

**Influence of neuromuscular fatigue of the lower limb on postural control and associated central processes in young and older adults**

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## CONTRIBUTION TO THE LITERATURE

This thesis presents the research of Etienne Bisson in collaboration with his thesis supervisors Dr. Martin Bilodeau and Dr. Yves Lajoie. The sum of this work resulted in the following contributions to the literature.

### **Manuscripts to be submitted and included in this thesis:**

**Bisson, E.J.**, McEwen, D., Lajoie, Y., & Bilodeau, M. Changes in postural sway and attentional demands due to ankle neuromuscular fatigue with aging.

**Bisson, E.J.**, Lajoie, Y., & Bilodeau, M. The influence of age and surface compliance on changes in postural control and attention due to ankle neuromuscular fatigue.

### **Published manuscripts included in this thesis:**

**Bisson, E.J.**, Remaud, A., Boyas, S., Lajoie, Y., & Bilodeau, M. (2012). Effects of fatiguing isometric and isokinetic ankle exercises on postural control while standing on firm and compliant surfaces. *Journal of NeuroEngineering and Rehabilitation*, 9:39.

**Bisson, E.J.**, McEwen, D., Lajoie, Y., & Bilodeau, M. (2011). Effects of Ankle and Hip Muscle Fatigue on Postural Sway and Attentional Demands during Unipedal Stance. *Gait & Posture*, 33(1): 83-87.

### **Related published manuscripts:**

Boyas, S., Remaud, A., **Bisson, E.J.**, & Bilodeau, M. (2011). Impairment in postural control is greater when ankle plantarflexors and dorsiflexors are fatigued simultaneously compared with separately. *Gait & Posture*, 34: 254–259.

**Bisson, E.J.**, Chopra, S., Azzi, E., Morgan, A. & Bilodeau, M. (2010). Acute effects of fatigue of the plantarflexor muscles on different postural tasks. *Gait & Posture*, 32(4): 482-486.

## ABSTRACT

This thesis investigates the differential effects of muscle fatigue on center of pressure (COP) sway and associated central processes (attentional demands and sensory re-weighting) in older compared with young adults. More specifically, we first sought to determine whether the effect of muscle fatigue on unipedal stance was greater during a dual-task in older versus young adults, and second, to determine whether the effect of muscle fatigue on bipedal stance was greater in a condition with less reliable proprioceptive information in older versus young adults. Our main results show that with different muscle groups fatigued (ankle or hip) and postural tasks with varying difficulty (unipedal stance or bipedal stance on compliant surface), young adults increased their COP sway displacement and velocity with muscle fatigue, but not the associated attentional demands. When the central nervous system needed to increase the weight of the vestibular inputs due to sensory information being less reliable at the ankle joints from standing on a compliant surface (peripheral somatosensory information), COP sway displacement and velocity in young adults were greater with ankle muscle fatigue. We also found that healthy older adults were able to compensate for muscle fatigue just as well as young adults when visual information was available during a unipedal stance or when visual information was not available during a bipedal stance on a firm surface. However, when standing on a compliant surface, older adults showed a greater increase in COP sway displacement compared to young adults and increased attentional demands when visual information was not available during a bipedal stance. Our results suggest that healthy young and older adults are able to compensate for ankle muscle fatigue to limit postural control alterations during quiet standing under different conditions, and that the extent of postural control alterations largely depends on the tasks performed. The compensation strategies may be less efficient for older adults with less reliable proprioceptive information and without vision. Thus, a frailer group of older adults, with already reduced proprioception and/or reduced vision could possibly have more difficulty to efficiently use the same compensation strategies, and may be more at risk of falling when fatigued.

