in this study.

2.3.2 Physiological and Psychosocial Measures of Anxiety

A significant interaction between height and group was observed on EDA for the (n=9 fearful and n=19 non-fearful) for who EDA data was available ($F_{(3,78)}=3.42$, $p=0.021$). Although

contrasts revealed significant linear trends of increased EDA across heights in both groups ($p<0.001$), the fearful group had a greater change between ground and 3.2m (76.5%) compared to the non-fearful group (21.7%). There was a significant main effect of vision on EDA ($F_{(2,52)}=8.13$, $p=0.001$) whereby significantly higher mean EDA was observed in the peripheral vision occluded compared to either the eyes open or eyes closed conditions ($p<0.01$).

There was a significant interaction between height and group observed for balance confidence ($F_{(3,102)}=11.85$, $p<0.001$). Contrasts revealed significant linear trends of decreased confidence across heights for both groups ($p<0.001$), with a greater change between ground and 3.2m observed in the fearful (47.4%) compared to the non-fearful group (17.6%). State anxiety was influenced by a significant main effect of height ($F_{(3,102)}=133.22$, $p<0.001$). Contrasts revealed a significant linear trend of increased state anxiety across heights independent of group ($p<0.001$), with an average increase between ground and 3.2m of 41.7%.

The change in EDA activity between the ground and 3.2m was significantly correlated to the change in state anxiety between heights ($r^2=0.404$, $p<0.05$). The change in EDA was not significantly correlated to the change in fear experienced between the ground and 3.2m ($r^2=0.35$, $p>0.05$) or the change in confidence ($r^2= -0.17$, $p>0.05$).

2.3.3 COP Measures

A significant interaction between height and group was observed on the mean position of A-P COP ($F_{(3,102)}=5.46$, $p=0.002$). Contrasts revealed a significant linear trend of increased posterior shifts in the mean A-P COP (away from the edge) across heights in both groups ($p<0.001$), with greater shifts observed in the fearful (48.6%) compared to non-fearful group (26.8%) between ground and 3.2m (Figure 2.1A). A significant main effect of visual condition on the mean position of A-P COP was observed ($F_{(2,68)}=13.76$, $p<0.001$), with the largest posterior mean COP displacements observed in eyes open compared to eyes closed or peripheral vision occluded conditions ($p<0.005$).

There was a significant interaction between height and group on the MPF of A-P COP displacement ($F_{(3,102)}=5.01$, $p=0.003$). As depicted in Figure 2.1B, contrasts revealed significant linear trends of increased MPF of A-P COP displacement across heights in both groups ($p<0.001$); yet fearful participants had a greater increase in the MPF of A-P COP displacement from ground level to 3.2m (186%) compared to the non-fearful group (144.5%). The change in reported fear of falling was significantly correlated with the change in the MPF of A-P COP displacement ($r^2=0.48$, $p=0.003$) between ground level and 3.2m. A significant main effect of vision on the MPF of A-P COP displacement was observed ($F_{(2,68)}=27.24$, $p<0.001$), with higher

a higher MPF observed with eyes closed compared to eyes open or the peripheral vision occluded conditions ($p<0.05$).

There was a significant interaction between group and height on the RMS of A-P COP displacement ($F_{(3,102)}=3.10$, $p=0.030$). As depicted in Figure 2.1C, a significant linear trend of increased RMS of A-P COP displacement was observed across heights in the fearful group ($p<0.05$), with average increases of 16.0% between ground and 3.2m (Figure 2.1). Conversely, a significant linear trend of decreased RMS of A-P COP displacement across heights was observed in the non-fearful group ($p<0.05$) with average decreases of 8.5% between the ground and 3.2m (Figure 2.2). The change in reported fear of falling score was significantly correlated with the change in RMS of A-P COP displacement between the ground and 3.2m ($r^2=0.37$, $p=0.028$).

2.4 Discussion

When standing at 3.2m, ten out of thirty-six participants reported being fearful while the remaining twenty-six participants experienced little to no fearfulness. Non-fearful participants leaned further back from the edge and demonstrated increased MPF and decreased RMS of COP displacements at 3.2m compared to ground level. Although fearful participants also leaned further away from the edge and demonstrated increased MPF of A-P COP when standing at 3.2m, they demonstrated increased RMS of A-P COP displacements compared to decreased RMS of A-P COP displacement observed among non-fearful participants. Interestingly, participants in both groups reported increased state anxiety and decreased balance confidence.

These findings do not support the hypothesis that the effects of surface height on postural control are independent of emotional state. Instead, it is evident that two different postural control strategies are observed depending on whether a person is fearful or not. The COP changes observed in non-fearful participants with increased surface height are consistent with previous observations at surface heights up to 1.6m (Carpenter et al., 1999; 2001; Adkin et al., 2000; Brown et al., 2006). Similar postural changes have also been reported in participants viewing affective pictures that elicited strong negative emotional responses (Azevedo et al., 2005; Facchinetti et al., 2006). However, the postural changes observed among fearful participants are inconsistent with previously observed changes (Carpenter et al., 1999; 2001; Adkin et al., 2000; Brown et al., 2006) and suggests that there is a relationship between fear of falling and human postural control.

The current results provide the first empirical evidence to reconcile divergent findings with respect to the postural changes observed between individuals standing on elevated

surfaces (Carpenter et al., 1999; 2001; Adkin et al., 2000; Brown et al., 2006) and individuals with a self-reported fear of falling when standing on the ground (Maki et al., 1991). Previously, the increased amplitude of COP displacements observed among fearful compared to non-fearful older adults (Maki et al., 1991) was not consistent with the decreased amplitude of COP displacements observed in young adults when standing on elevated surfaces up to 1.6m (Carpenter et al., 1999; 2001; Adkin et al., 2000; Brown et al., 2006). In the current study, only those participants who reported a robust fear response at 3.2m engaged in a postural strategy similar to that observed among fearful older adults (Maki et al., 1991). This finding supports the argument that surface heights of 1.6m were not high enough to elicit a fear response similar to that experienced by individuals with a fear of falling (Brown et al., 2006).

These findings substantiate previous results observed in studies using surface heights higher than 3.2m to study height-related postural changes (Nakahara et al., 2000; Simeonov and Hsiao, 2006). Simeonov and Hsiao (2006) reported larger amplitude COP displacements among construction workers with experience working at high heights when standing at 9m compared to when standing on the ground. However, this study was limited in that no physiological and/or psychological measurements of fear and anxiety were recorded making it difficult to discern the emotional state of participants during the study. Additionally, the eye-to-target distance varied between heights in this study, allowing for the influence of height vertigo to affect posture (Brandt et al., 1979; Bles et al., 1980). Likewise, Nakahara et al. (2000) reported increased amplitude COP displacements when standing at 10.2m compared to when standing on the ground. However, in their study, participants stood outdoors on a roof-top lacking any visual target in the near visual field and in the presence of environmental factors, such as wind. Therefore, both the inconsistent eye to target distance and uncontrolled environmental factors could have affected postural control in this study. The fact that the current study controlled for these limitations and corroborated previously reported postural changes (Maki et al., 1991; Nakahara et al., 2000; Simeonov and Hsiao, 2006) provides strong evidence to suggest that humans adopt characteristic postural strategies when experiencing changes in their level of fear.

There was no significant interaction observed between vision and height in either group on any of the three posturographic measures. This finding lies in contrast to previous reports (Carpenter et al., 1999; 2001) demonstrating that the effects of height on posture depend on the availability of vision. One possible explanation for this observation may be that a height of 3.2m or greater is high enough to elicit a sufficient emotional response whereby participant may not need to be visually reminded that they are in a situation of elevated postural threat. In contrast, when standing at a moderate height of 1.6m, a constant visual update of postural threat may be required. Additionally, there were no observed postural differences between the eyes open

and peripheral vision occluded conditions when standing at 3.2m suggesting that the postural changes that occur when standing under conditions of elevated postural threat do not depend on the availability of peripheral vision. This finding, when coupled with the observed positive correlation between fear and both the RMS and MPF of A-P COP displacement, further suggests that the influence of altered emotional state plays a greater role in mediating postural changes than do changes to the visual environment when standing at elevated surface heights.

One limitation of this study is that there were no visible cues, such as hand railings, in the horizontal periphery in the eyes open condition. Therefore, it may be possible that in different settings, where peripheral visual cues are present, the availability of such cues may interact with emotional state to influence postural stability.

It is evident that two different emotional constructs, fear and anxiety, are associated with two different postural behaviours in humans. Furthermore, fear and anxiety can influence postural control independently of manipulations to visual input when standing at heights high enough to impose substantial postural threat. These findings have the potential to impact a variety of fields of study. An improved understanding of how emotion and balance control interact is essential for the design of preventative and rehabilitative therapies for fall prevention and anxiety related balance disorders.

Figure 2.1: COP Summary Measures

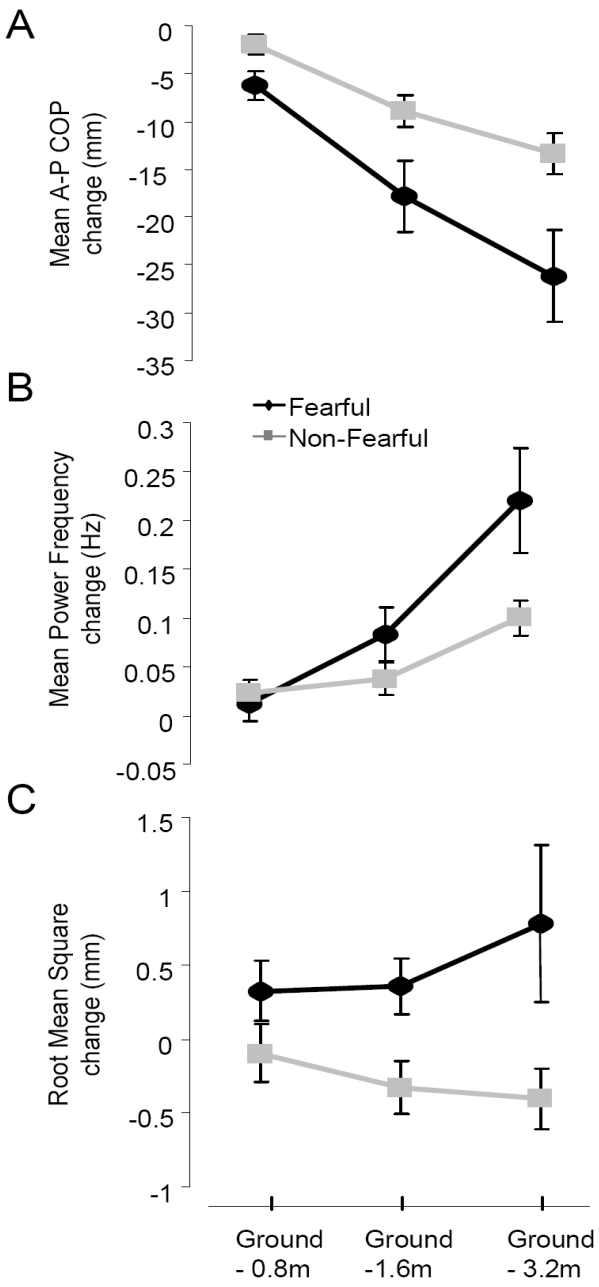

Figure 2.1
A comparison of the average within subject's change in (A) mean position, (B) MPF and (C) RMS of COP in the A-P direction between the ground and different surface heights pooled across visual condition. Black lines with filled circles depict fearful participants. Light Grey lines with filled squares depict non-fearful participants. A change in mean position indicated by a negative value reflects a postural displacement in the posterior direction.

Figure 2.2: Representative COP Data

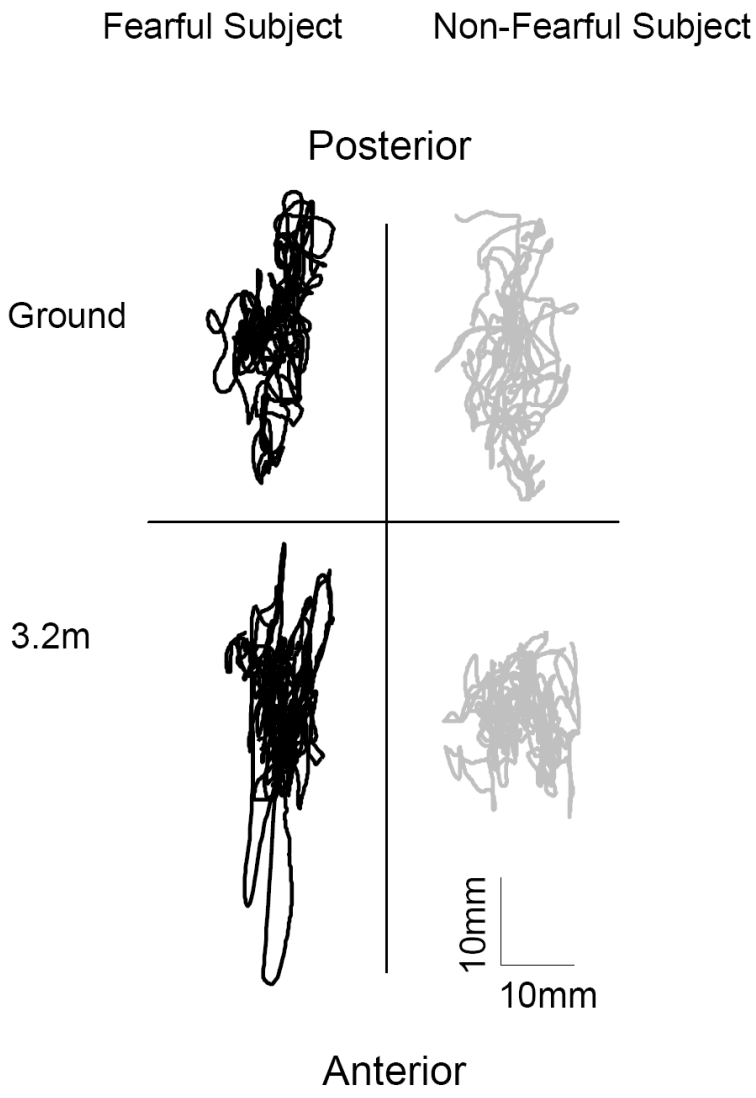

Figure 2.2
Representative x-y plots of COP signals from single representative participants from the fearful and non-fearful groups. These plots summarize changes in postural control that occur with increasing surface heights. Anterior represents the edge of the elevated platform. The fearful participant is depicted in black and the non-fearful participant in light grey.

2.5 Chapter 2 Bridging Summary

The results of Chapter 2 achieved the primary goal of this thesis which was to better understand how fear and anxiety impair static postural control. From these results it is clear that two different emotional constructs, fear and anxiety, are associated with two different postural behaviours in humans. Furthermore, it is clear that fear and anxiety can influence postural control independently of manipulations to visual input.

The following chapter will begin to investigate the possibility that the postural behaviours that are observed when standing under conditions of height-induced fear and anxiety are associated with changes in how proprioceptive information from the lower limb is utilized by the central nervous system (CNS). In Chapter 3, two separate experiments were performed on two separate groups of participants while they stood under conditions of low and high postural threat. In Experiment #1 the proprioceptive system was probed by indirectly activating muscle spindle sensory receptors and comparing changes in soleus tendon reflex (STR) amplitude and latency during states of height-induced fear and anxiety. Simultaneously, the cortical potential evoked in response to phasic mechanical stimulation of muscle spindles (TEP) was compared between threat conditions in order to determine whether a change in STR excitability is associated with a concomitant change in the magnitude of the afferent volley delivered to the somatosensory cortex. In Experiment #2, the amplitude and latency of the cortical potential evoked in response to phasic electrical stimulation (SEP) of the primary Ia afferents along which proprioceptive information from the soleus travels to the CNS was compared between threat conditions. This experiment was designed to determine whether the somatosensory cortex changes in terms of its sensitivity to incoming afferent information during states of height-induced fear and anxiety, independent of any change in STR excitability. The results from Experiment #1 demonstrate that STR excitability is facilitated during states of height-induced fear and anxiety while the magnitude of the afferent volley delivered to the somatosensory cortex (TEP amplitude) does not significantly change between threat conditions. The results from Experiment #2 demonstrated that the sensitivity of the somatosensory cortex (SEP amplitude) also does not significantly change between threat conditions. Possible mechanisms underlying the observed facilitation of STR excitability and null effect of threat on TEP and SEP amplitude are discussed.

CHAPTER 3: PROPRIOCEPTIVE ADAPTATIONS DURING STATES OF HEIGHT-INDUCED FEAR AND ANXIETY

3.1 Introduction

Recent evidence has highlighted the potential for emotions, such as fear and anxiety, to influence human balance control. For example, young and older adults adopt different postural control strategies depending on the level of fear they experience when standing on the edge of an elevated surface height (Carpenter et al., 1999; 2001; 2006; Adkin et al., 2000; 2002; Davis et al., 2009; Huffman et al., 2009). However, the exact neural mechanisms that contribute to the observed changes in postural control remain unclear.

One possible functional adaptation that may contribute to the postural changes that are observed during states of height-induced fear and anxiety is an increase in muscle spindle sensitivity and a subsequent change in spinal reflex excitability (Carpenter et al., 2004; Sibley et al., 2007). Previous investigations have demonstrated that human muscle spindles are adaptive in nature (e.g. Vallbo and Hulliger, 1981; Prochazka et al., 1985). Based on the findings from studies that have compared recordings from feline Ia afferents in response to direct stimulation of gamma motor neurons and in response to induced muscle stretch (Prochazka et al., 1985; 1976; 1988; Hulliger et al., 1989) and human studies that have presumed to record directly from gamma motor neurons and Ia afferents (Ribot-Ciscar et al., 1986), it has been argued that muscle spindle sensitivity to stretch can be facilitated by increased gamma-motor drive relative to alpha-motor drive. In addition to heightened gamma-motor drive, it is also possible that direct activation of the sympathetic nervous system may serve to facilitate increases in muscle spindle sensitivity. There is evidence that feline muscle spindles receive direct innervation from the autonomic nervous system (Barker and Saito, 1981) that facilitates increases in muscle spindle firing rates when activated (Hunt, 1960). Likewise, performing mental arithmetic or a static handgrip contraction to directly activate the human sympathetic nervous system has been shown to facilitate stretch reflex excitability (Hjorstkov et al., 2005; Kambayashi et al., 2009).

Independent of whether increased muscle spindle sensitivity is related to increases in gamma-motor drive or sympathetic nervous system activation, an increase in soleus muscle (SOL) spindle sensitivity could produce at least three functional outcomes in humans. First, increased sensitivity of static bag and chain fibres of the SOL muscle spindle could increase

tonic Ia afferent firing rates and thereby reduce the sensitivity of the SOL lower motor neuron pool to phasic afferent stimuli through homo-synaptic post activation depression (HPAD) (Hultborn et al., 1996). For example, a characteristic decrease in SOL H-reflex amplitude is observed when HPAD is induced experimentally by direct stimulation of Ia afferents emanating from SOL (Rothwell et al., 1986; Crone and Nielsen, 1989) or by passive lengthening of SOL (Romano and Schieppati, 1987; Hultborn et al., 1996). Second, increased sensitivity of dynamic bag fibres of the SOL muscle spindle could result in increased amplitudes of spinal reflexes in response to mechanical stretch of the spindle (Rossi-Durand, 2002). Third, increased muscle spindle sensitivity may also result in amplified afferent signals travelling along the posterior column-medial lemniscal (PCML) pathway to higher cortical centres (Llewellyn et al.,1990; Nielsen et al.,1994).

Studies that have experimentally manipulated threat and arousal have provided evidence of proprioceptive adaptation in humans that could be attributed to increased muscle spindle sensitivity. For example, significant decreases in SOL H-reflex amplitude have been observed when individuals stand quietly on elevated surfaces (Sibley et al., 2007) or when they are engaged in a threatening task such as walking along a raised narrow beam (Llewellyn et al., 1990). This decrease in SOL H-reflex amplitude has been suggested to result from increased tonic Ia discharge and HPAD of the SOL lower motor neuron pool (Sibley et al., 2007). With respect to increases in the dynamic sensitivity of SOL muscle spindles, facilitation of the soleus tendon reflex (STR) has been demonstrated when humans stand under conditions of elevated postural threat (Horslen, 2010) or are presented with arousing stimuli (Bonnet et al., 1995). Although not well studied, there is some evidence suggesting that changes in muscle spindle sensitivity might also be reflected at the cortical level (Llewellyn et al., 1990). For example, it has been demonstrated that cortical responses are increased in response to unpredictable balance perturbations while standing under conditions of elevated postural threat compared to when standing on the ground (Adkin et al., 2008; Sibley et al., 2010). However, it remains unclear whether elevated muscle spindle sensitivity, cortical sensitivity, or combinations thereof contribute to the observed findings (Adkin et al., 2008; Sibley et al., 2010).

It is possible to address this uncertainty by investigating how increased SOL muscle spindle sensitivity may contribute to increases in spinal reflex excitability as well as the gain of afferent information delivered to the somatosensory region of the parietal cortex by simultaneously evoking STRs and cortical potentials (TEPs) via mechanical stimulations of SOL using tendon taps. In doing so, it is possible to dissociate whether heightened spindle sensitivity and increased STR excitability also results in a larger magnitude afferent volley to the cortex. Likewise, it is also possible to assess how the sensitivity of the somatosensory region of the parietal cortex to incoming afferent information is changed between experimental

conditions, independent of any changes in spindle sensitivity, by comparing the latency and amplitude of somatosensory evoked potentials (SEPs) elicited by mild electrical stimulation of the tibial nerve innervating SOL (Gandevia and Burke, 1984; Nelson et al., 2000; Staines et al., 2000; McIlroy et al., 2003). In such protocols, electrical stimulation of the tibial nerve at a site proximal to SOL, the popliteal fossa, precludes any change in muscle physiology (e.g. increased SOL muscle spindle sensitivity) from contributing to the observed change in SEP amplitude.

Therefore, two experiments were performed to achieve the two aims of this study. Experiment #1 was designed to investigate whether elevated muscle spindle sensitivity during states of height-induced fear and anxiety results in facilitated spinal reflexes and a concomitant increase in the gain of afferent information delivered to the cortex by comparing changes in STR excitability and TEP amplitude. Experiment #2 was designed to investigate the potential change in cortical sensitivity to incoming afferent information during states of height-induced fear and anxiety, independent of any changes in muscle spindle sensitivity, by comparing changes in SEP amplitude.

Based on previous observations (Horslen, 2010; Bonnet et al., 1995; Hjorstkov et al., 2005; Kambayashi et al., 2009), it was hypothesized that there would be a significant increase in both TEP and STR amplitude when standing under conditions of elevated postural threat compared to when standing under conditions of low postural threat. Furthermore, it was hypothesized that there would be a null effect of threat manipulation on SEP amplitude reflecting no change in the sensitivity of the cortex to incoming afferent information, independent of any change in spindle sensitivity.

3.2 Methods

3.2.1 Participants

Two independent groups of participants volunteered for two separate experimental protocols in this study. In Experiment #1, 35 young healthy adults (17 female, mean ± SE; age 22.6 ± 0.6 years; height 173.9 ± 1.7cm; and weight 70.6 ± 1.8kg) volunteered to participate. In Experiment #2, 31 young healthy adults (16 male, mean ± SE; age 24.9 ± 0.8 years, height 174.5 ± 0.9cm; and weight 68.9 ± 0.4kg) volunteered to participate. All participants were recruited from the local undergraduate and graduate student community. Each participant completed a survey of their relevant medical history prior to testing. All participants were free of any relevant neurological, vestibular and/or orthopaedic conditions and were not taking any prescription medications that may have affected their balance performance during the study. Each participant provided written informed consent prior to testing. The University of British Columbia Clinical Research Ethics Board has approved all experimental procedures.

3.2.2 Experiment #1: Mechanically Evoked Somatosensory Potentials (TEP)

In Experiment #1, participants were separated into one of two groups: Free Standing or Braced Standing. During testing, those in the Free Standing group stood unsupported during all experimental procedures whereas those in the Braced Standing group stood in custom-made ankle braces designed to immobilize the ankle joint in the A-P direction (Figure 3.1). The ankle braces were used to prevent the characteristic posterior lean and posterior shift in COP that occurs when participants stand under conditions of elevated postural threat (Davis et al., 2009). Such a posterior lean has the potential to confound any observed change in STR or TEP amplitude between threat conditions by imposing uncontrolled biomechanical variability. Therefore, it was essential to have participants stand in the Free Standing group as well as the Braced Standing group in order to quantify the effect of threat-associated posterior leaning as well as the effect the braces themselves may have on STR and TEP amplitude.