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## CHAPTER 1. INTRODUCTION

The ability to perform a multitude of physical activities and most daily living activities requires adequate postural control. In order to maintain an upright stance, the central nervous system must integrate and (re-)weight information from different sensory systems (visual, vestibular and somatosensory) to have a good representation of the body in space, and to continuously modulate commands to the neuromuscular system. Unfortunately, there are significant age-related changes in sensory and neuromuscular systems structures involved in postural control (Lord *et al.*, 2007; Shumway-Cook & Woollacott, 2007); thus, the occurrence of falls increases as age increases. In fact, one third of adults aged 65 and over will experience at least one fall each year (Tinetti *et al.*, 1988; O'Loughlin *et al.*, 1993; Lord *et al.*, 1993). Despite the numerous strategies to prevent falls such as exercise interventions (Sherrington *et al.*, 2004) and changing the environment and/or medications (Lord *et al.*, 2007), the overall occurrence of falls still remains the same. Furthermore, the consequences of falls are disastrous. In Canada, almost 50% of falls cause injury, and it is estimated that falls cost the Canadian health care system \$2.8 billion a year (Public Health Agency of Canada, 2005). Also, regardless of whether there is an injury or not, older adults may begin to fear falling, which can reduce their quality of life through loss of independence and reduction in physical activity. Physical inactivity is related to a threefold increase in the risk of falls recurrence (Public Health Agency of Canada, 2005).

In 2006, 4.3 million Canadians (13.7% of the population) were over 65 years of age (nearly 1.2 million were over 85) and projected statistics for 2056 indicate that over 25% of the Canadian population will be over the age of 65 (Statistics Canada, 2006). Thus, the

problem of falls is a growing phenomenon and many health care providers and policy makers are interested in falls prevention. This is one reason why research on falls and aging has increased substantially in the last decade.

Fortunately, the occurrence of falls can be reduced with proper exercise training programs (Sherrington *et al.*, 2004). Sherrington and colleagues (2004) pooled the results from nine systematic reviews and concluded that targeted supervised exercise programs prescribed by a professional are the most effective exercise program to reduce fall incidence. However, even unsupervised exercise programs can reduce the incidence of falls if there is a balance component like Tai chi (Sherrington *et al.*, 2004). Adding strength, endurance or flexibility to the program can also be beneficial (Lord *et al.*, 2007).

Exercise at high intensity or performed over a sustained period of time, however, can cause a certain amount of stress (fatigue) to the sensory and neuromuscular systems. Muscle fatigue can be defined as an acute impairment in the ability to exert force, regardless of whether or not the task itself can still be performed successfully (Enoka & Stuart, 1992; Bigland-Ritchie & Woods, 1984). Other than reducing muscle strength (see Westerblad *et al.*, 2002; Enoka & Stuart, 1992; Bigland-Ritchie & Woods, 1984 for reviews), muscle fatigue caused by physical activity has been shown to alter proprioception (Forestier *et al.*, 2002; Hiemstra *et al.*, 2001), increase joint stiffness (Hoang *et al.*, 2007; Leger & Milner, 2000; Zhang & Rymer, 2001) and increase reaction time (Vuillerme *et al.*, 2002b; Simoneau *et al.*, 2006). It, therefore, seems evident that fatigue could have a significant negative impact on postural control after exercising. In young adults, numerous studies have demonstrated postural control alterations, characterized by an increase in center of pressure (COP) sway

displacement and/or COP sway velocity, across several tasks (e.g., unipedal stance, bipedal stance, eyes open, eyes closed) following fatigue of the ankle (Vuillerme *et al.*, 2001; Vuillerme *et al.*, 2002b; Lundin *et al.*, 1993; Corbeil *et al.*, 2003), knee (Gribble & Hertel, 2004b), hip (Gribble & Hertel, 2004a; Salavati *et al.*, 2007), back (Davidson *et al.*, 2004) and neck (Gosselin *et al.*, 2004) muscle groups. Even though an increase in COP sway displacement and velocity is evident with muscle fatigue, no authors have reported any falls during their studies, indicating that young subjects are still able to stand quietly when fatigued. However, muscle fatigue can also affect central processes associated with postural control (Vuillerme *et al.*, 2002b; Simoneau *et al.*, 2006). Thus, postural control may not be altered enough after fatigue to lead to a fall, but it could decrease the ability to perform a second task while standing and/or to respond to a sudden perturbation.