Participants from both groups stood quietly at the edge of a hydraulic platform (2.13m x 1.52m surface area, M419-207B10H01D, Penta-lift, Canada) under two different conditions of postural threat; Low Threat and High Threat. During the Low Threat condition the hydraulic platform was resting at its lowest height (0.8m). Previous work has shown that standing 0.48m away from the edge of a platform at a height of 0.8m does not produce a postural effect that is significantly different from when standing on the ground (Carpenter et al., 2001). Therefore, a second support surface (0.61m x 1.52m) was placed in front of, and flush, with the front edge of the platform. During the High Threat condition, participants stood at the edge of the hydraulic lift after it was elevated to a height of 3.2m. While standing in each threat condition, participants were instructed to stand with their eyes open and fixated on a target placed at eye level 3.87m in front of them with their arms hanging freely and feet placed at the front edge of the platform with stance width equal to foot length. At all times, participants were securely harnessed to the ceiling for their safety in the event of a fall. The harness tether was kept slack and did not provide haptic cues or balance support during standing trials.

While standing in each threat condition, participants in both the Free Standing and Braced Standing groups received 2 blocks of 120 mild mechanical taps delivered to their right Achilles tendon for a total of 240 taps per threat condition. A 30s rest period was provided between blocks during which participants were instructed to lean backward against the back of a chair that provided some postural support. Pilot data demonstrated that STR peak-peak amplitude remained stable over the course of testing and that there was no systematic increase or decrease reflex excitability associated with repeated stimulation.

A computer driven magnetic linear motor (E2000-AT, LIN Mot, USA) was used as the tendon hammer to deliver mechanical taps to the Achilles tendon. The tendon hammer travelled a distance of 1cm and took 13ms to reach peak displacement. The distance between the tendon hammer and skin was measured at the beginning of each block of testing in each threat condition to ensure that a constant distance of 5mm was maintained between the tendon hammer and the skin over the Achilles tendon throughout the experiment. Based on findings from initial pilot work, taps were applied to the Achilles tendon at an inter-stimulus interval of 1.2-1.7s to ensure that any postural perturbation caused by a given tendon tap and/or tendon reflex response fully subsided before a subsequent tap was delivered.

The force of each tap was recorded with a dynamic force sensor (Isotron Dynamic Force Sensor and Conditioner, Endeveco, USA) mounted on the contact surface of the tendon hammer. The force of each tap was amplified 10x and sampled at 1000Hz (Spike 5, CED, UK). Clinical investigations of STR sensitivity have demonstrated that a tendon tap force ranging from 21-50N is adequate to elicit an STR in healthy young adults (Marshal and Little, 2002). Therefore the force of each tap was kept within this range for all participants included in the study. In order to evoke an optimal STR, the tendon hammer contact location was adjusted in the vertical plane to ensure that the tap force for each participant was kept above sensory perception threshold and evoked a clear STR. The force of each tap was monitored on-line during testing to ensure that a consistent tap force was delivered between threat conditions and was recorded for off-line analysis.

3.2.3 STR and TEP Recording Procedure

In Experiment #1, electroencephalography (EEG) signals were recorded using the ANT WaveGuard cap system (ANT, Netherlands). EEG signals were recorded along the sagital midline from the Cz and referenced to Fpz' (2cm caudal to Fpz) locations on each participant's scalp. The electrode placement location was determined according to the international 10/20 system for EEG recordings. All EEG signals were grounded to a single electrode located between Cz and Fpz' in the WaveGuard cap. The impedance between all three electrodes was tested prior to and following the experiment (EZM5 impedance meter, Grass Instruments, USA) to ensure that the electrode impedance was less than10Kohm during testing. All EEGs signals were amplified 20000x, sampled at 2048Hz (Porti7, ANT, Netherlands), band-pass filtered off-line between 1-100Hz (MatLab, Mathworks, USA) and imported into a separate analytical software package (Spike5, CED, UK) for post-processing.

Electromyography (EMG) was used to record the STR and background SOL EMG activity by placing two surface Ag/AgCl electrodes ~4cm apart in a belly-tendon preparation on

the right SOL. Background EMG activity in the tibialis anterior muscle (TA) was recorded by placing two surface electrodes ~2cm apart in a belly-belly preparation on the right TA. Both EMG preparations shared a common ground with the EEG recordings in the WaveGuard cap. All EMG signals were amplified 2000x, sampled at 2048Hz (Porti7, ANT, Netherlands) and band-pass filtered (30-300Hz) off-line (MatLab, Mathworks, USA).

3.2.4 STR and TEP Analysis Procedure

During post-processing, each recording was inspected to remove any tendon taps that did not meet inclusion criteria for use in the calculation of the spike-trigger average of the STR and TEP. The inclusion criteria analysis was performed in a three step process. First, the ranges of the 240 tap forces delivered during each of the Low Threat and High Threat conditions were calculated for each participant. The condition with the narrowest range was used as the standard from which a mean ± 2SD threshold band was calculated. Second, individual taps that did not fall within this standard mean ± 2SD threshold band in either threat condition were removed from subsequent analysis. Third, each recording was visually inspected to remove any remaining stimuli that were contaminated by artifacts related to eye-blinks or facial muscle contractions. Data from individual participants were only included in the subsequent analysis if there were at least 100 stimuli that met these inclusion criteria for each threat condition.

24 participants (10 female, mean ± SE; age 23.0 ± 0.7 years; height 175.3 ± 1.8cm; and weight 70.9 ± 2.0kg) (12 in the Free standing group and 12 in the Braced Standing group) passed the inclusion criteria analysis. For those 24 participants, spike-triggered averages were calculated for the STR and TEP signal between 100ms prior to, and 300 ms after, the stimulus onset (Spike 5, CED, UK). Peaks related to P1, N1, P2 and N2 components of the TEP waveform were identified and used to calculate the times to peak, and the peak-peak amplitudes between P1-N1 and P2-N2 (Gandevia and Burke, 1984; Cohen et al. 1990). The peak-peak amplitude and latency of the STR were calculated from the spike-triggered average of the STR from each threat condition. Background EMG activity in SOL and TA were calculated as the mean level of activation of the full-wave rectified EMG signal 100ms prior to stimulus onset.

3.2.5 Physiological and Psychosocial Estimates of Height-induced Fear and Anxiety

Electrodermal activity (EDA) of the non-dominant hand was used to provide an estimate of the level of physiological arousal participants experienced during each threat condition. Participants were fitted with disposable recoding electrodes on the thenar and hypothenar eminences to measure their skin conductance (2502 Skin Conductance Unit, CED, UK) with a range of 0-100 μmho. The skin conductance signal was collected at a sampling frequency of 1000Hz. EDA was averaged across the first 60s of each trial and subsequently averaged across trials for each threat condition.

Before testing in each threat condition, participants were instructed to rate how confident they were that they would be able to maintain their balance and avoid a fall during the threat condition on a scale of 0% (no confidence) to 100% (complete confidence) (Adkin et al., 2002). Immediately following each standing trial, participants were instructed to rate how stable they felt during the trial on a scale of 0% (very unstable) to 100% (completely stable) and how fearful of falling they were during the trial again on a scale of 0% (completely unafraid) to 100% (extremely afraid) (Adkin et al., 2002). Participants also completed a 16-question survey of their perceived anxiety modified from Adkin et al. (2002). The scores from all 16 questions were summed to generate a total score of perceived state anxiety for each threat condition.

3.2.6 Statistical Analysis

All dependent variables were compared between standing conditions (Low Threat and High Threat) and between groups (Free Standing and Braced Standing) using 2x2 (condition x group) mixed design ANOVAs (SPSS, IBM, USA). Within-subjects effect sizes (Cohen's d values) were calculated for each dependent variable as well. The criteria for statistical significance was set to $p<0.05$.

3.2.7 Experiment #2: Somatosensory Evoked Potentials (SEP)

In Experiment #2, participants stood under the same threat conditions described in Experiment #1: Low Threat and High Threat. While standing in each threat condition, participants received 2 blocks of 120 mild cutaneous electrical stimulations (S88 with SIU5 stimulus isolation unit, Grass Instruments, USA) separated by a rest period of ~30s, for a total of 240 stimuli per threat condition (see details below). All participants in Experiment #2 stood unsupported; a braced standing group was not included. The rationale for not including a braced standing group was based on the fact that the location of SEP stimulation, the popliteal fossa, is proximal to the lower limb musculature. Therefore, the ascending afferent volley

evoked by the cutaneous electrical SEP stimulation would not have been subject to any changes in muscle physiology or lower motor neuron pool excitability associated with the threat-associated posterior COP shift.

Prior to the experiment, all participants performed a practice trial with the hydraulic lift resting at its lowest height of 0.8m to remove potential first trial effects. The order of presentation of Low and High Threat conditions was counter-balanced across participants to minimize potential order effects. At the end of the experiment, participants performed a post-test standing control trial in the Low Threat condition that was used to confirm the stability of the SEP signals over time.

3.2.8 COP Measures

Ground reaction forces and moments were sampled (#K00407, Bertec, USA) at 100 Hz (Power 1401, CED, UK) and low-pass filtered offline using a 5 Hz dual-pass Butterworth filter (MatLab, Mathworks, USA) before calculating Centre of Pressure (COP) in the anterior-posterior (A-P) direction. Mean position of the COP during each trial was calculated in the A-P direction and subtracted from the COP signal. From this unbiased signal, the Root Mean Square (RMS) and Mean Power Frequency (MPF) of COP displacement were calculated in the A-P direction.

3.2.9 SEP Stimulation Procedure

SEPs were evoked by electrical stimulation of the right tibial nerve. The anode (10cm x 3cm, coal rubber pad, AMG Medical Inc, Canada) was placed just superior to the patella and the Ag-AgCl cathode (0.25cm in diameter, Kendall, USA) was placed in the popliteal fossa. To determine the optimal SEP stimulation intensity for each participant, a series of SOL H-reflexes were elicited via a sub-maximal 0.5ms square wave pulse to the tibial nerve. The SEP stimulus intensity was set to 40-60% of the intensity required to elicit a small M-wave. This intensity was just above sensory perception threshold for each participant and not sufficient to elicit a SOL H-reflex or M-wave. Previous reports have demonstrated that using stimulation intensities equal to 40-60% of the intensity required to elicit an M-wave provides an optimal range for the SEP to fluctuate within and not become saturated (Gandevia and Burke, 1984).

In order to ensure that the intensity of the stimulation to the tibial nerve did not change between standing conditions, an M-wave test pulse equal to 50% of M-max (DS5, Digitimer inc. UK) was evoked prior to and immediately following each 120s standing trial in a sub-group of ten participants. The peak to peak amplitude of each evoked M-wave was monitored in order to confirm the consistency of the stimulus over the duration of the testing period. A stimulation

intensity required to evoke an M-wave test pulse equal to 50% of M-max was chosen so that a shift in electrode placement or any other change in the consistency of the stimulus over time could be identified by either an increase or a decrease in the M-wave test pulse amplitude.

3.2.10 SOL H-reflex and, Somatosensory Evoked Potential Recording and Analysis Procedure

A different recording system from the one used in Experiment #1 was used to collect EEG in Experiment #2. Sintered Ag/AgCl scalp electrodes (EASYCAP, Germany) were placed along the sagittal midline at the Cz and Fpz' (2cm caudal to Fpz) locations on the participant's scalp according to the international 10/20 system for EEG recordings. A ground electrode was placed on the back of the participants' neck (5cm x 5cm, coal rubber pad, AMG Medical Inc, Canada). The impedance between all three electrodes was tested before and after testing (Grass EZM5 impedance meter, Grass Instruments, USA) to ensure that the electrode impedance was kept at less than 10Kohm during testing. The EEG signal was amplified 20000x, sampled at 10000Hz and band-pass filtered between 1-1000Hz (Grass, P511 AC amplifier, USA). Each recording was visually inspected offline, to remove any stimuli that may have been contaminated by artifacts related to eye blinks or facial contractions. The remaining stimuli were used to create a spike-triggered average (Spike 5, CED, UK) of the SEP signal between 100ms prior to, and 150 ms after, the stimulus onset. The ensemble spike-triggered average was baseline corrected using the mean of the signal 100 ms prior to stimulus onset and band-pass filtered between 1-100Hz using customized software (LabVIEW, National Instruments, USA). Peaks related to P1, N1, P2 and N2 components of the SEP waveform were identified and used to calculate time to peaks, and the peak-peak amplitude between P1-N1 and P2-N2 (Gandevia and Burke, 1984).

Two surface Ag/AgCl EMG electrodes were applied in a belly-tendon preparation on the right SOL muscle in order to record SOL H-reflexes. Two surface Ag/AgCl electrodes were placed ~2cm apart in a belly-belly preparation to collect background EMG activity in SOL. All EMG signals were amplified 2000x, sampled at a 1000Hz and band-pass filtered between 30-300Hz (P511 AC Amplifier, Grass Instruments, USA).

3.2.11 Physiological and Psychosocial Estimates of Height-Induced Fear and Anxiety

Both EDA and psychosocial estimates of height-induced fear and anxiety were recorded in the same manner described for Experiment #1.

3.2.12 Statistical Analysis

All dependent variables were compared between Low and High Threat conditions using paired-samples t-tests (SPSS, IBM, USA). Paired t-tests were also used to compare SEP amplitudes measured at the low height during the experiment, and the post-test control trial. Within-subjects effect sizes (Cohen's d values) were calculated for each dependent variable as well. Correlation analysis was performed using a Pearson correlation on the changes between the high threat and low threat conditions for the physiological and posturographic variables. The criteria for statistical significance was set to $p<0.05$.

3.3 Results

3.3.1 Experiment #1: Mechanically Evoked Somatosensory Potentials (TEPs)

In the Low Threat condition, the TEP waveform was characterized by distinct P1-N1 and P2-N2 components (Figure 3.2A). The mean time to peak for the P1 and N1 peaks occurred at 35.46 ± 0.92ms and 48.12 ± 0.96ms, respectively, following stimulus onset. The mean P2 peak latency was 56.90 ± 0.95ms and the mean N2 latency was 71.40 ± 1.48ms. The mean peak-peak amplitude of the P1-N1 and subsequent P2-N2 components were 4.80 ± 0.61μV and 6.62 ± 0.68μV, respectively. A similar TEP waveform was observed in the High Threat condition. There were no observable differences in the grand average waveforms between threat conditions with respect to the timing or amplitude of the P1-N1 or P2-N2 components of the TEP waveform (Figure 3.2A).

The lack of observable differences in TEP timing and amplitude between Low and High Threat conditions was confirmed statistically. A mixed design ANOVA revealed no significant difference between threat conditions for the time to peak of the P1 ($F_{(1,22)}$=2.311, p=0.143, δ=0.13), N1 ($F_{(1,22)}$=0.335, p=0.568, δ=0.07), P2 ($F_{(1,22)}$=1.727, p=0.202, δ=0.12) and N2 ($F_{(1,22)}$=0.085, p=0.773, δ=0.04) peaks when standing in the High Threat compared to Low Threat condition (Table 3.1). There was also no significant main effect of threat condition on the amplitude of the P1-N1component ($F_{(1,22)}$=0.904, p=0.352, δ=0.07) or the P2-N2 component ($F_{(1,22)}$=2.468, p=0.131, δ=0.14) of the TEP waveform (Table 3.1). However, there was a significant main effect of group on the peak-peak amplitude of the P1-N1 ($F_{(1,22)}$=6.302, p=0.020, δ=0.74) whereby larger P1-N1 amplitudes were observed in the Braced Standing group compared to the Free Standing group. There were no significant interaction effects between threat condition and group.

Despite very little change in the observed TEP, there was a distinct increase in the STR peak-peak amplitude in the High Threat compared to the Low Threat condition (Figure 3.3B).

This observation was confirmed statistically across participants. There was a significant main effect of threat condition on both the peak-peak amplitude ($F_{(1,22)}$=4.430, p=0.047 δ=0.12) and peak latency ($F_{(1,22)}$=5.109, p=0.034, δ=0.15) of the STR. The peak-peak amplitude of the STR was significantly larger and occurred significantly earlier when standing in the High Threat condition compared to the Low Threat condition, independent of whether participants were in the Free Standing or Braced Standing group (Figure 3.4A). Furthermore, there was a significant main effect of threat condition on both the mean level of background SOL EMG activity ($F_{(1,22)}$=9.547, p=0.005, δ=0.30) and mean level of TA EMG activity ($F_{(1,22)}$=9.895, p=0.005, δ=0.48). In both the Free Standing and Braced Standing group, there was a significant decrease in the mean level of background SOL activity and a significant increase in mean level of background TA activity (Figure 3.4C).

There was a significant main effect of threat condition on the level of confidence ($F_{(1,22)}$=62.64, p<0.001, δ=1.57), state anxiety ($F_{(1,22)}$=24.06. p<0.001, δ=0.085) and fear ($F_{(1,22)}$=33.51, p<0.001, δ=1.17). As shown in Table 3.1, there was a significant increase in both self-reported fear and state anxiety and a significant decrease in self-reported confidence when standing in the High Threat condition compared to the Low Threat condition. There was also a significant main effect of height observed on EDA ($F_{(1,22)}$=29.498, p<0.001, δ=0.54) whereby participants demonstrated higher EDA in the High Threat compared to the Low Threat condition (Table 3.1).

3.3.2 Experiment #2: Electrically Evoked Somatosensory Potentials (SEPs)

In the Low Threat condition, the mean SEP waveform was characterized by a P1 peak with a mean latency of 38.98 ± 1.44 ms following stimulus onset, followed by an N1 peak at 49.61 ± 1.78 ms (Figure 3.1B). Subsequently, the P2 and N2 peaks were observed with mean latencies of 64.54 ± 2.66 ms and 80.42 ± 3.60 ms, respectively. In the High Threat condition the mean latency of the P1 peak was 38.98 ± 1.38 ms following stimulus onset, followed by an N1 peak at 50.55 ± 2.04 ms. The secondary P2 and N2 peaks were observed at mean latencies of 64.17 ± 2.49 ms and 79.09 ± 3.19 ms, respectively. There was no observable difference between threat conditions in the time to peak for any component of the SEP and there was no observed difference in the artifact amplitude (Figure 3.2B). Furthermore, there was no observable change in the amplitude of either the P1-N1 or P2-N2 components of the SEP between the Low Threat and High Threat conditions (Figure 3.2B).

These observations stand in stark contrast to changes observed in COP displacement and EDA between threat conditions. As shown in Figure 3.5B, there was a dramatic decrease in the amplitude of COP displacements despite there being no observable change in SEP

amplitude between threat conditions. Moreover, EDA increased in anticipation of the standing trial, and reached higher peak amplitudes in the High compared to Low Threat condition (Figure 3.5C).

The lack of observable differences in SEP amplitudes between Low and High Threat conditions was confirmed statistically (Figure 3.2B). Paired t-tests revealed no significant difference between the amplitude of the P1-N1component ($t_{(30)}$=-1.26, p=0.212, δ=0.040) or the P2-N2 component ($t_{(30)}$ =-0.69, p=0.945, δ=0.070) of the SEP waveform when standing in the High Threat compared to Low Threat condition (Table 3.1). Additionally, there was no significant difference between the time to peak of the P1 ($t_{(30)}$=-0.001, p=0.999, δ<0.001), N1 ($t_{(30)}$=-0.875, p=0.388, δ=-0.089), P2 ($t_{(30)}$=0.543, p=0.591, δ=0.026) or N2 ($t_{(30)}$=1.116, p=0.273, δ=0.071) peaks when standing in the High Threat compared to Low Threat condition (Table 3.1). Furthermore, there was no significant difference between standing conditions in the peak-peak amplitude of the M-wave test pulse recorded in a sub-set of ten participants ($t_{(9)}$=0.841, p=0.421, δ=0.069) confirming the stability of electrode placement during testing.

In contrast, participants' mean A-P COP was shifted significantly further from the edge of the platform ($t_{(30)}$=-7.867, p<0.001, δ=0.836), while MPF of A-P COP significantly increased ($t_{(30)}$=-4.337, p<0.001, δ=0.605) and RMS of A-P COP significantly decreased ($t_{(30)}$=4.622, p<0.001, δ=-0.455) when standing in the High compared to Low Threat condition (Table 3.1). Mean EDA increased significantly ($t_{(30)}$=-4.794, p<0.001, δ=0.923) and tonic levels of SOL EMG activity did not significantly change ($t_{(30)}$=0.785, p=0.439, δ=0.134) when standing in the High compared to Low Threat condition. There was also a significant increase in participants' self-reported level of state anxiety ($t_{(30)}$=-6.872, p<0.001, δ=1.113) and self-reported fear ($t_{(30)}$=-6.916, p<0.001, δ=1.261) and a significant decrease in participants' self-reported level of balance confidence ($t_{(30)}$=5.538, p<0.001, δ=1.024) when standing in the High threat compared to Low Threat condition (Table 3.1).

Neither the change in P1-N1 or P2-N2 amplitude or latency between the Low Threat and High Threat condition were correlated to the change observed in any of the physiological or psychological dependent variables. Furthermore, there was no significant correlation between the change in peak-peak amplitude of the M-wave test pulse and the change in either P1-N1 amplitude (r^2 =0.027, p=0.651) or P2-N2 amplitude (r^2=0.023, p=0.676).

3.4 Discussion

The primary aims of Experiment #1 were to determine whether or not muscle spindle sensitivity increases during states of height-induced fear and anxiety and whether this increase in spindle sensitivity results in amplified afferent information being delivered to the

somatosensory cortex. The results from Experiment #1 demonstrated that STR excitability was facilitated and STR latency was reduced when participants stood in the High Threat condition compared to the Low Threat condition. Furthermore, these changes were observed in both the Free Standing and Braced Standing group. This same manipulation also caused a significant decrease in SOL and a significant increase in TA EMG activity independent of bracing condition. Therefore, the observed increase in STR excitability in the High Threat condition cannot be explained by changes in background EMG activity. More specifically, the reciprocal inhibitory influence associated with heightened TA EMG activity and decreased SOL EMG activity has been demonstrated to inhibit STR excitability (Crone et al., 1987). However, the potential influence of heteronymous muscle contraction in the High Threat condition, i.e. peroneus longus or medial gastrocnemius, cannot be completely ruled out as a potentially facilitating influence on STR excitability. Heteronymous muscle activation notwithstanding, it is likely that increased SOL muscle spindle sensitivity is indeed the underlying cause of the observed increase in STR excitability in the current study. Furthermore, it appears that this facilitating sensory adaptation is strong enough to overcome the inhibitory influence on the SOL lower motor neuron pool imposed by the increase in TA EMG activity.

In Experiment #1, the changes in EDA and psychosocial estimates of fear and anxiety between threat conditions occurred independent of whether participants stood in either the Free Standing or Braced Standing group. This finding clearly demonstrates that the custom-made braces used to control ankle angle during testing did not attenuate the fear or and/or anxiety imposed in the High Threat condition.

3.4.1 The Cause of Heightened Muscle Spindle Sensitivity and STR Facilitation

It has been demonstrated that muscle spindles are directly innervated by the autonomic nervous system and that activation of the sympathetic nervous system facilitates spinal stretch reflexes (Hunt,1960; Barker and Saito, 1981; Hjorstkov et al., 2005; Kambayashi et al., 2009). Therefore, the enhanced sympathetic nervous system activation (indexed by elevated EDA response) that occurs during states of height-induced fear and anxiety may lead to increased SOL muscle spindle sensitivity and thus explain the facilitation of STR excitability observed in the High Threat condition. However, despite the observed increases in spinal stretch reflex sensitivity to directly enhanced sympathetic out-flow (Hjortskov et al., 2005; Kambayashi et al., 2009), more invasive physiological studies have demonstrated that sympathetic nervous system activation does not facilitate tonic muscle spindle firing rates in animal models (Passatore et al., 1996; Hellström et al., 2005) or in humans (Macefield et al., 2003). Furthermore the firing rates of muscle spindles in response to phasic stretch has also been demonstrated to be unaffected

by experimental activation of the sympathetic nervous system (Birznieks et al., 2008). Therefore, it is unlikely that the observed increase in spindle sensitivity and subsequent facilitation of STR excitability is a consequence of the enhanced sympathetic nervous system activation that occurs during states of height-induced fear and anxiety.

Alternatively, the observed increase in spindle sensitivity and STR reflex facilitation observed may occur as a result of heightened gamma-motor drive to SOL muscle spindles (Prochazka et al., 1976; 1985; 1988; Ribot-Ciscar et al., 1986). However, this possible explanation is contentious considering the limitations of the work conducted in both human and animal models studying the phenomenon of alpha-gamma decoupling. For example, the conclusions made by Ribot-Ciscar et al. (1986) rely on debatable assumptions that the experimental methods used in the study actually achieved the goal of recording from gamma efferents. Likewise, the muscle spindle 'wind-up' theory proposed by Prochazka et al. (1988) relies on a two part experimental paradigm whereby the pattern of Ia afferent firing observed in response to different types of phasic muscle stretch and contraction of muscles in intact cats in the first experiment were re-produced in response to direct stimulation of gamma dynamic and/or gamma static motor-neurons in anaesthetized cats in the second experiment (Prochazka et al., 1985). In this case, the spindle 'wind-up' theory relies on studies assuming that because a given pattern of Ia afferent firing can be re-produced via experimental stimulation of gamma-motor neurons in anesthetized cats, that physiological gamma-motor activity was responsible for the producing those same patterns of Ia activity in fully intact cats. However, more recent investigations have demonstrated that the firing rate of primary Ia afferents of hand muscles are increased and the firing rates of secondary type II afferent remain unchanged during an active drawing task when attention to the task is paid in comparison to when participants were instructed to not pay attention to the drawing task (Hospod et al., 2007). In these experiments, the increase in Ia firing rates and null effect of attention on II firing rates was attributed to an increase in gamma-motor drive to the dynamic bag II fibres of the muscle spindle, thereby demonstrating that gamma-motor drive can be selectively controlled by the central nervous system (Hospod et al., 2007). Despite this more recent indirect evidence, the possibility that the gamma-motor system can be decoupled from the alpha-motor system to facilitate increases in muscle spindle sensitivity remains uncertain. Therefore, it will not be possible to conclude that alpha-gamma decoupling and heightened gamma-motor drive is the underlying cause of the observed STR facilitation in Experiment #1 until direct micorneurographic recordings of gamma and alpha motor neurons are obtained from humans in the current experimental paradigm.

3.4.2 Supraspinal Ia Afferent Signal Attenuation

Despite the observed facilitation of STR excitability in the High Threat condition, the threat manipulation used in the current study produced a null effect on both TEP amplitude and latency in Experiment #1. Furthermore, the results from Experiment #2 also demonstrate a null effect of elevated postural threat on both cortical SEP amplitude and latency. Taken together, the results from Experiment #1 demonstrate that stretch reflex excitability is facilitated during states of height-induced fear and anxiety. However, this proprioceptive adaptation does not appear to result in a larger afferent volley to the somatosensory cortex, as demonstrated by the null effect of threat condition on TEP amplitude. Furthermore, the results from Experiment #2 clearly show that the sensitivity of the somatosensory cortex to incoming afferent information does not change during states of height-induced fear and anxiety as demonstrated by the null effect of threat condition on SEP amplitude.

These findings are of importance considering their impact on the current theoretical explanations of how the human central nervous system adapts to control posture during situations where balance is challenged or threatened. More specifically, the findings of the current study refute the postulate of Llewellyn et al. (1990) that 'proprioceptive sensitivity is elevated to provide supraspinal areas with increased feedback gain and resolution' (pg 27). If this theory were correct, a significant increase in TEP amplitude between the Low Threat and High Threat conditions would have been observed in the current study. Therefore, it can be concluded that the postulate put forth by Llewellyn et al. (1990) is incorrect with respect to stance; heightened spindle sensitivity does not result in the heightened gain of cortical information during stance. Instead, it appears that the heightened Ia volley associated with the increase in muscle spindle sensitivity and STR excitability, is gated or dampened before it reaches the cortex.

The simple explanation for the observed null effect of threat on TEP amplitude despite the observed facilitation of STR excitability is that the afferent volley evoked by mechanical stretch of the Achilles tendon is gated at some point along the PCML pathway under threatening conditions. For example, it is possible that second order sensory neurons emerging from the nucleus graciles or third order sensory neurons emerging from the thalamus are differentially modulated under conditions of elevated postural threat in order to gate or dampen amplified afferent information travelling to the cortex. The gating of afferent sensory afferent information has been observed before (Abbruzzese et al., 1981; Rushton et al., 1981; Dietz et al., 1985; Duysens et al., 1990; 1995; Morita et al., 1998a). In these experiments, electrically evoked SEPs were found to be depressed during different phases of the gait cycle (Dietz et al., 1985; Duysens et al., 1990; 1995) and prior to the onset of and during voluntary ankle movement (Abbruzzese et al., 1981; Rushton et al., 1981; Morita et al., 1998a). The observed SEP attenuation was reasoned to serve as a functional adaptation to facilitate voluntary motor

control in such situations (Morita et al., 1998a). Therefore, it is plausible that a similar gating mechanism may be activated in order to facilitate greater cortical control over posture during states of height-induced fear and anxiety (Huffman et al., 2009).

Alternatively, it is plausible that instead of gating the incoming afferent volley at a sub-cortical locus, the somatosensory cortex is directly inhibited to allow for the heightened afferent volley to be utilized by sub-cortical balance command centres other than the cortex (e.g. the brainstem, cerebellum or lower motor neuron pool).

However, if sensory gating or cortical inhibition was indeed occurring to explain the results of Experiment #1, an attenuation of the electrically evoked SEP would have been observed in Experiment #2. This was not the observed result of Experiment #2. However, it is important to consider that the current study was limited by the fact that TEPs and SEPs were evoked in different experimental populations. Therefore, although it is unlikely that the heightened afferent volley associated with the observed increase in STR excitability in Experiment #1 was gated and/or inhibited when participants stood in the High Threat condition, the results of Experiment #2 cannot be solely relied upon to rule out this possibility.

Therefore, future studies should be conducted to better understand the observed attenuation of Ia afferent discharge observed in Experiment #1. For example, it would be worthwhile to elicit TEPs and SEPs from the same individuals in order to make within subject comparisons to better understand the effects of elevated postural threat on these two dependent measures. Additionally, it may be worthwhile to investigate changes in the evoked potentials recorded from surface electrodes placed at different levels along the PCML pathway and at the cervical spine (Cameron et al., 2008; Murakami et al., 2008) in order to observe possible attenuation of Ia phasic afferent traffic at the nucleus graciles and brainstem following mechanical stretch of SOL muscle spindles. However, such experiments may prove difficult in a standing model considering the large number of stimuli required to record mechanically evoked TEPs at the cervical spine (Cohen et al., 1984). Alternatively, it may be possible to record evoked potentials in response to mechanical stretch of SOL muscle spindles from indwelling thalamic electrodes in clinical populations (e.g. Katayama and Tsubokawa, 1987; Klostermann et al., 2002) during states of height-induced fear and anxiety. And finally, direct afferent, thalamic and cortical recordings from semi-intact animal preparations may ultimately provide the necessary insight to truly understand how the pathway along which Ia afferent traffic travels can be differentially regulated in response to experimental manipulation.

3.4.3 The Utility of Studying Changes in TEP Amplitude during Stance

Only two studies have examined TEPs in humans. Cohen et al. (1984) was the first to descriptively compare SEPs and TEPs evoked in participants lying prone. Similarly, the magnitudes of TEP responses to mechanical stretch of the Achilles tendon have been compared between the paretic and functional limbs of hemi-paretic patients while lying prone (Frascarelli et al., 1993).

Despite the observed null effect of height-induced fear and anxiety on TEP amplitude in the current study, both the latency and amplitude of the TEP evoked during stance in the current study corroborate that of TEPs described previously in participants lying prone (Cohen et al., 1984; Frascarelli et al., 1993). Specifically, the mean peak-peak amplitude of the P1-N1 (4.80 ±0.61 μV) component of the mechanically evoked TEP in the Low Threat condition of the current study is of similar size to that observed by Cohen et al. (1984) (3.2 ± 3.1 μV) and Frascarelli et al. (1993) (3.67 ± 0.44 μV). Likewise, the mean latency of the P1-N1 (35.46 ± 0.92 ms) component of the mechanically evoked TEP in the Low Threat condition of the current study falls within the range of P1-N1 latencies observed by Cohen et al. (1984) (27-37 ms). P1-N1 latencies were not reported by Frascarelli et al. (1993).

Therefore, the results of the current study provide the first evidence supporting the feasibility of using TEPs as a quantitative method for investigating possible changes in cortical responses to mechanical stretch of SOL muscle spindles during stance. This is an important finding considering the potential utility of studying changes in TEP amplitude in future clinical and basic research studies. For example, it will be possible to determine in future studies whether the sensory deficits and balance impairments observed among sufferers of peripheral neuropathy secondary to diabetes (e.g. Bloem et al., 2002) are related to problems in spindle sensitivity, sensory transmission, cortical perception, or any combination thereof by comparing differences in SEP and TEP amplitude in a standing model. Likewise, it has recently been demonstrated that proprioceptive adaptation during visual motor learning paradigms occurs at the level of the muscle spindle (Ostry et al., 2010). In future studies it will be possible to determine whether this proprioceptive adaptation is reflected at the cortical level by comparing changes in TEP amplitude in such paradigms.

Table 3.1: Results Summary Measures

	Experiment #1		Experiment #2	
Dependent Measure	**Low Threat**	**High Threat**	**Low Threat**	**High Threat**
Neurophysiolgical Measures				
P1-N1Amplitude (μV)	4.80 ± 0.61	5.03 ± 0.63	1.75 ± 0.27	1.95 ± 0.30
P2-N2 Amplitude (μV)	6.62 ± 0.68	7.15 ± 0.79	2.21 ± 0.25	2.22 ± 0.24
P1 Latency (ms)	35.46 ± 0.92	34.87 ± 0.94	38.98 ± 1.44	38.98 ± 1.38
N1 Latency (ms)	48.12 ± 0.96	47.84 ± 0.80	49.61 ± 1.78	50.55 ± 2.04
P2 Latency (ms)	56.9 ± 0.95	56.4 ± 0.88	64.54 ± 2.66	64.17 ± 2.49
N2 Latency (ms)	71.40 ± 1.48	71.05 ± 1.73	80.42 ± 3.60	79.09 ± 3.19
Physiological Measures				
Mean EDA (mOhm)	**18.11 ± 1.91**	**24.72 ± 2.50**	**18.75 ± 1.41**	**30.44 ± 2.95**
Mean SOL EMG (mV)	**0.012 ± 0.002**	**0.009 ± 0.002**	0.020 ± 0.01	0.023 ± 0.01
Mean TA (mV)	**0.007 ± 0.002**	**0.015 ± 0.002**	---	---
M-wave Amplitude (mV)	**---**	**---**	2.06 ± 0.46	1.98 ± 0.43
Psychological Measures				
State Anxiety	**28.36 ± 1.75**	**45.41 ± 4.01**	**28.42 ± 1.49**	**54.68 ± 4.77**
Fear	**2.92 ± 1.27**	**24.79 ± 3.32**	**3.42 ± 1.32**	**37.84 ± 5.23**
Confidence	**96.87 ± 0.94**	**77.71 ± 2.50**	**95.35 ± 1.50**	**76.48 ± 3.75**
Posturographic Measures				
Mean A-P position (mm)	**---**	**---**	**-44.54 ± 2.72**	**-31.39 ± 2.70**
A-P MPF (Hz)	**---**	**---**	**0.226 ± 0.02**	**0.30 ± 0.02**
A-P RMS (mm)	**---**	**---**	**4.68 ± 0.26**	**3.70 ± 0.22**

Table 3.1

Mean change (+/-SEM) of all neurophysiological, physiological and psychosocial measures observed between the Low Threat and High Threat conditions observed in Experiment #1 and Experiment #2. Significant main effects of threat condition are highlighted in **bold text** ($p<0.05$).

Figure 3.1: Experimental Set-Up

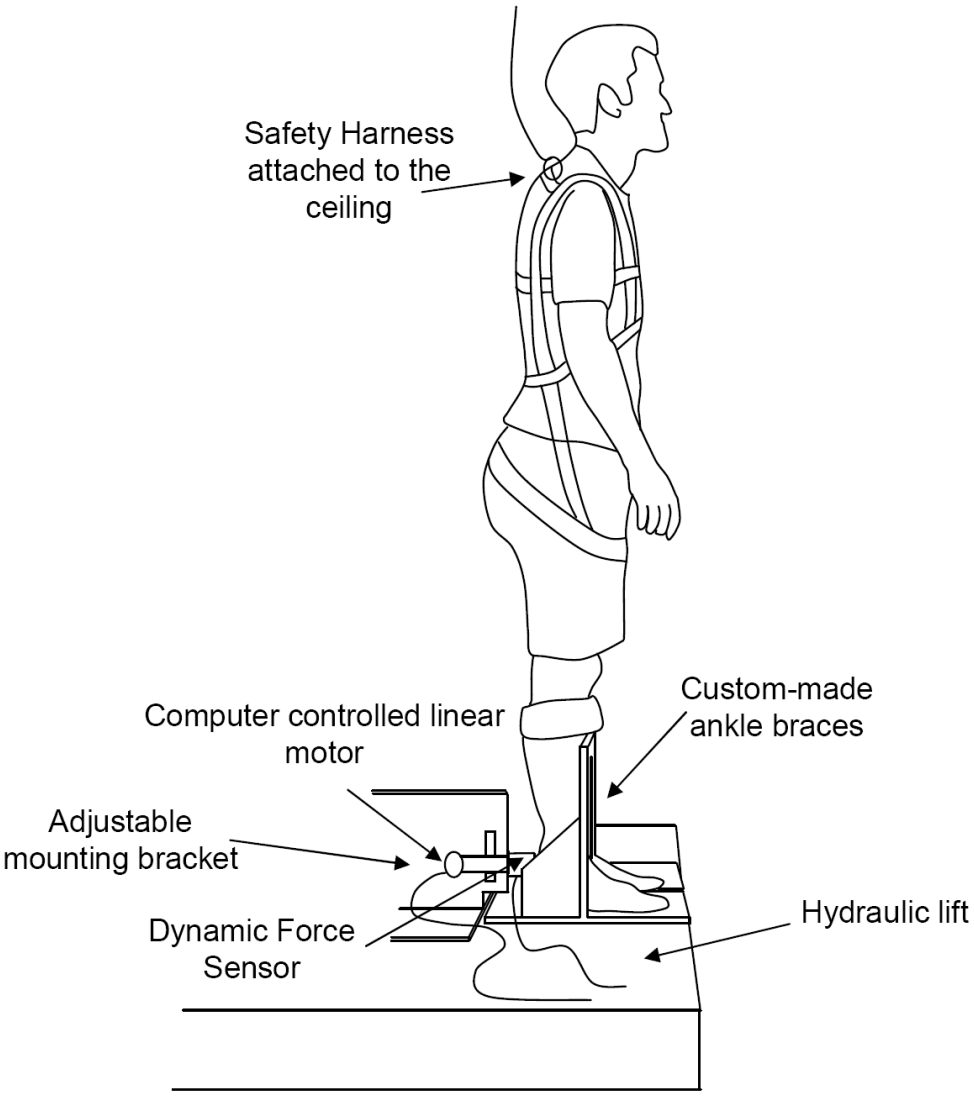

Figure 3.1:
The experimental set up used to support stance in the braced standing condition. Participants stood in custom-made ankle braces designed to attenuate postural sway in the anterior posterior direction.

Figure 3.2: SEP and TEP Grand Average Waveforms

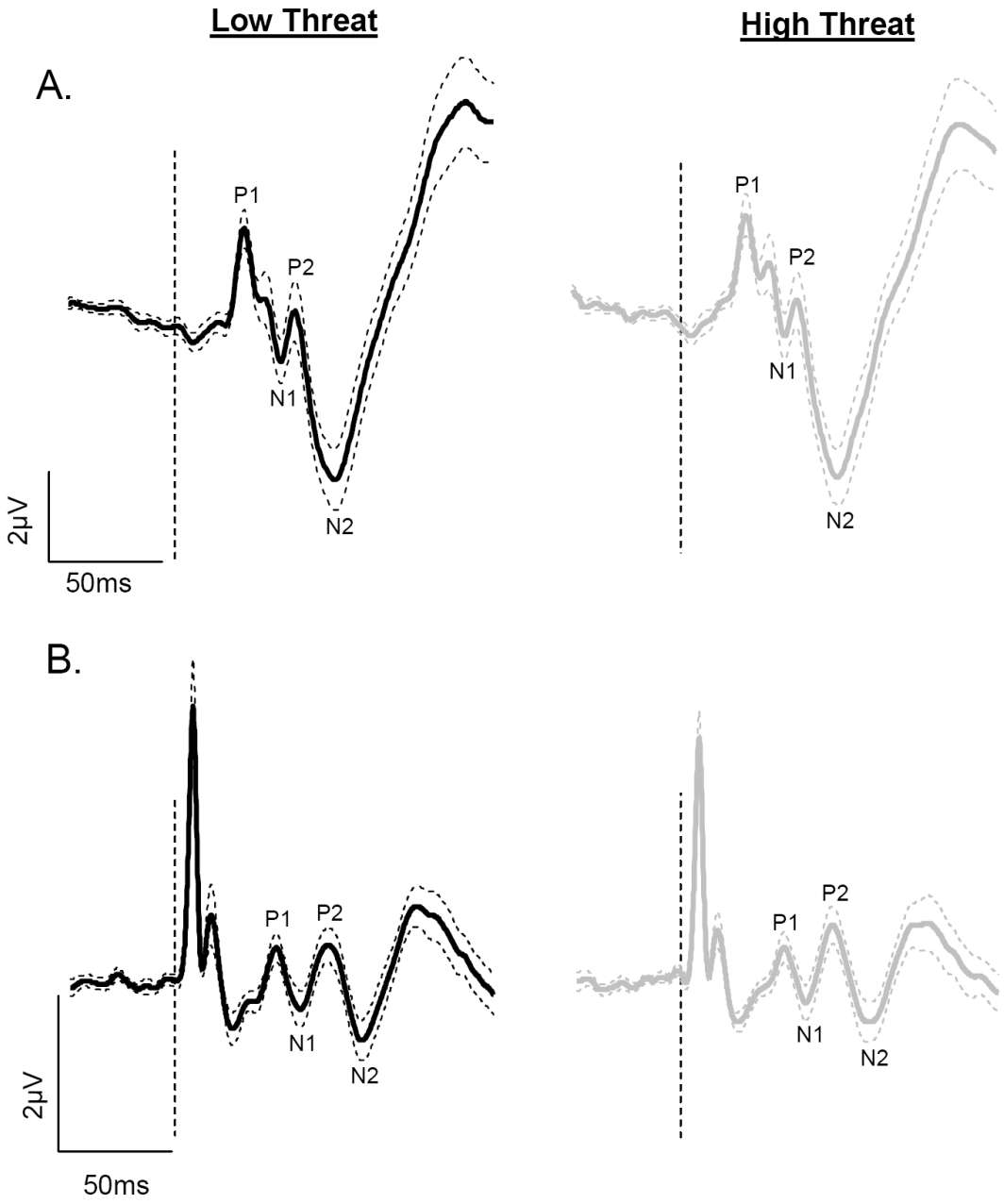

Figure 3.2:
A) Grand Average TEP traces (Mean +/- SEM) observed in the Low threat condition (black traces) and high threat condition (grey traces) across all 24 participants in Experiment #1. B) Grand Average SEP traces (Mean +/- SEM) observed in the Low threat condition (black traces) and high threat condition (grey traces) across all 31 participants in Experiment #2. Dashed vertical line indicates the time of stimulus onset.

Figure 3.3: Representative TEP and STR Data

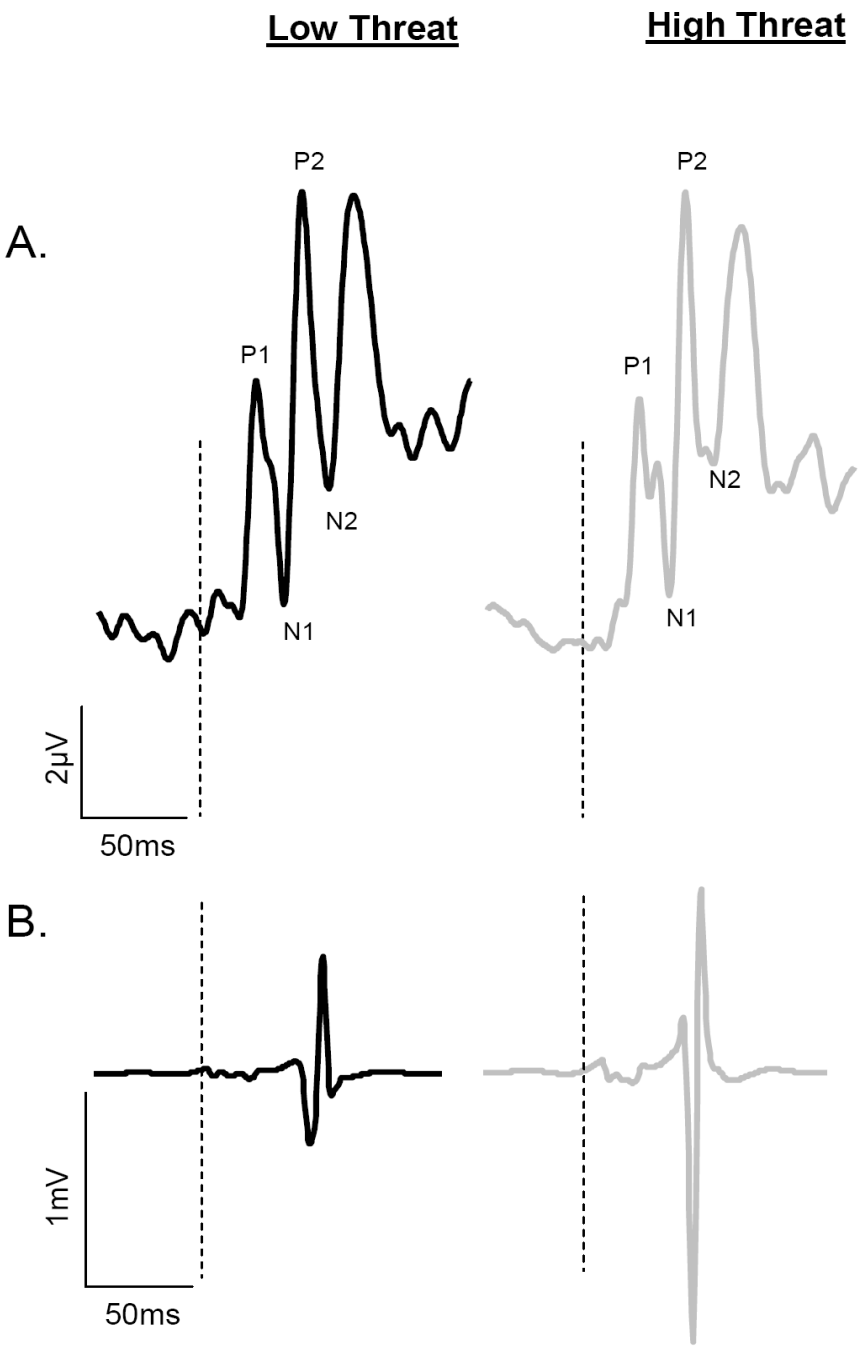

Figure 3.3
Concomitant changes in TEP and STR peak-peak amplitude between low (black traces) and high (grey traces) threat conditions from a representative participant. (A) Changes in TEP P1-N1 and P2-N2 amplitude. Dashed vertical line indicates the time of stimulus onset. (B) Changes in STR peak-peak amplitude. Dashed vertical line indicates the time of stimulus onset.

Figure 3.4: Experiment #1 Mean STR and Background EMG values

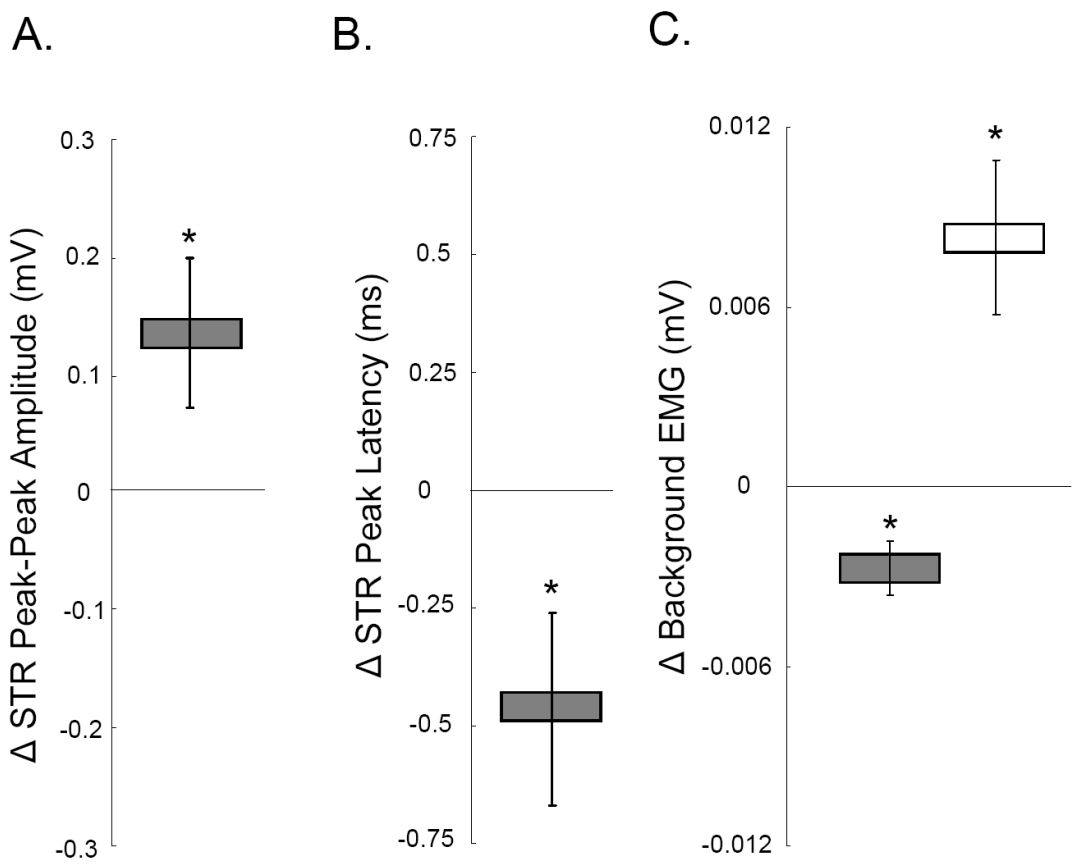

Figure 3.4
(A) Mean change (+/-SEM) of STR peak-peak amplitude between the low threat and high threat conditions. (B) Mean change (+/- SEM) of STR peak latency between the low threat and high threat conditions. (C) Mean change (+/- SEM) of the background EMG activity 100ms prior to stimulus onset for SOL (grey bar) and TA (white bar) between the low threat and high threat conditions. All changes between threat condition were significantly affected by height ($p<0.05$) as indicated by *.