Since muscle fatigue affects COP sway and increases the attentional cost of postural control in young adults, it could have a more pronounced impact on older adults. As a consequence of the age-related deterioration of the different sensory and neuromuscular systems structures required for postural control, older adults have greater COP sway (Horak *et al.*, 1989) and less efficient proprioception (Shaffer & Harrison, 2007; Goble *et al.*, 2009) compared to their younger counterparts. Because older adults have been shown to have more difficulty in re-weighting less-to-more reliable sensory information when one or more systems are altered (Horak *et al.*, 1989; Teasdale *et al.*, 1991a; Abrahamova & Hlavacka, 2008; Teasdale *et al.*, 1991b), a greater increase in COP sway and attentional demands with muscle fatigue could be observed in this age group compared to a younger group.

The older adult population in Canada is growing in size and also becoming more physically active (in 2007, 49% of older adults were at least moderately active compared to 39% in 1994). If changes in postural control and attention due to exercise-induced fatigue are similar or even greater in older compared with young adults, older adults may be at a greater risk of falling. Therefore, health care providers could be underestimating the risk of falling of older adults if they evaluate them in the fresh (rested) state only.

Thus, this thesis investigated the differential effects of muscle fatigue on COP sway and associated central processes (attentional demands and sensory re-weighting) in older compared to young adults. More specifically, this doctoral thesis first aimed to determine whether the effect of muscle fatigue on unipedal stance is greater during a dual-task in older versus young adults, and secondly, to determine whether the effect of muscle fatigue on bipedal stance is greater in a condition with less reliable proprioceptive information in older versus young adults.

Before detailing the findings of the four manuscripts included in this doctoral work, a summary of the methods is presented in Table 1 and a summary of the results in Table 2 of this section. A review of the literature follows this introduction (Chapter 2) to better situate the reader on the sub-topics of this thesis. Also, the research questions and hypotheses for each study are stated in Chapter 3. Following this, the four manuscripts are presented (Chapter 4-7). Finally, Chapter 8 consists of a general discussion and conclusion. At the end of the document, the reader can find a detailed description of the participation of each collaborator to this thesis (Chapter 9) and a list of references and appendices (Chapter 10-11).

**Table 1. Summary of the methods**

	Objective 1		Objective 2	
	Study 1	Study 2	Study 3	Study 4
Group	YA	YA and OA	YA	YA and OA
Primary (postural) task	SL-EO	SL-EO	FT-EC	FT-EC
Type of surface	FS	FS	FS vs CS	FS vs CS
Secondary (cognitive) task	SRT	SRT	n/a	CRT
Fatigue type	CON	CON	CON vs ISO	ISO
Muscle group fatigued	DF/PF vs. HF/HE	DF/PF	PF	PF

Note: YA = young adults; OA = older adults; SL-EO = unipedal with vision; FT-EC = bipedal without vision; FS = firm surface; CS = compliant surface; SRT = simple reaction time task; CRT = choice reaction time task; CON = concentric maximal voluntary contractions (MVCs) until force reaches 50% MVC; ISO = isometric contraction at 50% MVC until exhaustion; DF = dorsiflexors; PF = plantarflexors; HF = hip flexors; HE = hip extensors; n/a = not applicable.

<b>Table 2. Summary of the neuromuscular fatigue effects on quiet standing</b>							
Area	COP parameters					RT	
	AP SD	ML SD	AP VEL	ML VEL	AP COP		
<b>Objective 1 – Unipedal Stance with Eyes Open, Simple RT</b>							
<b>Article 1</b>							
YA Hip	ns	ns	ns	↑	↑	n/a	ns
YA Ankle	ns	ns	ns	↑	ns	n/a	ns
<b>Article 2</b>							
YA	ns	↑	ns	ns	ns	ns	ns
OA	ns	↑	ns	ns	ns	↓	ns
<b>Objective 2 – Bipedal Stance with Eyes Closed, Choice RT</b>							
<b>Article 3</b>							
YA FS	ns	↑	ns	↑	ns	n/a	n/a
YA CS	↑	↑	↑	↑	↑	n/a	n/a
<b>Article 4</b>							
YA FS	↑			↑	↑		ns
YA CS	↑	n/a	n/a	↑	↑	n/a	ns
OA FS	↑			↑	↑		ns
OA CS	↑			↑	↑		↑

Note: Arrows represent significant effects of fatigue where bigger arrows denote a greater effect for CS than FS condition. COP = center of pressure; AP = antero-posterior; ML = medio-lateral; SD = standard deviation; VEL = velocity; RT = reaction time; YA = young adults; OA = older adults; MVC = maximal voluntary contraction; HF = hip flexors; HE = hip extensors; PF = plantarflexors; DF = dorsiflexors; FS = firm surface; CS = compliant surface; ns = not significant; n/a = not reported.