Figure 3.5: Representative SEP, COP and EDA Data

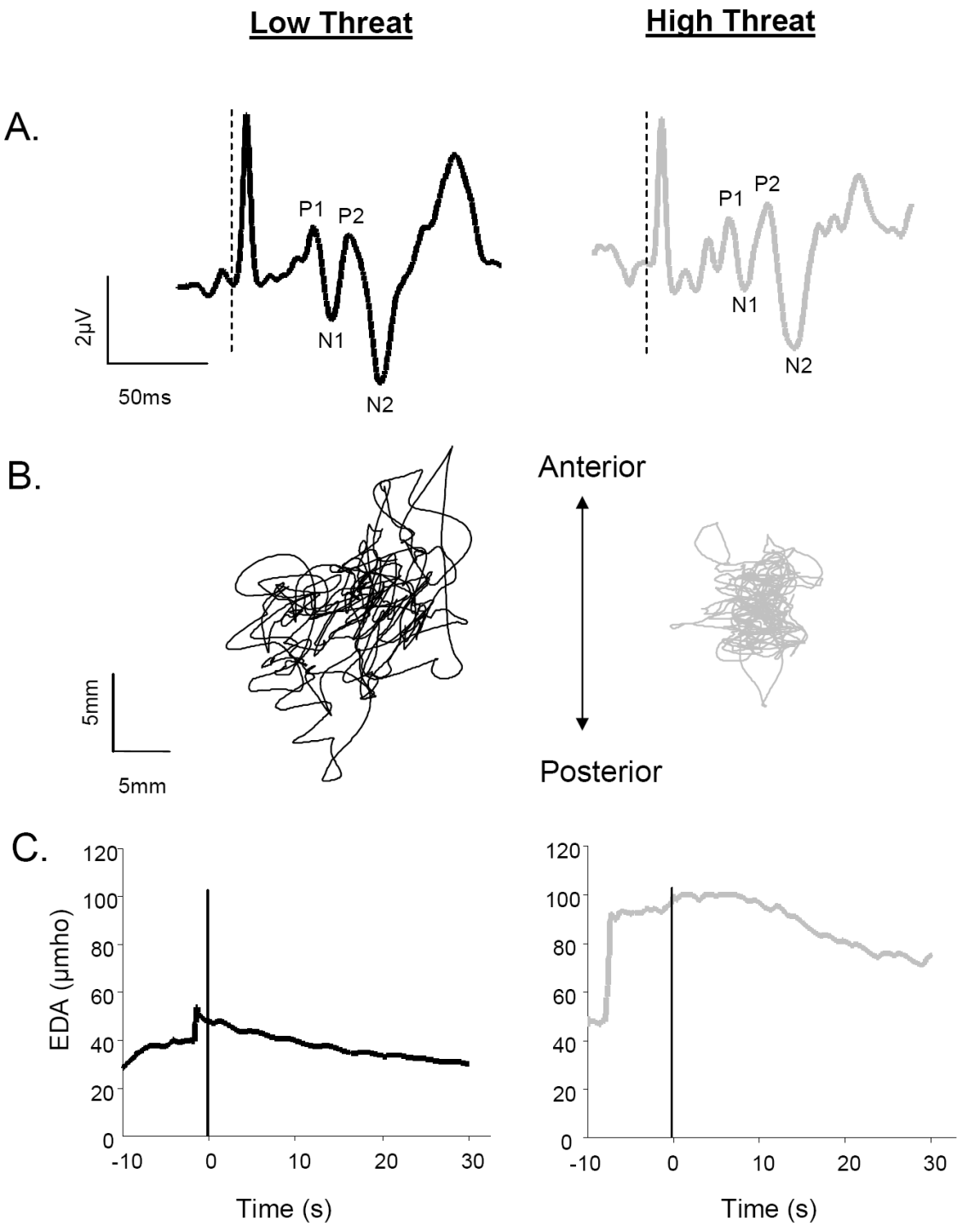

Figure 3.5

Concomitant neurophysiological, physiological and postural changes between low (black traces) and high (grey traces) threat conditions from a representative participant. A) Changes in SEP P1-N1 and P2-N2 amplitude. Dashed vertical line indicates the time of stimulus onset. B) Changes in the pattern of centre of pressure (COP) displacements. C) Changes in mean level of electrodermal activity (EDA). Solid vertical line at time=0 indicates the trial start time.

3.5 Chapter 3 Bridging Summary

In summary, the results from Chapter 3 demonstrate that muscle spindle sensitivity is facilitated when humans stand under conditions of elevated postural threat. However, this increase in spindle sensitivity does not produce a concomitant increase in the magnitude of the afferent volley received by the somatosensory cortex following phasic mechanical stimulation of the spindle. Furthermore, there is no observable change in the cortical sensitivity to incoming afferent information during states of height-induced fear and anxiety, independent of the heightened spindle sensitivity that occurs under such circumstances.

Chapter 4 was designed to delve deeper into the possible proprioceptive adaptations that occur under states of height-induced fear and anxiety. Specifically, in addition to the increase in spindle sensitivity that occurs under states of height-induced fear and anxiety, it appears that additional proprioceptive adaptations are occurring at the level of the lower motor neuron pool. Specifically, the electrical analog of the soleus tendon reflex (STR), the soleus Hoffmann reflex (SOL H-reflex), is attenuated during states of elevated postural threat (Llewellyn et al., 1990; McIlroy et al., 2003; Sibley et al., 2007). This is an interesting observation considering that STR facilitation is observed under similar circumstances (Horslen, 2010, Chapter 3) and that both reflexes involve the same neural pathways. It has been proposed that two well-studied mechanisms, homo-synaptic post activation depression (HPAD) and/or descending pre-synaptic inhibition (PSI) may contribute to the observed threat-associated attenuation of SOL H-reflex excitability (Sibley et al., 2007). The specific aim of Chapter 4 was to test the relative contribution of PSI mechanisms on the lower motor neurons innervating SOL during states of height-induced fear and anxiety. To do so, a threat manipulation, elevated surface heights, was paired with performance of a modified version of the Jendrássik manoeuvre (JM) that is known to dis-inhibit PSI influences. Therefore, if descending PSI is in fact the underlying mechanism responsible for the threat-associated decrease in SOL H-reflex excitability (Sibley et al., 2007; Llewellyn et al., 1990), performance of the JM while standing under conditions of height-induced fear and anxiety should dis-inhibit the typical decrease in SOL H-Reflex sensitivity observed during such states.

The results from this experiment demonstrate that performance of the modified JM potentiates SOL-H-reflex excitability independent of threat condition. However, the results of this study failed to replicate the previously reported threat-associated attenuation of SOL H-reflex excitability (Sibley et al., 2007). Furthermore, a significant interaction between the presence of postural threat and performance of the modified JM was not observed. Therefore, it is not possible to deduce the relative contribution, if any, descending PSI may impose on spinal reflex excitability during states of height-induced fear and anxiety.

CHAPTER 4: USING THE JENDRÁSSIK MANOEUVRE TO DIS-INHIBIT THREAT-ASSOCIATED SOLEUS H-REFLEX ATTENUATION

4.1 Introduction

When participants stand under conditions of height-induced fear and anxiety, they adopt characteristic postural changes that may possibly compromise their stability (Carpenter et al., 1999; 2001; 2006; Adkin et al., 2000; 2002; Brown et al., 2006; Davis et al., 2009; Huffman et al., 2009). Recent work has demonstrated that height-induced fear and anxiety also influences local stretch reflex pathways that may contribute, in part, to the observed changes in postural control. For example, it appears that elevated muscle spindle sensitivity contributes to larger amplitude and shorter latency soleus tendon reflexes (STRs) when participants stand under conditions of elevated postural threat (Horslen, 2010; Chapter 3). However, despite the observed STR facilitation when standing at high heights, a significant decrease in soleus Hoffmann reflex (SOL H-reflex) amplitude has been reported when individuals stand quietly on an elevated surface (Sibley et al., 2007). Furthermore, a decrease in SOL H-reflex amplitude has also been observed in other threatening conditions such as when individuals are faced with the threat of a perturbation during a seated balance control task (McIlroy et al., 2003), or are engaged in a novel, and potentially threatening, gait task that involves walking along a raised narrow beam (Llewellyn et al., 1990). Taken together, this body of work (Llewellyn et al., 1990; McIlroy et al., 2003; Sibley et al., 2007; Horslen, 2010; Chapter 3) suggests that elevated threat produces a differential effect on STR and SOL H-reflex amplitudes.

Recent studies would suggest that the difference in STR and SOL H-reflex excitability observed during states of height-induced fear and anxiety is not related to the changes in tonic soleus (SOL) and tibialis anterior (TA) EMG activity that occur under such circumstances (Horslen, 2010; Chapter 3; Sibley et al., 2007). The reciprocal inhibitory effects of the observed increases in TA EMG activation and the decrease in SOL EMG activation would be expected to inhibit STR excitability (Crone et al., 1987; Romano and Schieppati 1987) not facilitate STR excitability as observed in previous studies involving elevated postural threat (Horslen, 2010; Chapter 3). Similarly, the demonstrated decrease in SOL H-reflex excitability when standing at elevated surface heights was observed only when participants stood with their eyes open and not with their eyes closed despite similar decreases in SOL and increases in TA tonic EMG

activity in both visual conditions (Sibley et al., 2007). Therefore, the observed discrepancy between the effect of elevated fear and anxiety on STR and SOL H-reflex cannot be a simple consequence of the observed changes in tonic SOL and TA EMG activity that occur under such circumstances.

With changes in tonic EMG activity ruled out as a possible explanation, another mechanism that may explain the observed difference between the effect of elevated threat on STR and SOL H-reflex excitability is homo-synaptic post-activation depression (HPAD). HPAD is the result of increased SOL muscle spindle sensitivity causing an increase in tonic Ia afferent firing rates thereby depleting neurotransmitter stores and desensitizing pre-synaptic Ia afferent terminals to phasic electrical stimulation (Hultborn et al., 1996). Previous studies have demonstrated that when muscle spindle sensitivity is experimentally facilitated by having participants perform complex mental arithmetic (Ribot-Ciscar et al., 1986; 2000), STR excitability is facilitated whereas SOL H-reflex excitability can be reduced as a consequence of the HPAD effect associated with increased tonic Ia afferent discharge (Rossi-Durand et al., 2002). Therefore, it is plausible that a similar net effect of increased spindle sensitivity during states of height-induced fear and anxiety may be responsible for the observed increase in STR amplitude (Horslen, 2010; Chapter 3) and decrease in SOL H-reflex amplitude reported under such circumstances (Sibley et al., 2007; Llewellyn et al., 1990).

Alternatively, it could be argued that the observed difference between the effect of elevated threat on STR and SOL H-reflex excitability is related to a descending pre-synaptic inhibitory influence on the SOL lower motor neuron pool. Pre-synaptic inhibition (PSI) occurs when inhibitory interneurons are activated to depolarize the pre-synaptic terminals of the Ia afferents that form mono-synaptic connections onto agonist lower motor neurons (Pierrot-Deseilligny and Burke, 2005). Consequently, PSI results in decreased excitatory neurotransmitter release from Ia afferent terminals and reduced reflex excitability in response to Ia afferent stimulation (Katz. 1988; Rudomin, 1990). In humans, PSI has been reasoned to be one of the main causes of SOL H-reflex depression observed when standing or walking compared to when lying prone or in the supine position (Bove et al., 2006; Faist et al., 1996; Katz et al., 1988). Furthermore, PSI influences on SOL activated by peripheral mechanisms such as heteronymous muscle activation and/or common peroneal nerve stimulation have also been argued to serve as a mechanism to control voluntary movement (Hultborn et al., 1987; Crone and Nielsen, 1989; Meunier and Morin, 1989; Nielsen and Kagamihara, 1993; Nielsen and Petersen, 1994; Morita et al., 1998; Zehr and Stein, 1999). Finally, it has been demonstrated that experimentally induced PSI significantly attenuates SOL H-reflex excitability while STR excitability is relatively preserved (Morita et al., 1998b). Therefore, it is possible that

descending PSI may explain the differential effect of height-induced fear and anxiety on STR and SOL H-reflex sensitivity.

One way to test the relative influence of PSI on SOL H-Reflex excitability during states of elevated postural threat is to introduce a secondary manipulation that is known to modulate the effects of PSI in a predictable way; the Jendrássik Manoeuvre (JM). Contraction of human upper body muscles has long been known to potentiate phasic stretch reflexes of the lower limbs (Zehr and Stein, 1999). As such, it has served as a useful clinical tool to facilitate reflex excitability and much research has been done to better understand the spinal reflex mechanisms that are influenced by performance of the JM (Landau and Clare, 1964; Hagbarth et al., 1975; Kawamura and Watanabe., 1975; Delwaide and Toulouse, 1981; Zehr and Stein, 1996; 1999; Gregory et al., 2001; Nardone and Schieppati; 2008). From this work it has become clear that the timing of JM performance and reflex stimulation is critical to the potentiating effects of the JM (Kawamura and Watanabe, 1975; Delwaide and Toulouse, 1981) and that the potentiating effect of the JM is not achieved through an increase in gamma-motor drive (Hagbarth et al. 1975). Although it has been debated in the literature (Gregory et al., 2001; Nardone and Schieppati, 2008), more convincing experiments involving paired performance of the JM and common peroneal nerve stimulation prior to reflex excitation have demonstrated that PSI is dis-inhibited during JM performance (Zehr and Stein, 1999). From this work it has been argued that the JM potentiates SOL H-reflexes via down-regulation of PSI influences on the SOL lower motor neuron pool (Zehr and Stein, 1999).

Therefore, performance of the JM during states of height-induced fear and anxiety should attenuate any potential threat-associated facilitation of descending PSI that may be the underlying cause of the observed decrease in SOL H-reflex sensitivity observed when participants stand at elevated surface heights (Sibley et al., 2007; Llewellyn et al., 1990). Furthermore, since performance of the JM does not affect gamma-motor drive (Hagbarth et al., 1975), performance of the JM should not interfere with any increases in spindle sensitivity observed during states of height-induced fear and anxiety (Horslen, 2010, Chapter 3).

The specific aim of this study is to test the relative contribution of PSI mechanisms on the lower motor neurons innervating SOL during states of height-induced fear and anxiety by pairing a threat manipulation, elevated surface heights, with performance of the JM. If descending PSI is in fact the underlying mechanism responsible for the threat-associated decrease in SOL H-reflex excitability, performance of the JM while standing under conditions of height-induced fear and anxiety should attenuate the typical decrease in SOL H-Reflex sensitivity observed during such states (Sibley et al., 2007; Llewellyn et al., 1990). Therefore, it is hypothesized that a significant interaction between the presence of threat and performance of the JM will be observed. Specifically, standing under conditions of elevated postural threat

should significantly reduce SOL H-reflex excitability when standing normally, whereas SOL H-reflex excitability should not significantly decrease when performing the JM while standing under the same conditions of threat.

4.2 Methods

4.2.1 Participants

16 healthy young adults (9 female, mean ± SE; age 23.0 ± 1.1 years; height 173.2 ± 2.1cm; and weight 68.8 ± 2.7kg) were recruited from the local undergraduate and graduate student community to participate in the study. All volunteers were free of any relevant neurological, vestibular and/or orthopaedic conditions and were not taking any prescription medication that may have affected their performance during the study. Each participant provided written informed consent prior to testing. The University of British Columbia Clinical Research Ethics Board has approved all experimental procedures.

4.2.2 Experimental Procedure

During testing, participants stood at the edge of a hydraulic lift (2.13m x 1.52m surface area, M419-207B10H01D, Penta-lift, Canada) under two different conditions of postural threat; Low Threat and High Threat. During testing, participants stood in custom-made ankle braces in order to maintain a constant anterior-posterior (A-P) ankle angle throughout the experiment (Figure 3.1). The ankle braces were used because prior studies have shown that participants adopt a characteristic posterior lean when standing at elevated surface heights (Carpenter et al., 1999, 2000, 2006; Adkin et al., 2000; Davis et al., 2009), which if left uncontrolled, might have confounded measurements of SOL H-reflex excitability (i.e. Tokuno et al., 2008). When standing in the Low Threat condition, the hydraulic platform was positioned at its lowest height of 0.8m. Previous work has shown that standing 0.48m away from the edge of a platform raised to a height of 0.8m does not produce a postural effect that is significantly different from when standing on the ground (Carpenter et al., 2001). Therefore, a second support surface (0.61m x 1.52m) was placed directly in front of, and flush with, the front edge of the hydraulic lift in order to minimize any potential threat-associated with standing at a height of 0.8m. During the High Threat condition, participants stood at the edge of the hydraulic lift after it was elevated to a height of 3.2m. For each threat condition participants were instructed to stand quietly with their eyes open and fixated on a target placed at eye level 3.87m in front of them with their arms hanging freely.

Prior to testing, participants performed a grip force calibration trial in which their maximum voluntary grip force was calculated by having them squeeze two custom-made hand grip dynamometers that output a force value to the collection computer (Spike5, CED, UK). During testing in each threat condition, participants received 15-20 SOL H-reflex stimulations separated by a 10-15 second interstimulus interval under two different reinforcement conditions: Reinforced and Control. In the Reinforced condition, participants were cued by an auditory tone (1000Hz, 100ms duration) to perform a modified version of the JM by squeezing the custom-made hand grip dynamometers that were configured to provide an input signal to trigger SOL H-reflex stimulation. Specifically, SOL H-reflex stimulation was delivered to the participant when their exerted grip force reached 10% of their maximum voluntary grip force that was calculated from their grip force calibration trial. This protocol ensured that all SOL H-reflex stimulations in the Reinforced condition were delivered only after participants had initiated the modified JM. Previous studies have demonstrated that SOL H-reflex facilitation with JM reaches its peak ~300ms following cue onset (Kawamura and Watanabe, 1975, Delwaide and Toulouse, 1981). Therefore, individual stimulations were removed from the subsequent analysis if SOL H-reflex stimulation was not triggered within a 150-350ms range from tone onset. In the Control condition, participants did not perform the modified JM. Instead, they simply received a SOL H-reflex stimulation with a random delay of 150-350ms following the auditory tone (1000Hz, 100ms duration) while standing with their hands relaxed by their sides. In total, SOL H-reflexes were evoked in four different experimental conditions; Low Threat Reinforced, Low Threat Control, High Threat Reinforced and High Threat Control.

4.2.3 SOL H-Reflex Stimulation Procedure

SOL H-reflexes were elicited by electrically stimulating the right tibial nerve with a 0.5ms square wave pulse (S88 with SIU5 stimulus isolation unit, Grass, USA). The anode (10cm x 3cm, coal rubber pad, AMG Medical Inc, Canada) was placed just superior to the patella and the Ag/AgCl cathode (0.25cm in diameter, Kendall, USA) was placed in the popliteal fossa. Prior to the experiment, all participants underwent an M-H recruitment curve protocol to determine the stimulus intensity required to evoke their maximal SOL H-reflex peak-peak amplitude (H-max) and their maximal M-wave peak-peak amplitude (M-max). For each participant, a stimulation intensity sufficient to elicit a SOL H-reflex equal to 50% of H-max was identified and used for SOL H-reflex stimulation during testing. 50% of H-max was chosen because reflexes of this size are susceptible to both facilitation and inhibition (Zehr and Stein, 1999). This stimulation intensity was sufficient to evoke an M-wave with a peak-peak amplitude equal to ~5% of M-max (Figure 4.1A).

4.2.4 SOL H-reflex and Background EMG Recording and Analysis Procedure

Surface electromyography (EMG) was used to record the SOL H-reflex from SOL by placing two surface Ag/AgCl electrodes ~2cm apart in a belly-tendon preparation on the right SOL. Background EMG activity in SOL and TA was recorded during each experimental condition to quantify lower-limb muscle activity 100ms prior to stimulus onset. To do so, surface Ag/AgCl electrodes were placed ~0.5cm apart over the muscle bellies of SOL and TA in a belly-belly preparation. All EMG signals were amplified 2000x, sampled at 1000Hz and bandpass filtered between 30-300Hz (Telemyo, Noraxon, USA).

During post-processing (Spike5, CED, UK), the recording from each experimental condition was inspected to remove any individual simulations that did not meet inclusion criteria for use in the calculation of the SOL H-reflex peak-peak amplitude. First the mean peak-peak amplitude of the M-wave evoked during each experimental condition was calculated. Second, a threshold band was placed around the mean value that ranged from ± 2.5% of M-max. Individual stimulations that did not fall within this band were removed from each experimental condition (Figure 4.1B). This two-phase inclusion criteria ensured limited M-wave variability between experimental conditions.

12 participants (6 female, mean ± SE; age 22.5 ± 1.5 years; height 174.3 ± 2.3cm; and weight 69.9 ± 3.5kg) met inclusion criteria. The individual stimulations that remained following inclusion criteria analysis were used to calculate the average SOL H-reflex peak-peak amplitude and corresponding M-wave peak-peak amplitude for each experimental condition for each of these 12 participants. Additionally, the mean level of tonic EMG activity was calculated 100ms prior to simulation onset for both SOL and TA.

4.2.5 Psychosocial Estimates of Height-Induced Fear and Anxiety

Before each experimental condition, participants were instructed to rate how confident they were that they would be able to maintain their balance and avoid a fall during the experimental condition on a scale of 0% (no confidence) to 100% (complete confidence) (Adkin et al. 2002). Immediately following each trial, participants were instructed to rate how stable they felt during the trial on a scale of 0% (very unstable) to 100% (completely stable) and how fearful of falling they were during the trial again on a scale of 0% (completely unafraid) to 100% (extremely afraid) (Adkin et al. 2002). In addition, participants also completed a 16-question survey of their perceived anxiety modified from Smith et al. (1990) and Adkin et al. (2002). Participants scored each question on a scale from 1 (I did not feel this at all) to 9 (I felt this

extremely). The scores from all 16 questions were summed to generate a total score of perceived state anxiety for each experimental condition in each threat condition.
(Note: Measurements of electrodermal activity (EDA) were not analyzed in the current study because the experimental performance of the modified JM precluded accurate recordings from being obtained).

4.2.6 Statistical Analysis

All dependent variables were compared between threat conditions (Low Threat and High Threat) and between reinforcement conditions (Reinforced and Control) using 2x2 repeated measures ANOVAs (SPSS, IBM, USA). Within-subjects effect sizes (Cohen's d values) were calculated for each dependent variable. P-values<0.05 were used to indicate significant differences.

4.3 Results

A significant main effect of threat condition was observed on self-reported state anxiety ($F_{(1,11)}$=7.766, p=0.022, δ=1.045). Participants reported significantly higher state-anxiety scores in the High Threat condition compared to the Low Threat condition, independent of whether they were performing the modified JM in the Reinforced condition or simply standing in the Control condition. Although not significant, participants' self-reported confidence ($F_{(1,11)}$=4.312, p=0.062, δ=0.540) decreased and self-reported fear increased ($F_{(1,11)}$=2.613, p=0.134, δ=0.476). There were no main effects of reinforcement condition or interaction effects between threat condition and reinforcement condition observed on any of the psychosocial measure recorded in this study.

When standing in the Low Threat condition and performing the JM, SOL H-reflex reinforcement was observed for 10 out of the 12 participants included in the study. On average, the peak-peak amplitude of the SOL H-reflex was 1.29 times greater in the Reinforced condition than it was in the Control condition (Figure 4.2). Similarly, when standing in the High Threat condition, SOL H-reflex reinforcement was observed in 9 out of 12 participants. On average, the peak-peak amplitude of the SOL H-reflex was 1.31 times greater in the in the Reinforced condition than it was in the Control condition (Figure 4.2). This observation was confirmed statistically. There was a significant main effect of reinforcement condition on the peak-peak SOL H-reflex amplitude ($F_{(1,11)}$=8.861, p=0.009, δ=0.211). SOL H-reflex amplitude was significantly larger in the Reinforced condition compared to the Control condition, independent of whether participants were standing in the Low Threat or High Threat condition. Despite the significant main effect of reinforcement condition on SOL H-reflex amplitude, M-wave

amplitude was not significantly affected by reinforcement condition ($F_{(1,11)}$=0.708, p=0.418, δ=0.065). Although not significant, there was a trend toward a main effect of threat condition on SOL H-reflex amplitude ($F_{(1,11)}$=2.805, p=0.122, δ=0.120). M-wave peak-peak amplitude was not significantly affected by threat ($F_{(1,11)}$=0.150, p=0.760, δ=0.039). Furthermore, there was no significant interaction between threat condition and reinforcement condition on SOL H-reflex or M-wave amplitudes. Additionally, tonic SOL EMG activity and tonic TA EMG activity were not significantly affected by either Threat condition or Reinforcement Condition.

4.4 Discussion

The specific aim of this study was to determine the potential influence of descending PSI on the SOL lower motor neuron pool as a mechanism to explain the observed attenuation of SOL H-reflex excitability during states of height-induced fear and anxiety (Sibley et al., 2007; Llewellyn et al., 1990). To address this aim, participants performed a modified version of the JM that has been demonstrated to dis-inhibit experimentally induced PSI in humans (Zehr and Stein, 1999).

As predicted, performance of the modified JM was found to potentiate SOL H-reflexes in the majority of study participants, independent of whether they stood in the Low Threat or High Threat condition. This observation corroborates a number of previous studies that have found a potentiating influence of the JM on spinal reflex excitability (Landau and Clare, 1964; Hagbarth et al., 1975; Kawamura and Watanabe, 1975; Delwaide and Toulouse, 1981; Zehr and Stein, 1999; Gregory et al., 2001). However, insights into the interaction between JM reinforcement and height-induced fear and anxiety on the SOL H-reflex (Sibley et al., 2007) were hampered by two unexpected results. First, the results from the current study provided no evidence of attenuated SOL H-reflexes in the High Threat condition in comparison to the Low Threat condition as previously reported (Sibley et al., 2007). Furthermore, the threat manipulation in the current study did not evoke a significant increase in self-reported fear or a significant decrease in balance confidence similar to those that have been reported in previous studies (Carpenter et al., 1999; 2001; Adkin et al., 2000; 2002; Sibley et al., 2007; Davis et al., 2009; Huffman et al., 2009).

4.4.1 The Null Effect of Threat on SOL H-reflex Excitability

The first explanation for why the current study failed to replicate the reported threat-associated attenuation of SOL H-reflex excitability (Sibley et al., 2007) is that the height at which SOL H-reflex sensitivity was tested in the current study, 3.2m, is very different from the 1.6m height at which SOL H-reflex excitability has been tested previously (Sibley et al., 2007). It is

possible that different mechanisms may be engaged by the postural control system that affect SOL H-reflex excitability differently at 3.2m compared to 1.6m. For example, it has been demonstrated that SOL H-reflex excitability is attenuated when humans land from a drop from a height 76cm compared to 31cm (Leukel et al., 2008). As such, it was proposed that the SOL spinal stretch reflex pathway was inhibited as a 'prevention strategy' to protect the tendo-muscular system from injury caused by the high impact load onto the system imposed by a drop jump from 76cm (Leukel et al., 2008). It is not unreasonable to assume that humans are capable of landing a drop jump from a height of 1.6m. However, it would be very unreasonable to assume that humans are capable of landing a drop jump from a height of 3.2m. Therefore, it is possible that in the experiments by Sibley et al. (2007) when participants stood at a height of 1.6m, they adopted a similar 'injury prevention' strategy to dampen SOL stretch reflex excitability to prepare for the possible impact of a fall from such a height (Leukel et al., 2008). However, in the current study, because jumping from a height of 3.2m would have resulted in catastrophic consequences, participants did not adopt such 'injury preventing' adaptations.

Alternatively, the custom-made ankle braces, designed to prevent participants from a posterior lean in the High Threat condition (Davis et al, 2009; Carpenter et al., 1999; 2001; Brown et al., 2006), may have influenced SOL H-reflex sensitivity independent of the threat manipulation. For example, it is reasonable to suspect that cutaneous stimulation caused by the ankle braces may have altered normal afferent contributions from smaller diameter type II and type III fibres to spinal reflex excitability (Burke et al., 1982; Macefield et al., 1998) thereby confounding the typical threat-induced attenuation of the SOL H-reflex (Lewellyn et al., 1990; Sibley et al., 2007). For example, it has been demonstrated that direct stimulation of cutaneous afferents can attenuate PSI influences on spinal reflex excitability (Rudomin, 2009). Furthermore, it is possible that by preventing the threat-associated backward lean that typically occurs when standing under conditions of elevated postural threat, the ankle braces may have also precluded previously unobserved changes in the tonic activation of heteronymous muscle activity that is known to inhibit SOL H-reflex excitability from occurring (Hultborn et al., 1987; Crone and Nielsen, 1989; Meunier and Morin, 1989; Nielsen and Kagamihara, 1993; Nielsen and Petersen, 1994; Morita et al., 1998b; Zehr and Stein, 1999).

4.4.2 The Null Effect of Threat on Self-Reported Fear and Balance Confidence

The threat manipulation used in the current study did not evoke a significant fear response or a significant decrease in balance confidence when participants stood in the High Threat condition compared to the Low Threat condition. Multiple studies have demonstrated that heights of 3.2m (Davis et al., 2009; Huffman et al., 2009) and even heights of only 1.6m

(Carpenter et al., 1999; 2001; Adkin et al., 2000; 2002; Sibley et al., 2007) are sufficient to produce significant increases in self-reported fear and significant decreases in balance confidence. One possible explanation for this null effect is that the custom-made ankle braces may have provided a sense of security in the High Threat condition. However, this explanation is unlikely considering that significant main effects of threat have been observed on both self-reported fear and balance confidence, independent of whether participants stood in custom-made ankle braces or stood freely (Chapter 3).

A second possible explanation for the observed null effect of threat on psychosocial estimates of fear and balance confidence is that the statistical analysis used in the current study was under-powered. Statistically speaking, there were two substantial differences between the current study and previous studies that have used elevated surface heights to manipulate fear and anxiety. First, the observed effect size of the threat manipulation on self-reported fear and balance confidence were δ=0.476 and δ=0.540, respectively. These effect sizes are much smaller than the observed effect size of the threat manipulations on self-reported fear (δ=1.17) and balance confidence (δ=1.57) that have previously been observed in the same experimental paradigm (Chapter 3). Second, the stringent inclusion criteria used in the current study reduced the number of participants included in the final analysis from n=16 to n=12. Previous studies that have investigated the effects of postural threat have used much larger sample sizes (Davis et al., 2009, Huffman et al., 2009; Chapter 3). However, previous studies investigating the effect of elevated postural threat on SOL H-reflex excitability did report significant increases in self-reported fear as well as a significant decrease in SOL H-reflex excitability despite the fact that only 15 participants were included in the analysis (Sibley et al., 2007). Therefore, the fact that the participants in the current study were not as fearful as those in previous studies (Davis et al., 2009; Chapter 3), coupled with the possibility that too few participants were tested, may be the ultimate reason why no significant main effect of height was observed on either self-reported fear or balance confidence.

4.2.3 Conclusion

As predicted, performance of the modified JM was found to potentiate SOL H-reflexes in the current study. However, determining whether performance of the modified JM was capable of attenuating the theoretical influence descending PSI on SOL H-reflexes during states of height-induced fear and anxiety (Sibley et al., 2007) was not possible because of the null effect of the threat manipulation on SOL H-reflex excitability. As mentioned previously, this may have resulted as a consequence of the ankle-braces used in the current study and/or the lack of fearfulness observed among the participants included in the analysis. Therefore, future

studies investigating the effects of elevated postural threat on SOL H-reflex excitability should ensure that adequate levels of fear are reported by study participants. Similarly, a within subject comparison should be made in order to quantify the effect of bracing vs. free stance on SOL H-reflex excitability and determine the relative influence of the custom-made ankle braces on SOL H-reflex excitability. Alternatively, future studies should be conducted to determine the feasibility of using methods other than ankle braces to prevent the threat-associated leaning that occurs during states of height-induced fear and anxiety in order to quantify changes in proprioceptive function under such circumstances.

Figure 4.1: SOL H-reflex Inclusion Criteria

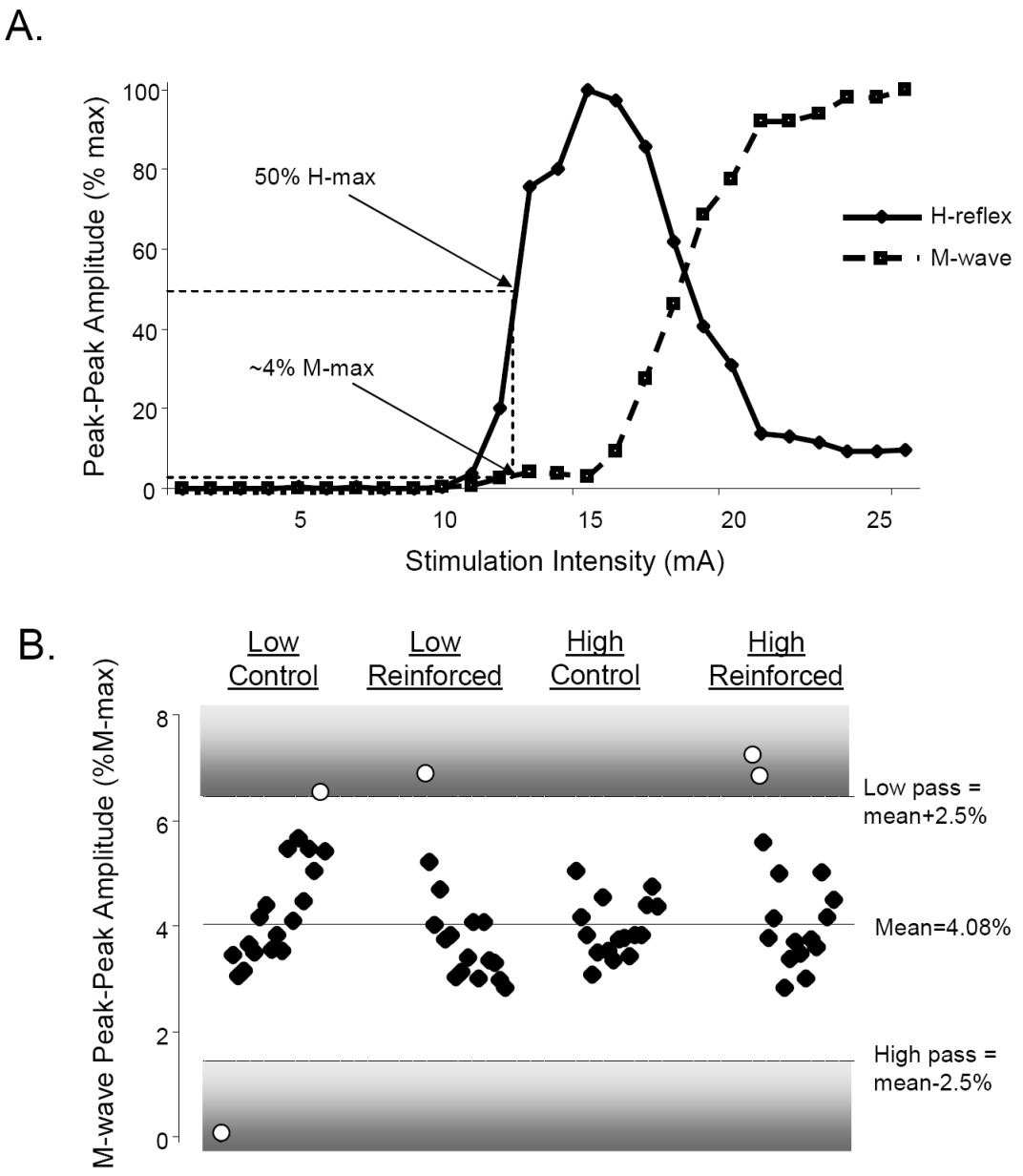

Figure 4.1
A) A typical M-H recruitment curve evoked from a representative participant. The stimulus intensity observed to evoke an H-reflex equal to 50% of H-max (top horizontal dashed bar) was chosen as the stimulus intensity to be used during subsequent testing so long as it was also sufficient to evoke a clearly visible M-wave (bottom horizontal dashed bar). B) A scatter plot of the observed peak-peak M-wave evoked from each stimulation during all four experimental conditions. Individual stimulations that produced an M-wave that did not fall within the inclusion criteria band (open circles ○) were not included in the spike triggered average of the H-reflex with those that did (dark diamonds ◆) for each respective experimental condition.

Figure 4.2: SOL H-Reflex Results

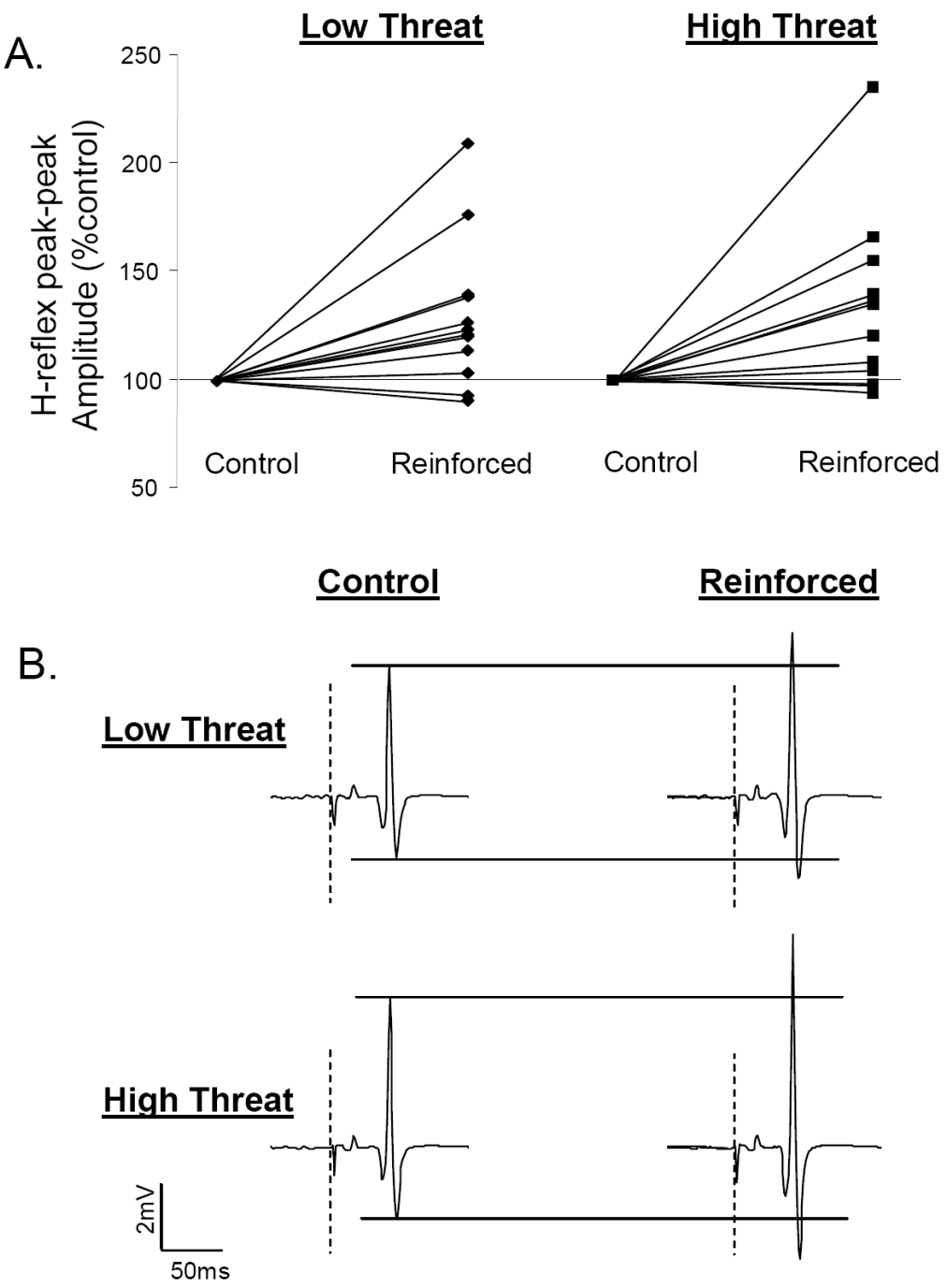

Figure 4.2
A) The change in H-reflex amplitude observed between experimental conditions (Control vs. Reinforced) for each of the 12 participants included in the study. B) Data from a representative participant demonstrating the observed effect of reinforcement. Vertical dashed bars indicate the time of stimulus onset. Horizontal solid bars depict the peak-peak amplitude observed in the Control condition.

4.5 Chapter 4 Bridging Summary

Unfortunately the results of Chapter 4 failed to replicate the typical threat-associated decrease in soleus H-reflex (SOL H-reflex) excitability that has been reported previously (Sibley et al., 2007). For this reason, it is not possible to deduce the relative influence of PSI on the soleus (SOL) lower motor neuron pool despite the fact that performance of the modified JM facilitated SOL H-reflex excitability in both the Low Threat and High Threat condition. As mentioned in the discussion, the failure to replicate the results of Sibley et al. (2007) may have been due to the use of the custom-made ankle braces in the current paradigm. For this reason, Chapter 5 was designed to test the feasibility of using real-time visual feedback of centre of pressure (COP) as an alternative method to prevent the threat-associated posterior lean that occurs at high heights. To do so, the participants in Chapter 5 performed two separate experiments. In Experiment #1 the effect of visual feedback alone, visual feedback-induced leaning and elevated postural threat on COP displacement frequency and amplitude and mean COP position were tested. In Experiment #2 the effect of visual feedback alone, visual feedback-induced leaning and elevated postural threat on SOL H-reflex excitability were tested. The results from Experiment #1 demonstrate that real-time COP visual feedback is indeed an effective tool for controlling mean COP position between heights. However, because visual feedback alone produced such a robust effect on COP displacement amplitude and frequency, it effectively masked the typical effect of elevated postural threat on these two COP summary measures. The results from Experiment #2 demonstrated that neither visual feedback alone, nor elevated postural threat significantly affected SOL H-reflex excitability. However, visual-feedback induced backward leaning significantly attenuated SOL H-reflex excitability. This latter finding sheds new light on the current understanding of the mechanisms that may mediate the previously reported threat-associated attenuation of SOL H-reflex excitability (Sibley et al., 2007).

CHAPTER 5: THE EFFECTIVENESS OF VISUAL FEEDBACK TO CONTROL THREAT-ASSOCIATED LEANING

5.1 Introduction

When humans stand at elevated surface heights they adopt a characteristic posterior shift in their mean anterior-posterior (A-P) centre of pressure (COP) position reflecting a backward lean away from the source of postural threat (Carpenter et al., 1999; 2001; 2006; Adkin et al., 2000; 2002; Brown et al., 2006; Davis et al., 2009; Huffman et al., 2009). This biomechanical change in posture is problematic for studies designed to investigate changes in spinal reflex pathways and proprioceptive function under such circumstances. More specifically, it is difficult to attribute observed changes in spinal reflex excitability as functional proprioceptive adaptations in response to elevated postural threat because of the possible confounding effects of leaning. For example, it has been demonstrated that the direction of COP displacement during stance significantly influences soleus H-reflex (SOL H-reflex) excitability (Tokuno et al., 2007; 2008). Additionally, it has been observed that there is a significant increase in tibialis anterior (TA) and a significant decrease in soleous (SOL) tonic muscle activity when standing freely at elevated surface heights (Carpenter et al., 2001). Both the reciprocal inhibitory influence of increased tonic TA activation and the level of tonic SOL activation have been documented to influence spinal reflex excitability (Crone et al., 1987; Romano and Schieppati 1987). Therefore, if not controlled for, it is not possible to interpret whether observed changes in spinal reflex excitability are associated with height-induced fear and anxiety, or changes in lower limb biomechanics and muscle activity due to the posterior shift in COP that occur when standing under conditions of height-induced fear and anxiety. It may also be possible that the backward lean drives the observed increase in frequency and decrease in amplitude of A-P COP displacement observed when standing at elevated surface heights (Davis et al, 2009; Carpenter et al., 1999; 2000; Brown et al., 2006). Therefore, by controlling the backward lean between threat conditions it will be possible to determine whether the characteristic increase in frequency and decrease in amplitude of COP displacement and decrease in SOL H-reflex excitability that occur in high threat conditions are simply artifacts of the posterior COP displacement and backward lean that occur in such situations.

For these reasons, previous studies investigating potential changes in spinal reflex excitability and proprioceptive function under conditions of height-induced fear and anxiety

(Horslen, 2010; Chapter 3) have used custom-made ankle braces designed to prevent study participants from adopting the characteristic threat-associated posterior COP displacement that typically occurs under such circumstances (Carpenter et al., 1999; 2001; 2006; Adkin et al., 2000; 2002; Brown et al., 2006; Davis et al., 2009; Huffman et al., 2009). However, using ankle braces may not have been the optimal tool to control the threat-associated backward lean considering that both these studies failed to replicate the effect of height-induced fear and anxiety on SOL H-reflex excitability similar to that previous reported (Lewellyn et al., 1990; Sibley et al., 2007). It is reasonable to suspect that cutaneous stimulation caused by the ankle braces may have increased afferent contributions from smaller diameter type II and type III fibres thereby reducing PSI influences on spinal reflex excitability (Rudomin, 2009) and confounding the typical threat-induced attenuation of the SOL H-reflex (Lewellyn et al., 1990; Sibley et al., 2007). Alternatively, it is possible that by preventing the threat-associated backward lean, the ankle braces may have also precluded previously unobserved changes in the tonic activation of heteronymous and homonymous muscle activity that are known to affect SOL H-reflex excitability from occurring (Hultborn et al., 1987; Crone and Nielsen, 1989; Meunier and Morin, 1989; Nielsen and Kagamihara, 1993; Nielsen and Petersen, 1994; Morita et al., 1998; Zehr and Stein, 1999). Therefore, the current study was designed to determine whether it is feasible to control for the threat-associated backward lean by using a method other than ankle braces that may not impose such equally confounding influences.

An alternative way to control for the threat-associated backward lean is to provide participants with real-time visual feedback of their A-P COP moment recorded online from measured ground-reaction forces. For example, it has been demonstrated that humans can use online visual feedback of their COP to make voluntary direction-specific shifts in their mean COP position (Duarte and Zatsiorsky; 2002: Latash et al., 2003). Therefore, by providing participants with real-time visual feedback of their mean A-P moment in the current paradigm, it will be possible for participants to shift their mean A-P COP position backward while standing in a low threat situation to a mean position equal to that observed when they stand at 3.2m. Shifting one's COP forward when standing under conditions of elevated postural threat may be difficult for participants who have a robust fear of heights (e.g. they would be unwilling to not lean back from the edge of the elevated lift).

Therefore, the specific aims of this study were to: 1) validate the effectiveness of providing real-time visual feedback of the mean A-P moment as a means to control for leaning across threat conditions; 2) further clarify an existing ambiguity with respect to the characteristic COP changes that occur during states of height-induced fear and anxiety; and 3) determine whether controlling for the threat-associated lean by providing participants with visual feedback

of their A-P COP moment will prove to be an effective method to clarify existing uncertainties regarding the effects of height-induced fear and anxiety on SOL H-reflex excitability.

The current study used two separate experiments to determine the effect of visual feedback, backward leaning and height-induced fear and anxiety first on participants' COP measures and second on their SOL H-reflex excitability. It is hypothesized that visual feedback will not significantly influence the frequency and amplitude of COP nor will it significantly affect SOL H-reflex excitability. Based on pilot work and the results of Sibley et al. (2007), it was hypothesized that the backward lean will not influence the frequency or amplitude of COP displacement but will result in a decrease in SOL H-reflex excitability. And finally, it was hypothesized that when the threat-associated backward lean is controlled for between threat conditions, the imposed height-induced fear and anxiety will result in an increase in the frequency and a decrease in the amplitude of COP displacement and a decrease in SOL H-Reflex excitability.