## CHAPTER 2. REVIEW OF THE LITERATURE

### 2.1. Fundamental concepts

#### 2.1.1. Postural control

Postural control during quiet standing is defined as the ability to maintain the body centre of mass (COM) within the base of support (Shumway-Cook & Woollacott, 2007). Despite its simple definition, postural control is a complex process where the central nervous system (CNS) must continuously modulate commands to the neuromuscular system. Postural muscle activity provides joint stiffness allowing the upright body to resist gravitational forces and the resulting ground reaction forces (Massion, 1998). In order to maintain this posture, the CNS must also integrate and (re-)weight information from different sensory systems (visual, vestibular and somatosensory) to obtain a coherent representation of the body's orientation and stability. By comparing this multisensory feedback information to the internal representation of the body, the CNS processes the neuromuscular outputs necessary to correct the position (difference between estimated and real position) in order to maintain the body's center of mass within the base of support, depending on the environmental constraints (Maurer *et al.*, 2006; Mergner & Rosemeier, 1998).

Since the center of mass (COM) of our body is located at the trunk when standing, and the base of support is determined by the position of our feet, the body tries to optimize its stability by oscillating like an inverted pendulum around the ankle joint. This has been termed the “ankle strategy” (Nashner, 1977), where the primary muscles activated are the plantarflexors. This bottom-up process is preferred in young adults standing on a stable surface, but a top-down process where postural oscillations mainly occur around the hip joint

(so called “hip strategy”) is preferred on a narrow, unstable surface (Horak & Nashner, 1986). This strategy requires greater activation of the hip muscles compared to the ankle strategy. Multiple patterns of combined ankle and hip strategies can be observed according to the sensory information available (Horak *et al.*, 1990; Horak & Hlavacka, 2001). During quiet standing, oscillations in the medio-lateral (ML) directions were found to be regulated at the hip joint through a “load-unload strategy” (Winter, 1996).

Due to destabilizing forces acting on the body and corrective actions by the postural control system to maintain an upright posture, the body is never truly still during quiet standing, but is constantly moving in small continuous oscillations (Shumway-Cook & Woollacott, 2007). To quantify this postural sway, the displacement of the COM is measured using motion analysis techniques, or the displacement of the center of pressure (COP) is measured with a force platform. Using this latter technique, COP sway has been shown to be controlled by a feedback model (Winter *et al.*, 1998; Winter *et al.*, 2001; Winter *et al.*, 2003) where the CNS adjusts the stiffness of the ankle musculature. With this stiffness theory, Winter *et al.* (Winter *et al.*, 1998) demonstrated that the COP is closely related to the COM, but always further within the base of support. However, it has been shown that stiffness is not the only mechanism regulated in postural control (Loram & Lakie, 2002a). Studies from Loram and colleagues (Loram & Lakie, 2002b; Loram & Lakie, 2002a; Lakie *et al.*, 2003) demonstrated that joint stiffness regulation in the calves involves a catch-and-release strategy, where the dynamic stiffness at the joints acts in a paradoxical manner: when the body sways forward, the soleus and gastrocnemius stretch provoking their own contraction, in order to bring back the COM closer to the center of the base of support (catch). Both muscles then relax when they shorten (release).

The contribution of the sensory systems in postural control is undisputable since it has been shown that an alteration of the sensory systems (visual, vestibular and somatosensory) increases COP sway (Horak & MacPherson, 1996). In fact, according to the re-weighting theory (Jeka *et al.*, 2000; Oie *et al.*, 2002), the redundancy of sensory information provided enables the CNS to re-weight each source of input depending on its reliability and importance for stabilization and orientation purposes. Since muscle fatigue is not likely to reduce visual, vestibular or haptic information, but has been shown to reduce knee proprioception (Hiemstra *et al.*, 2001; Lattanzio *et al.*, 1997) and ankle proprioception (Forestier *et al.*, 2002; Vuillerme *et al.*, 2007; Vuillerme & Boisgontier, 2008), the focus in this review, in relation to sensory systems, will be on the contribution of proprioception.