5.2 Methods

5.2.1 Participants

15 volunteers (9 male, mean ± SE; age 22.8 ± 0.7 years, height 173.7 ± 2.6cm; and weight 70.8 ± 3.6kg) agreed to participate in this study. Each participant completed a subject information sheet surveying their medical history prior to testing. Participants were excluded from the study if they reported any known neurological, vestibular and/or orthopaedic impairments or were on prescription medication that may have affected their balance at the time of testing. Each participant provided written informed consent prior to testing. The University of British Columbia Clinical Research Ethics Board approved all experimental procedures.

5.2.2 Experimental Procedure

Participants underwent two separate experimental protocols in this study. In Experiment #1, the effectiveness of using visual feedback of participants' centre of pressure (COP) to control the threat-associated posterior COP was tested. In Experiment #2, the effects of visual feedback of COP, leaning and height-induced fear and anxiety on H-Reflex sensitivity were tested.

5.2.3 Experiment #1

In Experiment #1, participants were instructed to stand quietly for two minutes on a force plate (#K00407, Bertec, USA) placed at the edge of a hydraulic platform (2.13m x 1.52m

surface area, M419-207B10H01D, Penta-lift, Canada) under two different conditions of postural threat; Low Threat and High Threat. During the Low Threat condition the hydraulic platform was resting at its lowest height (0.8m). Previous work has shown that standing 0.48m away from the edge of a platform at a height of 0.8m does not produce a postural effect that is significantly different from when standing on the ground (Carpenter et al., 2001). Therefore, a second support surface (0.61m x 1.52m) was placed in front of, and flush, with the front edge of the platform in order to minimize any imposed threat-associated with standing at a height of 0.8m. During the High Threat condition, participants stood at the edge of the hydraulic lift after it was elevated to a height of 3.2m.

Prior to the experiment, participants performed two calibration trials where they stood in the Low Threat condition for 120s and in the High Threat condition for 120s without visual feedback. The mean A-P moment for each threat condition was calculated from the data collected during the two calibration trials (Spike 5, CED, UK).

Following the two initial calibration trials, participants performed four experimental trials. The first three experimental trials were performed in the Low Threat condition. In each trial, participants stood for 120s and received different forms of visual feedback: No visual feedback (NVFB); visual feedback of the mean A-P moment recorded during the Low Threat calibration trial (VFBL); and visual feedback of the mean A-P moment recorded during the High Threat calibration trial (VFBH). The order of the first three experimental conditions was counter balanced to minimize any potential order effects. After completing the first three experimental trials, participants stood in the fourth and final experimental condition. In this condition, participants stood in the High Threat condition with visual feedback of their mean A-P moment recorded during the High Threat calibration trial (HVFBH).

During all four experimental trials, participants stood 3.87m from a real-time visual projection (EPSON, USA) of their A-P moment on the wall in front of them (Figure 5.1). Participants were instructed to keep their oscillating A-P moment within a target window equal to the mean ± 1SD of their A-P moment recorded during each respective calibration trial. The visual projection of the oscillating A-P moment signal was visually low-pass filtered (5Hz) to ensure that participants did not respond to high frequency oscillations on the screen. The projection on the wall was 200cm tall x 104cm wide. Participant's feet were placed at the edge of the forceplate and stance width was equal to their foot length. The area of their foot position was kept constant for all standing trials.

5.2.4 COP Measures

Ground reaction forces and moments recorded during both calibration trials and all four experimental trials were sampled at 100 Hz (Power 1401, CED, UK) and low-pass filtered offline using a 5 Hz dual-pass Butterworth filter (MatLab, Mathworks, USA) before calculating centre of pressure (COP) in the A-P direction. Mean position of the COP during each trial was calculated in the A-P direction and subtracted from the COP signal. From this unbiased signal, the Root Mean Square (RMS) and Mean Power Frequency (MPF) of COP displacements were calculated in the A-P direction.

5.2.5 EMG Recording and Analysis Procedure

The tonic electromyographic (EMG) activity of SOL and TA was recorded during each standing trial to quantify the amount lower-limb muscle activity observed while standing during both calibration trials and all four experimental trials. Surface Ag/AgCl electrodes were placed ~0.5cm apart over the muscle bellies of SOL and TA. All EMG signals were amplified 2000x, sampled at a 1000Hz (Telemyo, Noraxon, USA) and band-pass filtered between 30-300Hz (Spike5, CED, UK). The mean level of tonic activity observed in both SOL and TA was calculated over the entire 120s duration of each calibration and experimental trial.

5.2.6 Physiological and Psychosocial Estimates of Height-Induced Fear and Anxiety

Prior to each calibration and each experimental trial, participants were asked to rate how confident they were that they could maintain their balance to avoid a fall on a scale of 0% (no confidence) to 100% (complete confidence) (Adkin et al. 2002). After each of the 6 trials, participants were instructed to rate how stable they felt on a scale of 0% (very unstable) to 100% (completely stable) and how fearful of falling they were during the trial again on a scale of 0% (completely unafraid) to 100% (extremely afraid) (Adkin et al. 2002). In addition, participants were also asked to complete a 16 question survey of their perceived anxiety modified from Smith et al. (1990) and Adkin et al. (2002). Participant's scored each question on a scale from 1 (I did not feel this at all) to 9 (I felt this extremely). The scores from all 16 questions were summed to generate a total score of perceived anxiety for each of six standing trials.

Participants mean level of electrodermal activity (EDA) was recorded during each of the calibration and experimental trials in order to validate the psychosocial reports of perceived confidence and anxiety. Participants were fitted with disposable recoding electrodes on the thenar and hypothenar eminences to measure their skin conductance (2502 Skin Conductance

Unit, CED, UK) with a range of 0-100 μmho and at a sampling frequency of 1000Hz. Mean EDA was calculated from a 120s window over each of the six standing trials.

5.2.7 Statistical Analysis

To measure the effect of elevated postural threat independent of the visual feedback manipulation, all dependent variables were first compared between the Low Threat and High Threat calibration trials using paired-samples t-tests (SPSS, IBM, USA). The secondary analysis in this experiment was designed to address three specific questions: 1) what effect does visual feedback of COP have on COP summary measures?; 2) what effect does the threat-associated posterior lean have on COP summary measures?; and 3) what effect does height-induced fear and anxiety have on COP summary measures when the threat-associated posterior COP shift is controlled for using visual feedback? Therefore, planned comparisons were made between specific visual conditions using paired-samples t-tests to answer these specific questions. To address question #1, the effect of visual feedback on COP summary measures was compared between the VFBL condition and NVFB condition. In this analysis, participants stood in the same threat condition (Low Threat) with the only difference being the availability of visual feedback of their COP. To address question #2, the effect of leaning was quantified by comparing the VFBH condition and VFBL condition. In both conditions, participants were provided with visual feedback and stood in the same threat condition (Low Threat) with the only difference being the mean COP position participants were instructed to maintain. To address question #3, the effect of height-induced fear and anxiety when visual feedback was available was as quantified by comparing the HVFBH condition to the VFBH high condition. In this analysis, participants were provided with the same visual feedback of their A-P moment recorded during the High Threat calibration trial, with the only difference being the threat condition under which they stood (High Threat vs. Low Threat). Within-subjects effect sizes (Cohen's d values) were calculated for each dependent measure. P values < 0.05 were used to indicate significant differences for all comparisons.

5.2.8 Experiment #2

During the second experiment, participants stood in each of the four experimental conditions described in Experiment #1 (NVFB, VFBL, VFBH and HVFBH) while their SOL H-reflex sensitivity was tested.

5.2.9 SOL H-Reflex Stimulation Procedure

SOL H-reflexes were elicited by electrically stimulating the right tibial nerve with a 0.5ms square wave pulse (S88 with SIU5 stimulus isolation unit, Grass, USA). The anode (10cm x 3cm, coal rubber pad, AMG Medical Inc, Canada) was placed just superior to the patella and the Ag-AgCl cathode (0.25cm in diameter, Kendall, USA) was placed in the popliteal fossa. Prior to the experiment, all participants underwent an M-H recruitment curve protocol to determine the stimulus intensity required to evoke their maximal SOL H-reflex peak-peak amplitude (H-max) and their maximal M-wave peak-peak amplitude (M-max). For each participant, a stimulation intensity sufficient to elicit a SOL H-reflex equal to 50% of H-max was identified and used for SOL H-reflex stimulation during testing. 50% of H-max was chosen because reflexes of this size are susceptible to both facilitation and inhibition (Zehr and Stein, 1999). This stimulation intensity was sufficient to evoke an M-wave with a peak-peak amplitude equal to ~5% of M-max.

5.2.10 SOL H-reflex and Background EMG Recording and Analysis Procedure

Surface electromyography (EMG) was used to record the SOL H-reflex by placing two surface Ag/AgCl electrodes ~2cm apart in a belly-tendon preparation on the right SOL. Background EMG activity in SOL and TA was recorded during each experimental condition to quantify lower-limb muscle activity 100Ms prior to stimulus onset. To do so, Surface Ag/AgCl electrodes were placed ~0.5cm apart over the muscle bellies of SOL and TA in a belly-belly preparation. All EMG signals were amplified 2000x, sampled at a 1000Hz and band-pass filtered between 30-300Hz (Telemyo, Noraxon, USA).

During post-processing (Spike5, CED, UK), data from each of the four experimental trials were inspected to remove any individual simulations that did not meet inclusion criteria for use in the calculation of the average of the SOL H-reflex. The inclusion criteria analysis was performed in a two-phase process. First the mean peak-peak amplitude of the M-wave evoked during each experimental condition was calculated. Second, a band was placed around the mean value that ranged from ± 2.5% of M-max. Individual stimulations that did not fall within this band were removed from each experimental condition. This two-phase inclusion criteria ensured limited M-wave variability between experimental trials.

9 participants (6 male, mean ± SE; age 22.8 ± 1.0 years, height 176.1 ± 3.6cm; and weight 74.8 ± 4.4kg) passed inclusion criteria analysis. The individual stimulations that remained following inclusion criteria analysis were used to calculate the average SOL H-reflex peak-peak amplitude and corresponding M-wave peak-peak amplitude in each experimental condition for each of the 9 participants. Additionally, the mean level of tonic EMG activity was calculated 100ms prior to simulation onset for both SOL and TA.

5.2.11 Statistical Analysis

The effect of visual feedback, leaning and height-induced fear and anxiety on SOL H-reflex peak-peak amplitude were quantified using the same planned comparisons described for Experiment #1. Within-subjects effect sizes (Cohen's d values) were calculated for each dependent measure. P-values<0.05 were used to indicate significant differences.

5.3 Results

5.3.1 Experiment #1: The Effects of Visual Feedback on COP

There was a significant difference observed between the Low Threat and High threat calibration trials for participants self-reported anxiety ($t_{(8)}$= -3.451, p=0.009, δ=1.37), confidence ($t_{(8)}$= 2.753, p=0.025, δ=1.06) and fear ($t_{(8)}$= -4.527, p=0.002, δ=1.51) whereby participants reported significantly greater fear and anxiety and significantly lower confidence in the High Threat compared to the Low Threat calibration trial. Although not significant, there was a trend toward a larger EDA response in the High Threat condition compared to the Low Threat condition ($t_{(8)}$= -2.184, p=0.061, δ=0.65). A significant difference between calibration trials was also observed on the COP summary measures (Figure 5.2). Specifically, the mean A-P position was significantly displaced in the posterior direction when standing in the High Threat compared to the Low Threat calibration trial ($t_{(8)}$= -4.033, p=0.004, δ=0.081). The MPF of A-P COP displacement was significantly greater in the High Threat compared to Low Threat calibration trial ($t_{(8)}$= -4.613, p=0.002, δ=1.08) while the RMS of A-P COP displacement was not significantly different ($t_{(8)}$= -1.059, p=0.321, δ=0.16). Furthermore, the mean level of tonic SOL EMG activity was significantly lower in the High Threat compared to Low Threat calibration trial ($t_{(8)}$= 2.732, p=0.026, δ=0.61). There was no significant difference in the mean level of tonic TA activity between the High Threat and Low Threat calibration trials ($t_{(8)}$= -1.810, p=0.108, δ=0.61).

5.3.2 The Effect of Visual Feedback

In the secondary analysis, the effect of visual feedback of the A-P moment on their COP summary measures was compared. As expected, it was found that the presence of visual feedback did not affect any of the psychosocial estimates of fear and anxiety or their EDA response. Additionally, there was a significant effect of visual feedback on participants' COP summary measured (Figure 5.3). Specifically, visual feedback significantly increased the MPF of A-P COP displacement ($t_{(8)}$= -5.070, p=0.001, δ=2.17) and significantly decreased the RMS of A-P COP displacement ($t_{(8)}$= 2.651, p=0.029, δ=2.29) (Figure 5.3BC). However, visual

feedback did not significantly affect the mean A-P COP position ($t_{(8)}$= 0.247, p=0.811, δ=0.07) (Figure 5.3A). Furthermore, neither the mean level of tonic SOL EMG activation ($t_{(8)}$= -0.686, p=0.512, δ=0.18) or TA EMG ($t_{(8)}$= -1.447, p=0.186, δ=0.46) activation were significantly affected by visual feedback (Figure 5.4A). Furthermore, there were no significant effects on any of the psychosocial estimates of fear and anxiety or mean level of EDA when participants were provided with visual feedback compared to when they were not.

5.3.3 The Effect of Leaning

As expected, visual feedback of the A-P COP moment proved to be an effective tool for controlling mean A-P COP position. Specifically, when participants stood in the Low Threat condition and were provided with visual feedback of their A-P moment recoded from the High Calibration trial, participants mean A-P COP position was significantly shifted in the posterior direction ($t_{(8)}$= -4.832, p=0.001, δ=0.83) (Figure 5.3A). Leaning did not significantly affect the MPF ($t_{(8)}$= 0.812, p=0.440, δ=0.18) or RMS ($t_{(8)}$= -0.613, p=0.545, δ=0.17) of COP displacement (Figure 5.3BC). However, leaning did significantly decrease the tonic activation of SOL EMG ($t_{(8)}$= 5.125, p=0.001, δ=0.96) while the mean level of tonic TA EMG activation was not significantly affected ($t_{(8)}$= 0.009, p=0.993, δ=0.003) (Figure 5.4A). Furthermore, leaning did not significantly affect any of the psychosocial estimates of fear and anxiety or participants mean level of EDA.

5.3.4 The Effect of Threat

When participants' mean A-P COP position was held constant via visual feedback, standing under conditions of elevated postural threat significantly increased participants' self-reported anxiety ($t_{(8)}$= -3.376, p=0.010, δ=1.19), self-reported fear ($t_{(8)}$= -2.591, p=0.032, δ=0.86) and EDA ($t_{(8)}$= -3.206, p=0.012, δ=0.32) and significantly decreased balance confidence ($t_{(8)}$= 2.559, p=0.034, δ=0.80). However, despite the presence of visual feedback that was intended to ensure participants maintained a constant A-P COP position between threat conditions, the mean A-P COP position was significantly further from the edge of the hydraulic lift when standing in the High Threat condition ($t_{(8)}$= -2.910, p=0.020, δ=0.08) (Figure 5.3A). However, increased threat did not significantly affect the MPF ($t_{(8)}$= -1.386, p=0.203, δ=0.30) or RMS ($t_{(8)}$= 1.674, p=0.133, δ=0.59) of A-P COP displacement (Figure 3BC). Elevated threat did not significantly affect either the tonic level of either SOL EMG activation ($t_{(8)}$= -1.458, p=0.183, δ=0.25) or TA EMG activation ($t_{(8)}$= -1.302, p=0.229, δ=0.40) (Figure 5.4A).

Note: A summary of the mean values used to calculate the effect of visual feedback, leaning and threat are provided in Table 5.1

5.3.5 Experiment #2: The Effects of Visual Feedback, Leaning and Threat on SOL H- reflex Sensitivity

5.3.6 The Effect of Visual Feedback

In Experiment #2, the preliminary analysis performed was designed to test the effect of visual feedback on SOL H-Reflex excitability. As hypothesized, visual feedback did not significantly affect any of the psychosocial estimates of fear and anxiety or participants' mean level of EDA. Furthermore, there was no significant effect of visual feedback on the peak-peak SOL H-reflex amplitude ($t_{(8)}$= -1.275, p=0.238, δ=0.05) or M-wave amplitude ($t_{(8)}$= -0.818, p=0.437, δ=0.05) (Figure 5.5). Although not significant, there was a trend toward an increase in the mean level of tonic SOL EMG activation ($t_{(8)}$= -2.207, p=0.058, 0.49) and TA EMG activation ($t_{(8)}$= -1.426, p=0.192, δ=0.47) (Figure 4B).

5.3.7 The Effect of Leaning

The secondary analysis was designed to test whether using visual feedback to induce a posterior lean would affect SOL H-reflex excitability. As predicted, adopting a backward lean did not significantly affect on any of the psychosocial estimates of fear and anxiety or participants' mean level of EDA. However, leaning did significantly reduce SOL H-reflex peak-peak amplitude ($t_{(8)}$= 2.293, p=0.050, δ=0.24) (Figure 5.5). However, there was no significant effect of leaning on the peak-peak amplitude of the M-wave ($t_{(8)}$= 0.552, p=0.596, δ=0.05). Furthermore, leaning significantly reduced the mean level of tonic SOL EMG activation ($t_{(8)}$= 3.183, p=0.014, δ=1.13) but not the mean level of tonic TA EMG activation ($t_{(8)}$= -0.038, p=0.970, δ=0.04) (Figure 5.4B).

5.3.8 The Effect of Threat

In the final analysis, SOL H-reflex excitability was examined between threat conditions while participants' mean A-P COP position was held constant via visual feedback. Standing under conditions of elevated postural threat significantly increased participants' self-reported anxiety ($t_{(8)}$= -5.251, p=0.001, δ=1.47), self-reported fear ($t_{(8)}$= -3.698, p=0.006, δ=1.16) and EDA ($t_{(8)}$= -3.206, p=0.012, δ=0.45) and significantly decreased their balance confidence ($t_{(8)}$= 2.954, p=0.018, δ=0.92). However, there was no significant effect of elevated threat on either

SOL H-reflex peak-peak amplitude ($t_{(8)}$= -0.481, p=0.643, δ=0.04) or M-wave peak-peak amplitude ($t_{(8)}$= 0.632, p=0.545, δ=0.04) (Figure 5.5). Although not significant, there was a trend toward an increase in the mean level of tonic SOL EMG activation ($t_{(8)}$= -1.994, p=0.081, δ=0.55), whereas there was a significant increase in the mean level of TA EMG activation ($t_{(8)}$= -2.371, p=0.045, δ=0.60) (Figure 5.4B).

Note: A summary of the mean values used to calculate the effect of visual feedback, leaning and threat are provided in Table 5.1

5.4 Discussion

5.4.1 The Effects of Visual Feedback, Leaning and Threat on COP

The primary aim of Experiment #1 was to determine whether providing participants with real-time visual feedback of their A-P moment would prove to be a useful tool to prevent the threat-associated posterior COP displacement and backward lean that typically occur when standing under conditions of height-induced fear and anxiety. The results of Experiment #1 demonstrate that participants were able to use visual feedback to shift their mean A-P COP position backward to a location similar to that observed in the High Threat calibration trial. This result confirms that visual feedback is a useful tool for controlling mean A-P COP position (Duarte and Zatsiorsky et al., 2002; Latash et al., 2003). However, despite the fact that this primary aim was achieved, having visual feedback available dramatically changed how participants controlled their posture. Specifically, when visual feedback was available, the MPF of COP displacement observed in the VFBL, VFBH and HFVBH was dramatically larger than that observed when visual feedback was not available in the NVFB condition (Table 5.1). Likewise the RMS of COP displacement observed when visual feedback was available in the VFBL, VFBH and HFVBH conditions was dramatically smaller than that observed in the NVFB condition (Table 5.1). Previous work has demonstrated that when participants receive varying magnifications of COP visual feedback, the MPF of their COP displacement plateaus at ~ 0.4Hz and the RMS of their COP displacement floors out at ~ 2.5mm (Cawsey et al., 2008). Therefore, it is likely that the experimental set-up used in the current study (Figure 5.1) provided visual feedback at a magnification that was sufficient to cause both the MPF and RMS of COP displacement to reach their limits (Table 5.1). As such, the robust effect of visual feedback effectively masked any potential effects of leaning and/or threat on COP as reflected by the null lean effect and null threat effect observed on both the MPF and RMS of COP displacement. Unfortunately, the robust effect of visual feedback on COP displacement precludes any conclusions from being drawn with respect to the secondary aim of Experiment #1 to determine whether the threat-induced backward lean is the underlying cause of the increase in frequency

and decrease in amplitude of A-P COP displacement that are observed when standing at elevated surface heights (Carpenter et al., 1999; 2001; 2006; Adkin et al., 2000; 2002; Brown et al., 2006; Davis et al., 2009; Huffman et al., 2009). However, insight into this question can be drawn from experiments that have evoked a sense of threat among humans without producing a direction-specific shift in COP. For example, it has been demonstrated that viewing affective pictures produces increases in the frequency and decreases in the amplitude of COP displacement despite not causing a direction-specific shift in mean A-P COP position (Horslen, 2010). This finding suggests that the changes in COP frequency and amplitude observed in the current study may not be driven by the threat-associated backward lean. Therefore, in future studies investigating the effects of elevated threat and arousal on COP displacement it is recommended that manipulations other than high heights such as affective pictures and possibly virtual environments be used to evoke a sense of threat among study participants.

5.4.2 The Effects of Visual Feedback, Leaning and Threat on SOL H-reflex Excitability

Despite the fact that the results of Experiment #1 demonstrate that visual feedback is as equally confounding as the threat-associated posterior lean on measurements of COP displacement frequency and amplitude, this was not the case for SOL H-reflex excitability. Specifically, the results from Experiment #2 demonstrate that the availability of visual feedback did not significantly affect SOL H-reflex excitability. Furthermore, when participants' mean A-P position was held constant between threat conditions, elevated postural threat also did not significantly affect SOL H-reflex sensitivity. However, the visual feedback-induced posterior lean did significantly decrease SOL H-reflex excitability.

Taken together, these findings greatly contribute to the current theoretical understanding of how elevated postural threat influences SOL H-reflex excitability. Previous studies that have used custom-made ankle braces to prevent the threat-associated posterior lean (Horslen, 2010; Chapter 3) failed to demonstrate the typical decrease in SOL H-reflex excitability that has been demonstrated when participants stand freely at heights of 1.6m (Sibley et al., 2007). This suggests that by preventing the threat-associated posterior COP displacement and backward lean, the ankle braces may have also precluded previously unobserved changes in tonic activation of heteronymous muscle activity that are known to inhibit SOL H-reflex excitability (Hultborn et al., 1987; Crone and Nielsen, 1989; Meunier and Morin, 1989; Nielsen and Kagamihara, 1993; Nielsen and Petersen, 1994; Morita et al., 1998b; Zehr and Stein, 1999) from occurring at height. For example, when participants keep their feet in place and lean backward, two characteristic changes in lower-limb EMG have been documented: an increase in tonic TA activation and a decrease in tonic SOL activation (Carpenter et al., 2001; Sibley et

al., 2007; Chapter 3). Although it has not been observed experimentally, such a backward lean would also produce an increase in tonic quadriceps activation. According to the model developed by Hultborn et al. (1987), an increase in quadriceps EMG and tonic Ib afferent discharge inhibits SOL H-reflex sensitivity by facilitating peripheral pre-synaptic inhibition (PSI) influences on the SOL lower motor neuron pool. Therefore it is plausible that increases in tonic quadriceps EMG and Ib discharge from activated golgi tendon organs (GTOs) that occur as a consequence of the threat-associated posterior lean facilitates the influence of PSI on the SOL lower motor neuron pool thereby reducing SOL H-reflex excitability. This hypothesis would be supported by the fact that the posterior lean induced by visual feedback in the current study was found to significantly reduce SOL H-reflex excitability. This hypothesis may also explain why SOL H-reflex excitability was observed to decrease when participants when participants stood at a height of 1.6m considering that the mean A-P COP position was not monitored (Sibley et al., 2007) and why no such decrease was observed when leaning was prevented (Horslen, 2010; Chapter 3). In summary, it appears that the threat-associated decrease in SOL H-reflex excitability is a secondary consequence of threat-associated leaning, not a direct consequence of threat. Therefore, EMG should be recorded from heteronymous (e.g. biceps femoris) and homonymous (e.g. rectus femoris) muscles in future studies in order to investigate the relative influence of these two dependent variables as potential mediators of the attenuation of SOL H-reflex excitability during states of height-induced fear and anxiety (Sibley et al., 2007).. Specifically, a within-subjects comparison should be made to test the effect of elevated postural threat on SOL H-reflex excitability when participants stand freely and adopt the threat-associated posterior lean compared to when participants stand in a braced condition to prevent the threat-associated posterior lean.

Table 5.1: Results Summary Measures

	Visual Feedback Condition			
Dependent measure	**NVFB**	**VFBL**	**VFBH**	**HVFBH**
Experiment #1				
mean A-P Position (mm)	-44.17 ± 6.57	-45.31 ± 5.71	-31.27 ± 5.63	-29.80 ± 5.78
A-P MPF (Hz)	0.18 ± 0.03	0.39 ± 0.03	0.37 ± 0.05	0.41 ± 0.05
A-P RMS (mm)	4.81 ± 0.93	2.84 ± 0.29	2.99 ± 0.29	2.60 ± 0.22
Experiment #2				
SOL H-reflex amp. (mV)	5.87 ± 1.20	6.05 ± 1.19	5.12 ± 1.13	5.27 ± 1.11
M-wave amp. (mV)	1.32 ± 0.35	1.37 ± 0.37	1.32 ± 0.32	1.29 ± 0.31

Table 5.1

Mean value (+/-SEM) for all dependent measures observed in the experimental trials: no visual feedback (NVFB); visual feedback from the Low Threat calibration trial (VFBL); visual feedback from the High Threat calibration trial (VFBH) and visual feedback from the High Threat calibration trial while standing under conditions of High Threat (HVFBH). The values represent the mean values that were used in the planned comparisons to quantify the effect of visual feedback (VFBL-NVFB), leaning (VFBH-VFBL) and threat (HVFBH-VFBH) in the statistical analysis.

Figure 5.1: Experimental Set-Up

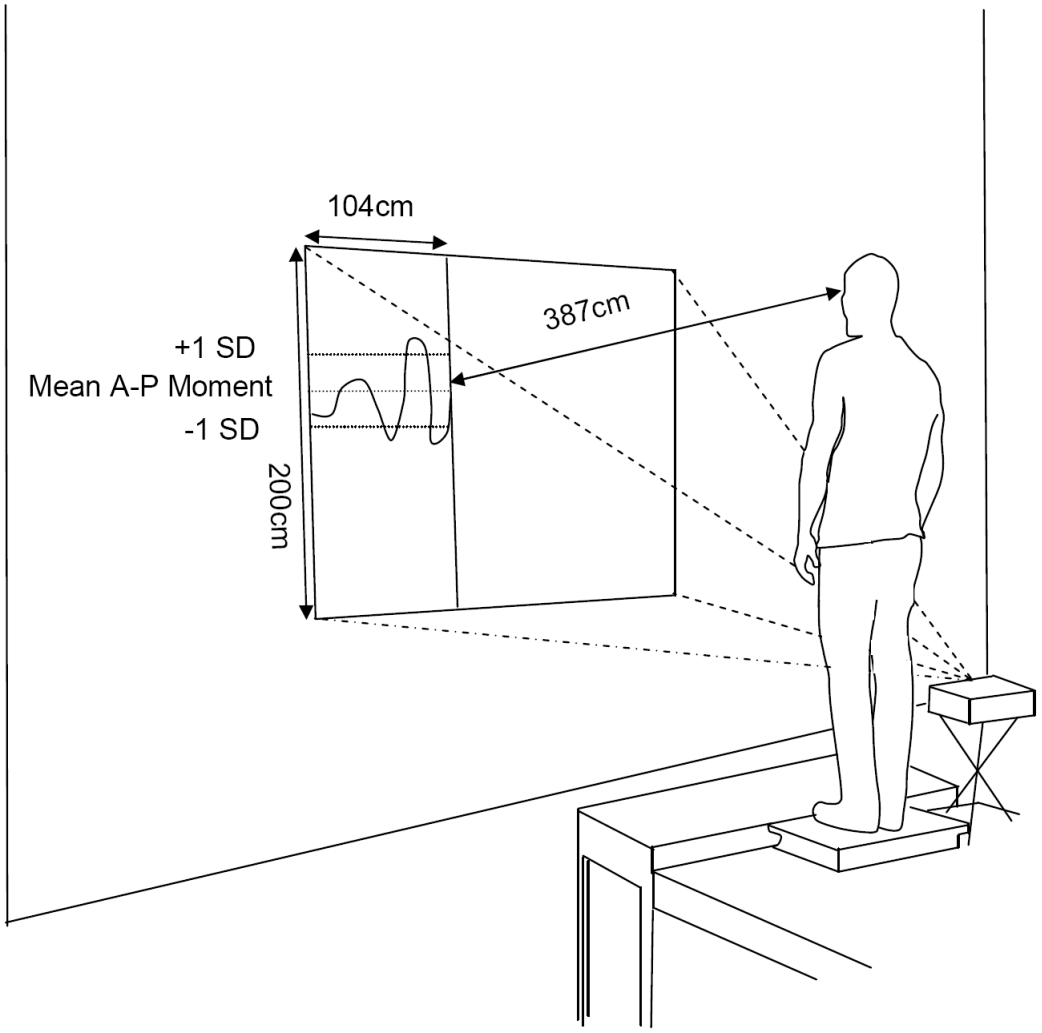

Figure 5.1:
A schematic diagram of the apparatus used to provide participants with real-time visual feedback of the A-P moment recorded from their ground reaction forces. Participants stood 387cm from a real-time projection of their A-P moment that they were instructed to control by keeping the oscillating signal within a band equal to their mean A-P moment recorded during each respective calibration trial ± 1SD.

Figure 5.2: Calibration Trial Summary Measures

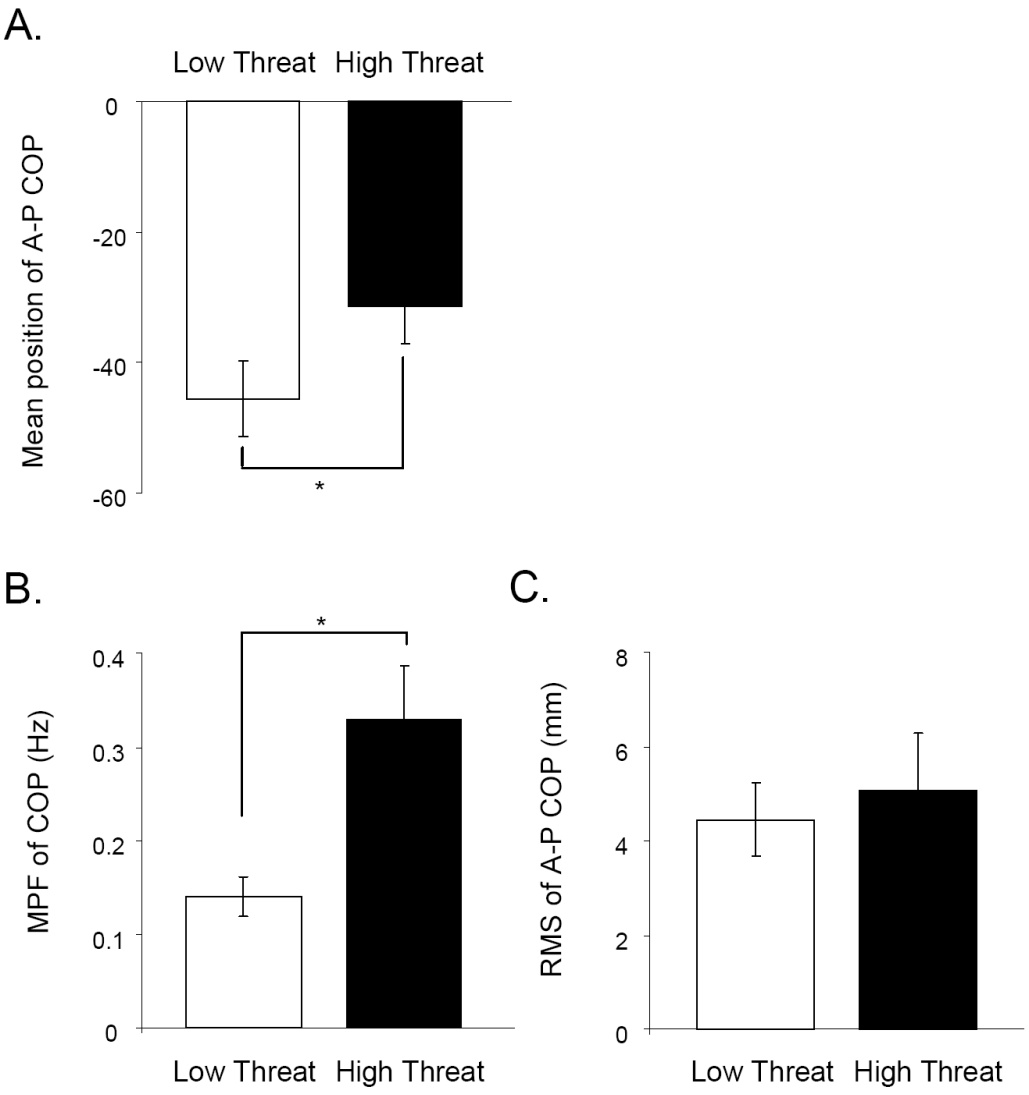

Figure 5.2
A comparison of the average (A) mean position, (B) MPF and (C) RMS of COP in the A-P direction between the Low Threat (white) and High Threat calibration (Black) trials. * indicates significant difference ($p<0.05$).

Figure 5.3: The Effect of Visual Feedback, Leaning and Threat on COP Summary Measures

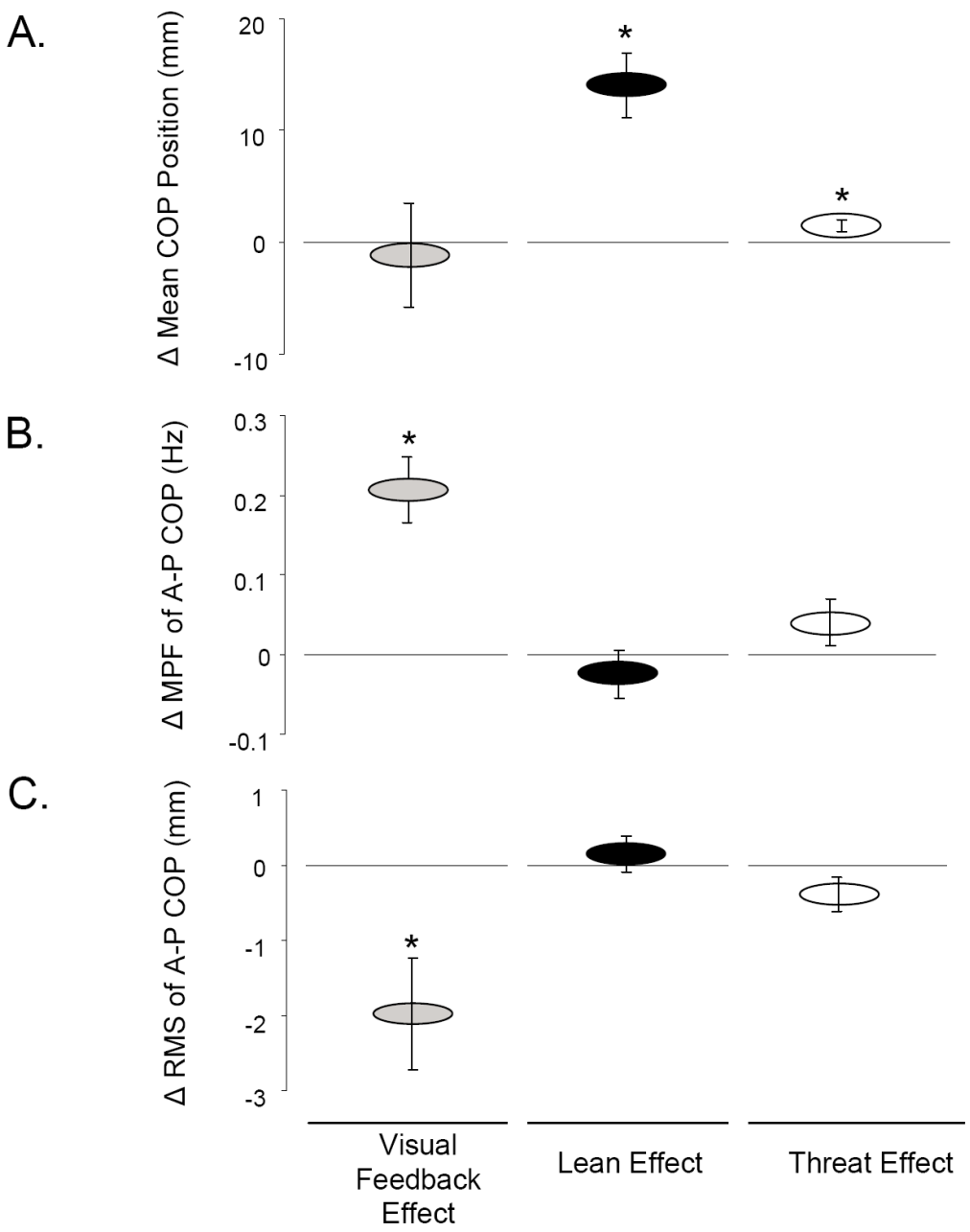

Figure 5.3:
A comparison of the mean change (± SEM) in (A) mean position, (B) MPF and (C) RMS of COP in the A-P direction as a result of visual feedback (grey circles), Leaning (black circles) and elevated postural threat (white circles). * indicates a change that is significantly different from zero ($p<0.05$).

Figure 5.4: The Effect of Visual Feedback, Leaning and Threat on Tonic EMG

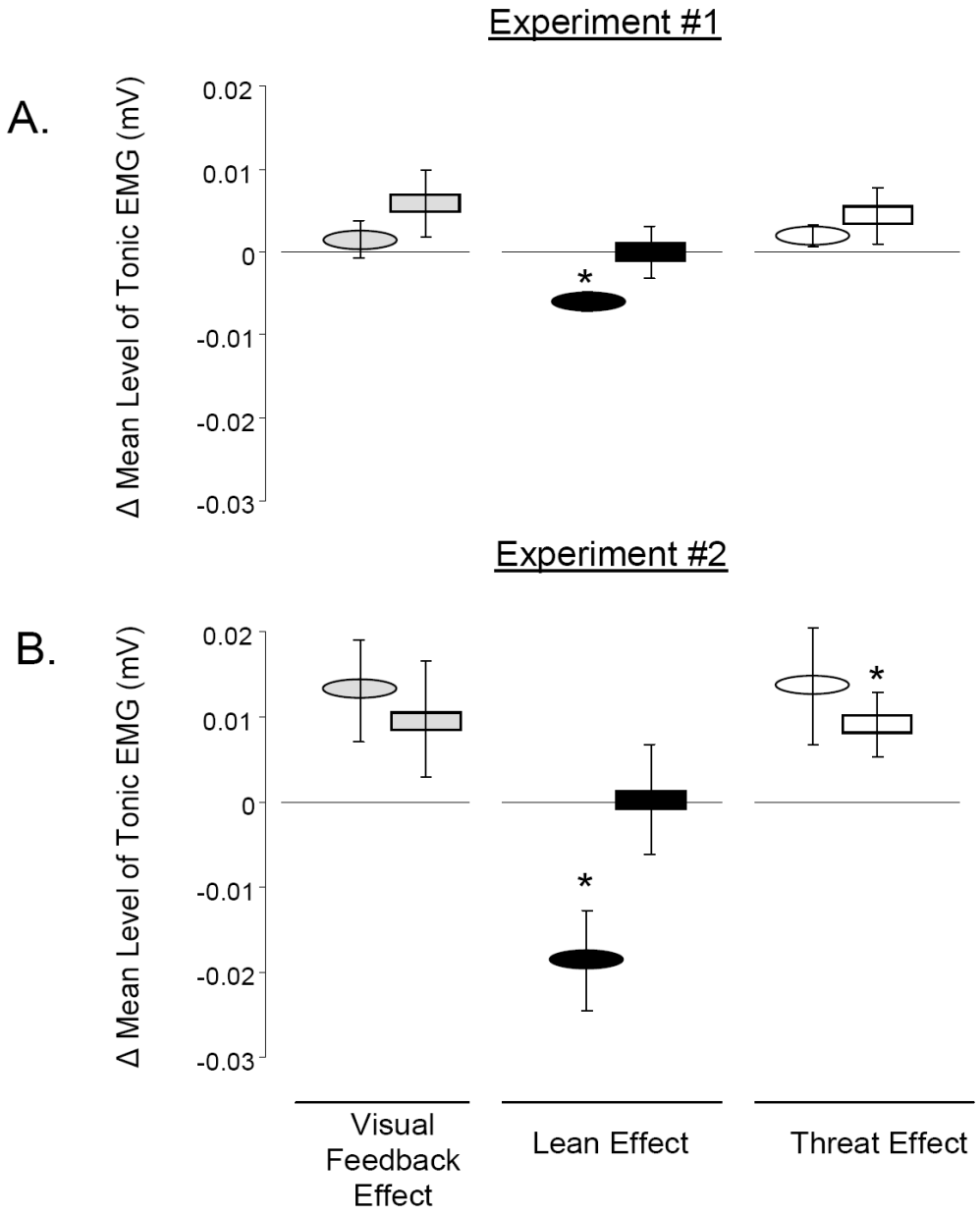

Figure 5.4
A comparison of the change in mean (± SEM) level of tonic EMG observed in soleus (circles) and tibialis anterior (rectangles) as a result of visual feedback (grey), leaning (black) and elevated postural threat (white). A) the results from Experiment #1 and B) the results from Experiment #2. * indicates a change that is significantly different from zero ($p<0.05$).

Figure 5.5: The Effect of Visual Feedback, Leaning and Threat on SOL H-reflex and M-wave Peak-Peak Amplitude

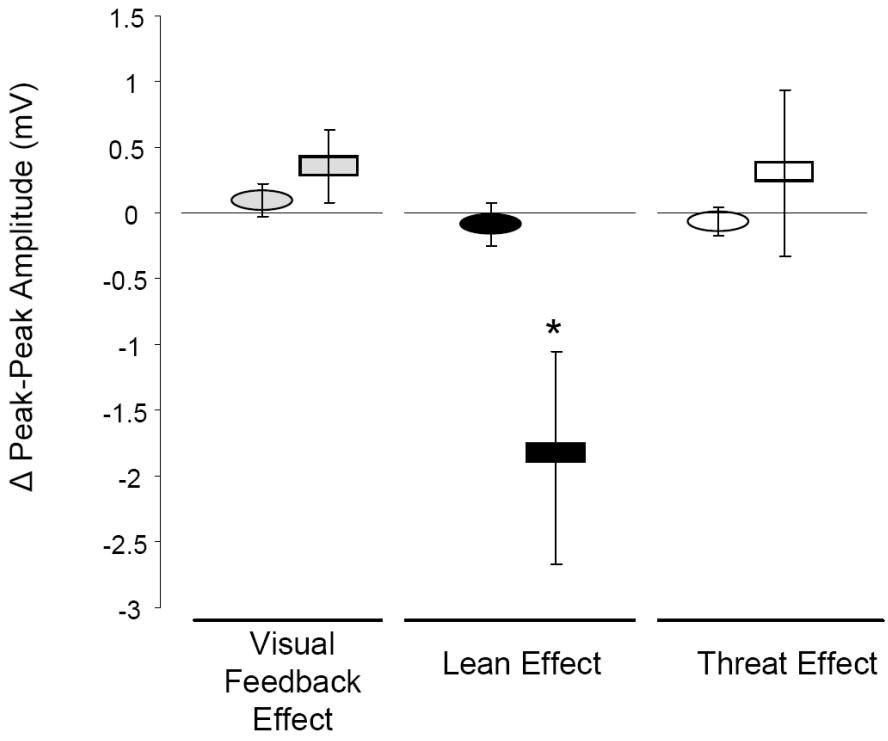

Figure 5.5:
A comparison of the change in mean (± SEM) peak-peak amplitude of the observed M-wave (circles) and H-Reflex (rectangles) as a result of visual feedback (grey), leaning (black) and elevated postural threat (white). * indicates a change that is significantly different from zero ($p<0.05$).

CHAPTER 6: GENERAL DISCUSSION AND CONCLUSIONS

6.1 The Differential Effects of Fear vs. Anxiety on Postural Control

One of the most substantial findings reported in this thesis is that the emotional experience of fear is associated with a very different postural behaviour than that observed in during the emotional experience of anxiety (Chapter 2). This difference in postural behaviour may be explained by the fact that fear and anxiety have different psychological and neuroanatomical underpinnings (Kalin et al., 2001).

Psychologically speaking, fear is elicited immediately by a single stimulus specific cue and lasts as long as the aversive stimulus is present (Rosen & Schulkin, 1998; Rosen, 2004). Whereas anxiety differs from fear in that it is a complex combination of a future-oriented cognitive state, negative affect, autonomic arousal associated with anticipation of upcoming negative events and can linger for extended periods of time (Rosen & Schulkin, 1998; Davis, 1998; Chua et al., 1999).

On the neuroanatomical level, there are also distinct differences in the structures and pathways controlling fear and anxiety (LeDoux, 1995, 1996a, 1996b; Kalin et al., 2001). Specifically, non-human animal work has demonstrated that the central nucleus of the amygdala serves as the major relay nuclei that co-ordinates an integrated fear response (LeDoux 1995, 1996a, 1996b). Similarly, tracing studies investigating the neural connectivity of the central nucleus have identified widespread amygdalar projections to the brainstem and hypothalamus that mediate the unconditioned fear response (LeDoux et al., 1984; Rosen et al., 1991; Sah et al., 2003). The bed nucleus of the stria terminalis (BNST), which is considered part of the extended amygdalar network, has projections that parallel those of the central nucleus to the brainstem and hypothalamus. It is of note that despite the similarity in connectivity, the central nucleus and the BNST are activated by different mechanisms (Lang et al. 2000). Specifically, the BNST is responsive to neuroendocrine signals that do not affect the central nucleus (Lee & Davis, 1997). This fundamental difference makes the central nucleus of the amygdala more likely to be involved in mediating immediate, short-lived fear responses and the BNST more likely to mediate long-term anxiety (Davis, 1998).

This understanding of the connectivity of the neural substrates that mediate fear and anxiety responses are important considering that such studies have revealed connections between the central nucleus of the amygdala and BNST with neural structures known to be

involved in the control of posture, such as the vestibular nuclei, cerebellum, reticular formation and locus coeruleous (Balaban & Beryozkin, 1994; Yates et al., 1994; Balaban, 1996; Porter & Balaban, 1997, Schuerger & Balaban, 1999), either directly or via the parabrachial nucleus (PBN) (Fulweiler & Saper, 1984; Herbert et al., 1990; Moga et al., 1990). Therefore, it is plausible that a height of 3.2m was sufficient to activate the central nucleus of the amygdala of the n=10 fearful participants in Chapter 2 whereas standing at a height of 3.2m was only sufficient to evoke an anxiety response among the remaining n=26 participants. As such, two different postural outcomes were observed as a consequence of activating two different neural pathways to structures known to be involved in the control of standing balance (Balaban and Beryozkin, 1994; Yates et al., 1994; Balaban, 1996; Porter & Balaban, 1997, Schuerger and Balaban, 1999; Fulweiler and Saper, 1984; Herbert et al., 1990; Moga et al., 1990).

This possible difference in the neuroanatomical substrates involved in mediating posture during states of anxiety vs. states of fear extends the current understanding of the postural outcomes during such states and also reconciles multiple discrepancies within the literature. For example, it has already been demonstrated that the magnitude of the increase in frequency and decrease in amplitude of COP displacement observed in response to elevated postural threat is scaled to the height at which individuals stand (Adkin et al., 2002). Specifically, as participants ascend from ground level, to 0.8m, to 1.6m, their posture becomes stiffer and stiffer as characterized by an increase in the frequency and decrease in the amplitude of COP displacement (Carpenter et al., 1999; Adkin et al., 2002). However, in previous studies that measured postural changes while standing at extreme heights of 9m (Nakahara et al., 2000) and 10.2m (Simeonov and Hsiao, 2006), a break-down of the characteristic stiffening strategy (Carpenter et al., 1999) was reported. Although, these two studies (Nakahara et al., 2000; Simeonov and Hsiao, 2006) were confounded by various factors, these findings do provide valuable insights into the roles of fear and anxiety on postural control. Specifically, it appears that as participants ascend to heights of 1.6m they experience anxiety and as such, the increase in anxiety is associated with a proportional increase in the stiffness of their posture (Adkin et al., 2002). However, when participants hit their critical height threshold, i.e. 3.2m for the n=10 fearful participants in Chapter 2, and 9m and 10.2m for all the participants in the studies performed by Nakahara et al. (2000) and Simeonov and Hsiao (2006), individuals switch to a fearful posture characterized by increased frequency of COP displacement and larger COP excursions reflecting a break-down of the stiffening strategy. This would suggest that anxiety is akin to an 'analog emotional response' that can be dialled up or down depending on the level of threat individuals are exposed to and their postural behaviour is scaled accordingly. However, when individuals reach their personal critical height threshold, fear, 'a digital emotional response', kicks in and a different postural behaviour is observed. This switch in posture can

be explained by the neuroanatomical differences mediating fear and anxiety. For example, it is possible that BNST activation occurs in response to the neuroendocrine signals involved in mediating anxiety up until a point where the central nucleus of the amygdala is activated when the critical height threshold is met. As such, two different emotional mechanisms may be involved in controlling posture..