Adverse effects of aging on postural control have been well documented (see Lord *et al.*, 2007 for a review). Numerous studies have found greater COP sway during quiet standing in older adults compared to young adults (Sheldon, 1963; Overstall *et al.*, 1977; Maki *et al.*, 1990) and this increase is greater as the task gets more difficult to perform (e.g., standing with the eyes closed or on a sway-referenced platform (Woollacott *et al.*, 1986; Redfern *et al.*, 2001b)). With normal aging, a natural re-weighting of sensory inputs by the CNS is necessary to compensate for the degeneration of some sensory afferents, and allows healthy older adults to be as stable as younger adults during unperturbed stance. Since some degree of degeneration occurs in all three sensory systems, older adults have more difficulty stabilizing their body, compared to young adults, when one or more sensory systems is altered or perturbed. This degeneration can lead to falls among the more frail older adults.

It has to be emphasized that changes in COP parameters with age do not necessarily reflect poor stability or impaired postural control. Accordingly, in the context of this thesis, changes in COP sway parameters were interpreted as alterations in postural control strategies to maintain stability.

### *2.1.2. Proprioception*

Proprioception was first defined by Sherrington (1906) as “the perception of joint and body movement as well as position of the body, or body segments in space.” Besides sense of movement and sense of position (called kinesthesia), proprioception also includes senses of force and heaviness. This information is provided by the proprioceptive receptors; joint receptors and muscle receptors (Golgi tendon organs and muscle spindles), but also by cutaneous mechanoreceptors. Some evidence also shows that a centrally generated sense of effort derived from the motor command contributes to the sense of force and heaviness, and also to kinesthesia (Proske & Gandevia, 2009).

Joint receptors were long thought to be the main receptors involved in informing the CNS about joint position sense and limb movement. However, it is now well known that other receptors, such as muscle and cutaneous receptors, play a large role in proprioception (Proske & Gandevia, 2012). By informing the CNS about the muscle’s contraction velocity and length, it is well accepted that muscle spindles are the main source of positional information during the intermediate range of motion, whereas joint receptors may play a role only in extreme ranges (Lattanzio & Petrella, 1998). Golgi tendon organs serve as active tension sensors (regulation of muscle force, sense of effort) (Proske & Gandevia, 2012). Cutaneous receptors (Meissner’s corpuscles, the Merkel’s disk, Pacinian corpuscles and

Ruffini endings) provide additional information (vibration, pressure and skin stretch) that contributes to signal joint position and movement. Two classes of receptors (i.e., Pacinian corpuscles and Ruffini endings), have been shown to contribute to proprioceptive integration in particular (Collins *et al.*, 2005; Roll *et al.*, 2002), although to a lesser extent than muscle spindles (Collins *et al.*, 2005). In relation to postural control, both muscle spindles (Kavounoudias *et al.*, 1999a; Smetanin *et al.*, 2002; Burke *et al.*, 1976) and cutaneous receptors at the foot and ankle (Roll *et al.*, 2002; Kavounoudias *et al.*, 1998; Kavounoudias *et al.*, 1999b) have been shown to play a critical role.

The importance of muscle spindles for postural orientation has been demonstrated using muscle vibration. Vibration of the gastrocnemius creates an illusion of forward lean (muscle lengthened) (Lackner & Levine, 1979), resulting in contraction of the gastrocnemius muscles. This creates a backward sway until the tibialis anterior is triggered to avoid falling (Kavounoudias *et al.*, 1999a; Smetanin *et al.*, 2002; Burke *et al.*, 1976). Plantar afferents play a complementary role to ankle muscle afferents in signaling changes in body sway during standing (Roll *et al.*, 2002; Kavounoudias *et al.*, 1998; Kavounoudias *et al.*, 1999b). Roll *et al.* (2002) have shown that when the body was restrained, an illusion of lean was reported by subjects in the direction of plantar stimulation, induced by vibration of the sole of the foot. Loss of plantar sensitivity, associated with aging or diabetic neuropathy in older adults, may affect postural orientation and stability. The impact of altered information from cutaneous receptors on postural orientation is even more clear when the postural task is more challenging (Meyer *et al.*, 2004; Hong *et al.*, 2007). Studies have shown that decreased plantar sensitivity increases COP sway when standing with eyes closed (Meyer *et al.*, 2004; Hong *et al.*, 2007), during tandem stance (Hong *et al.*, 2007) or during unipedal stance