In addition to the emotional differences observed between heights, differences in individuals' focus of attention between heights may also explain the threat-related changes in posture. For example, it is well known that instructing individuals to focus on an attention demanding task during stance can significantly affect their posture (ie. Woollacott and Shumway-Cook, 2002). However, more recent evidence has also demonstrated that instructing individuals to directly focus on their own movements during sway, i.e. adopt and *internal* focus of attention, is associated with increases in sway frequency (Vuillerme and Nafati, 2007). Considering that standing at elevated surface heights is associated with individuals adopting a more conscious control of posture (Huffman et al., 2009), it is possible that a shift towards a more internal focus of attention as well as an emotional response, may be associated with the postural outcomes observed during states of height-induced fear and anxiety.

6.2 Do the Proprioceptive Adaptations Observed Explain the Postural Outcomes Observed during States of Elevated Postural Threat?

One of the primary aims of this thesis was to determine whether the proprioceptive system adapts during states of height-induced fear and anxiety (Chapter 3) and whether this adaptation is in part responsible for the characteristic postural changes observed under such circumstances (Chapter 2). The results from Chapter 3 clearly demonstrate that muscle spindle sensitivity does indeed increase when humans stand under conditions of elevated postural threat. However, it is important to note that the participants recruited for Experiment #1 of Chapter 3 did not report a robust emotional experience of fear comparable to that reported by the n=10 fearful participants identified in Chapter 2. As such, the observed spindle facilitation in Chapter 3 may provide some insight into the underlying mechanisms that produce the observed changes in posture when participants experience elevated anxiety, not fear, when standing at high heights. For example, the observation in Chapter 2 that people who experience anxiety alone when standing at 3.2m also demonstrated smaller amplitude and higher frequency centre of pressure (COP) displacements may be explained by the observed increase in soleus tendon reflex (STR) excitability in Chapter 3. Assuming that the spinal reflexes that control posture function as a feedback mechanism, the heightened spindle sensitivity and increase in stretch reflex excitability observed at 3.2m would presumably produce mono-synaptic stretch reflexes in agonist muscles in response to smaller stretches spontaneous postural sway. As such,

according to an inverted pendulum model of postural control (Winter et al., 1990), more sensitive spindles would produce more frequent mono-synaptic stretch reflexes which would in turn produce more frequent ankle torques thereby causing more frequent and smaller COP excursions akin to those observed among the n=26 non-fearful group in Chapter 2.

In addition to explaining the postural outcome observed in Chapter 2, an increase in spindle sensitivity and spinal reflex excitability may also explain the postural outcomes observed among those with clinical anxiety disorders and co-morbid balance deficits. For example, it has been demonstrated that sufferers of postural phobic vertigo produce larger ankle torque, greater ankle torque variance and larger total sway area than otherwise healthy controls during quiet stance (Holmberg et al., 2003). Likewise, sufferers of postural phobic vertigo also demonstrate increased frequencies of sway in the 3-8.5Hz bandwidth compared to otherwise healthy controls during quiet stance (Krafczyk et al., 1999). Again, heightened muscle spindle sensitivity and more frequent activation of mono-synaptic stretch may explain the postural outcomes observed among this clinical population.

Heightened muscle spindle sensitivity and overly sensitive spinal reflexes may also explain the postural outcomes observed among those who have been experimentally manipulated to experience fear and/or anxiety by means other than elevated surface heights. For example, viewing images that are unpleasant in nature has been shown to significantly alter postural control (Azevedo et al., 2005; Facchinetti et al., 2006). Specifically, a 'freezing like' posture characterized by increased frequency of postural sway has been reported when participants view pictures of violent mutilations (Azevedo et al., 2005; Facchinetti et al., 2006). Again, heightened muscle spindle sensitivity and consequently more frequent mono-synaptic stretch reflexes would explain the increase in the frequency of postural sway observed in response to this experimental manipulation.

It is important to note that studies have not been performed to investigate the mechanisms underlying the postural outcomes observed among those suffering from clinical anxiety disorders (Krafczyk et al., 1999; Holmberg et al., 2003) and among healthy individuals exposed to violent images (Azevedo et al., 2005; Facchinetti et al., 2006). However, doing so may prove worthwhile considering that an improved understanding of the neurophysiological mechanisms responsible for the balance deficits observed may provide insight into potential treatments. For example it would be feasible to use the experimental methods used in Chapter 3 of this thesis to determine whether those suffering from pathological levels of anxiety engage the same proprioceptive adaptation as that observed among healthy individuals who stand under conditions of height-induced fear and anxiety. The findings from such a study would allow for a dissociation of whether the results presented in Chapter 3 are specific the height-

induced fear and anxiety or whether they represent a general proprioceptive adaptation that occurs in response to the experience of anxiety and/or fear.

6.3 Understanding the Supraspinal Ia Afferent Signal Attenuation

When standing under conditions of elevated postural threat, the observed increase in spindle sensitivity did not concomitantly facilitate the cortical response to incoming afferent information (Chapter 3). This finding is of interest considering that it advances our current understanding of how proprioceptive adaptation serves to facilitate the control of standing balance. For example, we can now expand the explanation provided by Llewellyn et al. (1990) that 'proprioceptive sensitivity is elevated to provide supraspinal areas with increased feedback gain and resolution' (pg 27) when balance is threatened or challenged. For example, we now know that this is not the case during quiet stance. However, this may be the case in situations where balance is perturbed during threatening situations or during gait. For example, it has been demonstrated that the cortical responses to whole-body perturbations (N100 waveforms) are larger during threatening situations compared to when standing in non-threatening conditions (Adkin et al., 2008; Sibley et al., 2010). Taken together the findings from these two studies (Adkin et al., 2008; Sibley et al., 2010) and the findings from Chapter 3 would suggest that the heightened afferent volley associated with increased muscle spindle sensitivity is irrelevant to the cortex with respect to the maintenance of static posture during threatening situations. However, when balance is compromised in response to a perturbation, the cortex relies on the 'increased feedback gain' in order to achieve an appropriate balance correcting response. This hypothesis is supported by the fact that not only are larger cortical responses to balance perturbation observed when standing at elevated surface heights (Adkin et al., 2008; Sibley et al., 2010), but larger amplitude balance corrections and larger amplitudes of EMG activity in the muscles facilitating the balance correction are observed as well (Carpenter et al., 2004). However, If this were indeed the case, it would be required that the heightened afferent discharge associated with increased muscle spindle sensitivity be attenuated and/or gated in some manner during quiet stance until a perturbation to balance is evoked. As mentioned in the discussion of Chapter 3, further experimentation using methods that would provide greater resolution of the afferent pathway along which proprioceptive information from the lower limbs travels will be required in order to test this working hypothesis.

However, this sensory gating hypothesis may not be the only explanation for the N100 facilitation observed during states of height-induced fear and anxiety (Adkin et al., 2008; Sibley et al., 2010). For example, it is possible that N100 facilitation during states of height-induced fear and anxiety has nothing to do with a heightened perception of incoming afferent

information, but instead is a result of facilitated cortical processing of sensory information from multiple modalities. This explanation is supported by the observation that the anxiety and fear related to increased postural threat result in a shift toward placing increased attentional (Quant et al., 2004; Huffman et al., 2010) and/or cognitive (Carretie et al., 2001) resources toward the processing of negative sensory information. Specifically it has been demonstrated the event-related potentials recorded in response to viewing images with a negative emotional valence are larger in amplitude compared to those recorded in response to viewing images with either a neutral or pleasant emotional valence (Carretie et al., 2001). Likewise, event-related potentials observed in response to viewing pictures of snakes and spiders are larger among individuals with specific spider and snake phobias compared to otherwise normal controls (Miltner et al., 2005). As such, this proposed 'negativity bias' in terms of sensory processing (Carretie et al., 2001) may be the ultimate cause of the N100 facilitation observed in response to height-induced postural threat (Adkin et al., 2008; Sibley et al., 2010) and the threat of postural perturbation (Quant et al., 2004). Furthermore, because the 'negativity bias' is related to the later processing of sensory information and not the early perception of sensory information, the attentional shift observed in response to postural threat (Huffman et al., 2010) and 'negativity bias' (Carretie et al., 2001) would also explain the null effect of elevated postural threat on the early components of afferent perception (P1-N1 amplitude) observed in the current paradigm (Chapter 3).

6.4 The Differential Effect of Threat on STR and SOL H-reflex Excitability

The results from Chapter 3 demonstrated that increased muscle spindle sensitivity facilitates STR excitability. However, previous studies have demonstrated elevated postural threat attenuates soleus H-reflex (SOL H-reflex) amplitude (Sibley et al., 2007). These two findings suggest that a functional mechanism is engaged at the level of the SOL lower motor neuron pool to produce this differential effect. Therefore, Chapter 4 of this thesis was designed to better understand the mechanism that may be responsible for producing this differential effect of height-induced fear and anxiety on STR and SOL H-reflex excitability. In Chapter 4, it was proposed that the decrease in SOL H-reflex amplitude that has been observed when standing at high height (Sibley et al., 2007) may have been cause by either homo-synaptic post activation depression (HPAD) caused by increased tonic Ia afferent discharge associated with heightened spindle sensitivity (Chapter 3) on to the SOL lower motor neuron pool or by descending pre-synaptic inhibition (PSI) onto Ia afferents emanating from SOL. As such, the influence of PSI on SOL H-reflex excitability during states of height-induced fear and anxiety was tested. Unfortunately, due to the possible confounding influences of the custom-made ankle braces used in the study as well as the minimal fear response observed among the participants

recruited for the study, this experiment failed to replicate the typical threat-associated decrease in SOL H-reflex excitability (Sibley et al., 2007). Therefore, the results from Chapter 4 do not provide direct insight into the possible mechanisms responsible for the differential effect of elevated postural threat on STR and SOL H-reflex excitability.

For this reason, the study outlined in Chapter 5 was designed to test the effectiveness visual feedback as an alternative experimental tool to overcome the biomechanical confounds that limit the interpretation of static posturography measures and spinal reflex measures during states of height-induced fear and anxiety as well as the possible confounding effects of the custom-made ankle braces. Similar to the results of Chapter 4, when the threat-associated backward lean was controlled for, no effect of elevated threat was observed in Chapter 5. However, backward leaning did significantly reduce SOL H-reflex excitability independent of the presence of threat. This is an interesting finding considering that it may indirectly address the differential effect of threat on STR and SOL H-reflex excitability. Specifically, possible changes in COP reflecting a threat-associated backward lean were not recorded in the study performed by Sibley et al. (2007). Furthermore, possible changes in the tonic activation of more proximal leg muscles such as rectus femoris and/or biceps femoris muscle activation that may occur when standing under conditions of elevated postural threat were not recorded by either Sibley et al. (2007) or during the work presented in this thesis. These two oversights are of note to the interpretation to the differential effect of threat on STR and SOL H-reflex excitability considering that according to the model developed by Hultborn et al. (1987), an increase in quadriceps EMG and subsequent increase tonic Ib afferent discharge inhibits SOL H-reflex excitability by facilitating peripheral PSI influences on the SOL lower motor neuron pool (Hultborn et al., 1987; Crone and Nielsen, 1989; Meunier and Morin, 1989; Nielsen and Kagamihara, 1993; Nielsen and Petersen, 1994; Morita et al., 1998b). Therefore, it is possible that uncontrolled backward leaning that is known to occur at heights of 1.6m (Carpenter et al., 1999;2001;2004; Davis et al., 2009) may have been the ultimate cause of the SOL H-reflex attenuation reported by Sibley et al. (2007), not elevated postural threat. This hypothesis is supported by the fact that the posterior lean induced by visual feedback in Chapter 5 was found to significantly reduce SOL H-reflex excitability and no that such decrease was observed when leaning was prevented in the study reported in Chapter 4. In summary, it appears that heightened muscle spindle sensitivity is the underling cause of STR facilitation whereas the threat-associated decrease in SOL H-reflex excitability is a secondary consequence of threat-associated leaning, not a direct consequence of threat. However, until future studies are performed to quantify the relative influence of elevated postural threat on quadriceps EMG and SOL H-reflex are performed this theory will remain a speculative working hypothesis.

6.5 Future Work Investigating Threat-Associated Proprioceptive Adaptation in Humans

In order to advance our understanding of the proprioceptive adaptations that occur during states of fear and anxiety and gain better insight into the exact mechanisms that contribute to increased spindle sensitivity, the first step will be to address the existing debate regarding the mechanism through which heightened spindle sensitivity is achieved. Based on the findings from studies that have compared recordings from feline Ia afferents in response to direct stimulation of gamma motor neurons and in response to induced muscle stretch (Prochazka et al., 1985; 1976; 1988; Hulliger et al., 1989) and human studies that have presumed to record directly from gamma motor neurons and Ia afferents (Ribot-Ciscar et al., 1986), it has been argued that muscle spindle sensitivity to stretch can be facilitated by increased gamma-motor drive relative to alpha motor drive. Alternatively, it has been argued that direct activation of the sympathetic nervous system may serve to facilitate increases in muscle spindle sensitivity. This argument is based on evidence that feline muscle spindles receive direct innervation from the autonomic nervous system (Barker and Saito, 1981) that facilitates increases in muscle spindle firing rates when activated (Hunt, 1960). Additionally, performing tasks such as mental arithmetic or a static handgrip contraction that directly activate the human sympathetic nervous system has been shown to facilitate stretch reflex excitability (Hjorstkov et al., 2005; Kambayashi et al., 2009).

Based on the results presented in Chapter 3 neither alpha-gamma decoupling or elevated sympathetic drive can be rejected as potential mechanisms responsible for potentiating spindle sensitivity in the current paradigm. Specifically, it is clear that height-induced fear and anxiety produced a robust sympathetic nervous system response as indicated by the increases in electrodermal activity (EDA) observed in such situations. EDA activity is considered a direct indication of sympathetic nervous system activation based on the fact that the eccrine sweat glands responsible for producing changes in EDA activity are directly innervated by the sympathetic nervous system, and not the parasympathetic nervous system (Critchley, 2002). However, because of limitations in terms of the experimental methods used in the current paradigm, it is not possible to determine whether heightened gamma-motor drive may have also contributed to the increase in STR excitability as well. For example, surface EMG does not provide sufficient resolution to quantify the potential involvement of alpha-gamma decoupling (i.e. Vallbo and Hulliger, 1981; Prochazka et al., 1976; 1985; 1988; Ribot-Ciscar et al., 1986, 2000; Vallbo). Likewise, both the STR and SOL H-reflex stimulation protocols used in the current paradigm are known to stimulate afferents from mechanoreceptors other than primary Ia afferents emanating from muscle spindles (Burke and Gandevia, 1983). As such, potential contamination due to afferent contributions from cutaneous receptors and golgi tendon organs

(GTOs), both of which are known to modulate spinal reflex excitability (i.e Hultborn et al., 1987; Rossi and Decchi, 1994) may have influenced the changes in STR excitability observed in the current paradigm. Therefore, in future work it will be necessary to obtain direct microneurographic recordings from human afferent and efferent projections and to directly stimulate primary Ia afferents and gamma efferents in order to address the possible contributions of heightened gamma-motor drive to STR facilitation. However, obtaining microneurographic recordings in a standing model may prove difficult considering the level of precision required to obtain accurate and reliable recordings from efferent and afferent nerves. For this reason, it may be worthwhile to use tools other than elevated surface heights to evoke a sense of fear and/or anxiety among study participants while lying prone. For example, it may be possible to expose participants to affective pictures (i.e. Azevedo et al., 2005; Facchinetti et al., 2006) or anxiogenic drugs (i.e. Matilla et al., 1988) in order to evoke feelings of fear and/or anxiety among humans in a situation where accurate microneurographic recordings can be obtained.

In addition to improving our understanding of proprioceptive adaptation at the level of the sensory organ, it will be important to also improve our understanding of how this altered information is integrated with sensory information from other modalities involved in balance control. The results from Chapter 3 of this thesis provide evidence suggesting the somatosensory cortex does not change in terms of its initial sensitivity to incoming afferent information from lower limb muscle spindles. There is indirect evidence to suggest that the later processing of afferent information from the lower limbs may be facilitated during states of height induced fear and anxiety (Adkin et al., 2009). However, it remains unclear as to whether or not proprioceptive information is re-weighted with respect to inputs from additional sensory modalities during the later stages of sensory integration. Therefore, in future studies, it may be useful to compare the evoked potentials generated in response to proprioceptive stimuli such as those used in Chapter 3 to evoked potentials generated in response to repeated galvanic vestibular stimulation (GVS) and/or direct visual stimuli in order to determine whether or not the CNS re-weights the relative importance of sensory information from each respective sensory modality during states of height induced fear and anxiety.

6.6 Future Work Investigating Threat-Associated Proprioceptive Adaptation in Animals

In addition to addressing the sympathetic drive vs. gamma motor drive debate in future human studies, it may be worthwhile to re-visit animal models in order to perform more invasive experiments (i.e. Prochazka et al., 1985; 1988; Llewellyn et al., 1990) that may provide better resolution. A variety of experimental models of fear an anxiety have been developed in the

rodent model. For example, it has been demonstrated that when rodents are placed in an elevated plus-maze (a raised platform with two open arms and two closed arms) they are reluctant to explore the open arms of the maze due to the fear imposed by the ~50 cm height of the maze (Pellow et al., 1985). Likewise, exposing rodents to predator stress (Cats or Cat odour) (Adamec and Shallow, 1993) or an inescapable threat of shock (Korte et al., 1999) produces robust fear and anxiety. Furthermore, it is possible to pharmacologically manipulate animals to experience fear and anxiety (i.e. Cole and Rogers, 1995; Lepicard et al., 2003) in ways that may be considered unethical in humans. In addition to experimentally manipulating animals to experience fear and anxiety, genetic strains of mice that are known to express anxiety-related behaviour are available to study (Griebel et al., 1993; Cole et al., 1995). Performing more invasive experiments in animal models with fewer between-subject variables such as differences in life history will ultimately provide the level of resolution required to dissociate the relative contributions sympathetic nervous system activation and/or changes in gamma motor drive to regulating the sensitivity of muscle spindle

Working with animal models of fear and anxiety may also provide indirect evidence to allow for a better understanding of the postural changes observed during states of fear and anxiety in humans. For example, it has been demonstrated that both genetically manipulated and pharmacologically manipulated levels of anxiety experienced by mice significantly affect their balance performance (Lepicard et al., 2003). Specifically, mice that were either genetically or pharmacologically manipulated to experience elevated anxiety were less capable of maintaining their balance during a rotating beam test and were subjectively described to adopt a less stable posture during testing (Lepicard et al., 2003). This finding suggests the possibility that there exists a mechanism that has been conserved over evolutionary time that influences balance during threatening situations. The availability of these models open the door for experiments designed to obtain direct recordings from not only peripheral nervous system structures, but also central nervous system structures in order to improve our understanding of the neuroanatomical structures and pathways that mediate fear and anxiety fear as well as balance control (Balaban and Beryozkin, 1994; Yates et al., 1994; Balaban, 1996; Porter & Balaban, 1997, Schuerger and Balaban, 1999; Fulweiler and Saper, 1984; Herbert et al., 1990; Moga et al., 1990). Performing such studies has potential to improve our understanding of the evolutionary biology of the relationship between fear and balance.

6.7 The Clinical Relevance of Thesis Findings

The ultimate goals of the research presented in this thesis were to improve the current understanding of how fear and anxiety impair static postural control and to determine whether

proprioceptive adaptation and altered reflex sensitivity contribute to the posturographic changes that occur during states of height induced fear and anxiety. Achieving these goals is of significant clinical relevance considering that a number of studies have demonstrated that people with a fear of falling enter a debilitating spiral of loss of confidence, restriction of physical activities and social participation, physical frailty, falls, and loss of independence (See Zijlstra et al., 2007 for review). This fear of falling and the consequence of falling exert a substantial burden on the public health care system (Zijlstra et al., 2007; Stevens et al., 2006; Carroll and Slattum, 2005; Englander et al., 1996).

Therefore, it is of significance that the findings reported in this thesis have the potential to contribute the design effective rehabilitative and fall prevention strategies to help alleviate the burden placed on the public health care system by falls. For example, the findings from Chapter 1 validate the usefulness of the elevated surface heights as an effective experimental tool to model the fear of falling experienced by older adults (Maki et al., 1991) in young healthy adults. For a long time, there has been a disconnect between the observed postural outcomes among older adults with a self-reported fear of falling and those observed among otherwise healthy young adults who had been experimentally manipulated to experience fear and anxiety (Carpenter et al., 1999; 2001; Adkin et al., 2000; 2002; Brown et al., 2006). For this reason, the elevated threat model had always been limited in terms of its applicability as a 'disease model'. However, the results of Chapter 1 demonstrate, for the first time, that when a robust fear response is elicited, elevated postural threat produces the same postural response in healthy young as that observed among fearful elderly (Maki et al., 1991; Davis et al., 2009).

The ability to model the fear experienced by older adults in an otherwise healthy young adults will prove useful in future studies. For example, it is known that age-related declines in visual acuity, vestibular function, proprioceptive sensitivity, and brain function responsible for integrating and processing this information, may contribute to the postural deficits commonly observed in older adults (Bugnariu and Fung, 2007). In future studies, the influence of these confounding age-related declines can be circumvented by experimentally manipulating otherwise healthy young adults to experience fear and anxiety thereby allowing for conclusions to be drawn about the direct the emotional experience of fear has on balance control.

This finding opens the door to the possibility of future collaborations between rehabilitation scientists, psychologists and clinical professionals to begin developing fall prevention and rehabilitation strategies that take into account not only the physical aspects of balance deficits but also the influence of emotion on balance control. In doing so, it is possible that such a comprehensive approach to balance research and fall prevention will lead to a reduction in the burden placed on the health care system by falls.

The second major clinical contribution that this thesis makes is the development of a novel protocol to better understand the adaptive nature of the proprioceptive system. The results of Chapter 2 provide data from the first known experiments that have examined the cortical potentials (TEPs) reflecting the perceptual response of the somatosensory cortex to direct mechanical stimulation of the lower limb proprioceptive system during stance. This finding is of clinical significance considering that by comparing changes in TEP and SEP amplitude during stance in a clinical setting, it will be possible to dissociate whether proprioceptive deficits contributing to postural instability are related to deficits in cortical perception, or are instead related to deficits at the level of the sensory receptor.

This improved resolution in terms of our ability to probe the human proprioceptive system provides a greater possibility for developing better-targeted rehabilitative therapies and treatments for those suffering from pathological movement disorders. Likewise, the ability to perform such studies during stance will lead to greater ecological validity of such findings.

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APPENDIX 1

The University of British Columbia
Office of Research Services
Clinical Research Ethics Board – Room 210, 828 West 10th Avenue, Vancouver, BC V5Z 1L8

ETHICS CERTIFICATE OF EXPEDITED APPROVAL: RENEWAL

PRINCIPAL INVESTIGATOR:	DEPARTMENT:	UBC CREB NUMBER:
Mark G Carpenter	UBC/Education/Human Kinetics	H06-70316

INSTITUTION(S) WHERE RESEARCH WILL BE CARRIED OUT:

Institution	Site
UBC	Vancouver (excludes UBC Hospital)

Other locations where the research will be conducted:
N/A

CO-INVESTIGATOR(S):
Bastiaan Bloem
Justin R. Davis
Allan Adkin
Adam Campbell
Romeo Chua
Brian C. Horslen

SPONSORING AGENCIES:
- Natural Sciences and Engineering Research Council of Canada (NSERC) - "Central and Peripheral Mechanisms Controlling Human Balance Control"
- Natural Sciences and Engineering Research Council of Canada (NSERC) - "State-anxiety Effects on Corticol Response to Predictable and Unpredictable Balance Perturbations"

PROJECT TITLE:
Central and Peripheral Mechanisms Controlling Human Balance Control

EXPIRY DATE OF THIS APPROVAL: July 23, 2011

APPROVAL DATE: July 23, 2010

CERTIFICATION:
In respect of clinical trials:
1. The membership of this Research Ethics Board complies with the membership requirements for Research Ethics Boards defined in Division 5 of the Food and Drug Regulations.
2. The Research Ethics Board carries out its functions in a manner consistent with Good Clinical Practices.
3. This Research Ethics Board has reviewed and approved the clinical trial protocol and informed consent form for the trial which is to be conducted by the qualified investigator named above at the specified clinical trial site. This approval and the views of this Research Ethics Board have been documented in writing.

The Chair of the UBC Clinical Research Ethics Board has reviewed the documentation for the above named project. The research study, as presented in the documentation, was found to be acceptable on ethical grounds for research involving human subjects and was approved for renewal by the UBC Clinical Research Ethics Board.

Approval of the Clinical Research Ethics Board by one of:

Dr. Peter Loewen, Chair
Dr. James McCormack, Associate Chair