(Meyer *et al.*, 2004). Thus, both ankle muscle afferents and plantar tactile afferents appear to provide the most important information about the quality of the support surface and the forces produced against those surfaces for postural orientation and stability (Horak & MacPherson, 1996; Peterka, 2002). In fact, healthy adults rely primarily on somatosensory information when all sensory afferents are available (Daly *et al.*, 2002; Lord *et al.*, 1991; Peterka, 2002).

Many studies have demonstrated a decline in sensitivity of muscle spindles with aging caused by an increase in capsular thickness, and a decrease in the number of intrafusal fibers (Shaffer & Harrison, 2007). These changes have been shown to decrease joint position sense, movement thresholds and dynamic position sense at the ankle (You, 2005; Madhavan & Shields, 2005; Verschueren *et al.*, 2002) and knee (Petrella *et al.*, 1997; Bullock-Saxton *et al.*, 2001), suggesting that older adults may have a reduced capability to discriminate joint angles during movement. Furthermore, normal aging is accompanied by physiological changes to cutaneous receptors, such as a decrease in innervation density, which affects Pacinian and Meissner's corpuscles (Shaffer & Harrison, 2007). The functional implication of these changes include diminished vibration perception, increased pressure detection thresholds (Perry, 2006; Tremblay *et al.*, 2005), and reduced spatial acuity evaluated by two point discrimination (Melzer *et al.*, 2004) and JVP grating domes (Tremblay *et al.*, 2005). The decline in plantar sensitivity with age has been associated with the increased COP sway in the older adult population (Melzer *et al.*, 2004; Menz *et al.*, 2005). Menz and colleagues (Menz *et al.*, 2005) have examined the association between foot and ankle characteristics with different types of balance measurements and found that plantar sensitivity (two-point discrimination) was associated with COP sway on firm and compliant surfaces.

### 2.1.3. Attention

Attention is defined as the information processing capacity of an individual (Woollacott & Shumway-Cook, 2002). Attention is a controlled cognitive process having limited resources (Shiffrin, 1988) and the more resources are needed for a specific stimulus, the more important will be its processing by the CNS, leaving less resources available for a second stimulus presented at the same time (Kahneman, 1973). Thus, if two tasks are performed together and they require more than the total capacity, the performance on either or both deteriorates (Woollacott & Shumway-Cook, 2002). According to the Wickens Multiple Limited Resources Theory (Wickens, 1984), the limited capacity of attention can vary according to the arousal of the person, and the amount of attention set for a task is flexible according to the necessities of the task (allocation policy).

Although postural control during quiet standing has often been taken for granted, studies using the dual-task paradigm have shown that it is attentionally demanding (Woollacott & Shumway-Cook, 2002). However, the performance of the postural task and the cognitive task depend highly on their level of difficulty and also on the instructions given to the subjects (Fraizer & Mitra, 2008). In fact, some studies have shown postural control improvement (less COP sway) during a dual task (Deviterne *et al.*, 2005; Riley *et al.*, 2003; Siu & Woollacott, 2007). A U-shape relationship between postural control and cognitive demands has been proposed, which further suggests that postural control can be improved or diminished depending on the level of difficulty of the secondary cognitive task (Lacour *et al.*, 2008). This beneficial effect of the secondary task may be due to an increase in the automatic processing of postural control by shifting the attention away from the postural task (Riley *et al.*, 2003).

There is no doubt that older adults need more attention to perform the same postural task than their younger counterparts (Woollacott & Shumway-Cook, 2002). A U-shape relationship has also been demonstrated in this population, but the beneficial range of the cognitive task is smaller and the detrimental range is larger, due to reduced attention capacities (Lacour et al., 2008). The detrimental effect of the dual task condition appears to be due in large part to the cognitive task (Lajoie *et al.*, 1993; Brown *et al.*, 2002; Teasdale *et al.*, 1993), suggesting that older adults adopt a “posture first” strategy (task prioritization). The best example of task prioritization is the “stop walking while talking” behavior adopted by frail older adults (Lundin-Olsson *et al.*, 1997). This prioritization on posture has been shown to be more important as the complexity of the postural task increases (Lajoie *et al.*, 1993; Brown *et al.*, 2002; Teasdale *et al.*, 1993). Thus, older adults are potentially more at risk of falling during a dual-task when the postural task is difficult.

#### *2.1.4. Muscle fatigue*

Localized muscle fatigue has been studied for several decades and numerous reviews of the literature are available (Bigland-Ritchie & Woods, 1984; Allen *et al.*, 2008; Allman & Rice, 2002; Enoka & Stuart, 1992; Gandevia, 2001; Giannesini *et al.*, 2003; Hunter *et al.*, 2004; Nordstrom *et al.*, 2007; Proske, 1993; Westerblad *et al.*, 2002). The total amount of force that a muscle can produce depends on multiple factors such as: size of the muscle, number of muscle fibers, type of fibers and number of fibers per motor unit. The ability to produce, regulate and maintain a given amount of force depends on the activation of the contractile system by the CNS (Gandevia, 2001). Muscle fatigue can be defined as an acute impairment in the ability to exert (maximum) force, regardless of whether or not the task itself can still be performed successfully (Bigland-Ritchie & Woods, 1984; Enoka & Stuart,

1992). Multiple central and peripheral mechanisms/structures at different stages of the neuromuscular system (from motor cortex to myofibril activation) alter the production, regulation and maintenance of force. Force reduction (and endurance time) depends on the amount of force or work exerted (i.e., force decreases rapidly during a maximal contraction and decreases slowly during a submaximal contraction) (Bigland-Ritchie & Woods, 1984; Enoka & Stuart, 1992), whereas the recovery time declines as the amount of force sustained increases. Thus, the extent to which central and peripheral mechanisms are involved during muscle fatigue is strongly dependent on the task performed (Bigland-Ritchie & Woods, 1984; Enoka & Stuart, 1992).

Central fatigue is defined as a progressive reduction in voluntary activation of muscles during exercise (Gandevia, 2001), due to a decrease in motoneuron excitation by supraspinal and spinal mechanisms (Boyas & Guevel, 2011). These mechanisms include a) reduction of the excitation supplied by the motor cortex due to depletion or accumulation of certain brain neurotransmitters, and b) inhibition (direct or indirect) of the motoneurons mainly due to excitation of group III and IV muscle afferents. Central fatigue is evidenced by a reduction in the level of voluntary activation, measured with percutaneous electrical stimulation (twitch interpolation). It has been shown that central fatigue contributes up to 25% of the force reduction during sustained, maximal contraction, and even more during low-intensity contractions (Gandevia, 2001).

Peripheral fatigue is defined as fatigue produced by changes at or distal to the neuromuscular junction (Gandevia, 2001). The mechanisms involved may include changes in: a) neuromuscular propagation, b) availability of metabolic substrates, c) excitation-

contraction coupling, d) interactions between contractile proteins, and d) blood flow. For more details, these mechanisms have been reviewed elsewhere (Bigland-Ritchie & Woods, 1984; Enoka & Stuart, 1992; Allen *et al.*, 2008; Barry & Enoka, 2007).

## **2.2. Localized muscle fatigue and postural control**

Despite the complexity of postural control and the numerous interactions between systems in order to maintain postural stability, the level of contraction required in the lower limb is fairly low (10% of maximal voluntary contraction (MVC)) during quiet standing (Okada, 1973). However, muscle fatigue has been shown to decrease the speed at which force can be generated (Bigland-Ritchie & Woods, 1984; Allen *et al.*, 2008; Enoka & Stuart, 1992; Gandevia, 2001) and to alter proprioceptive information from muscle afferents (Forestier *et al.*, 2002; Hiemstra *et al.*, 2001; Lattanzio *et al.*, 1997; Vuillerme *et al.*, 2007; Vuillerme & Boisgontier, 2008). Since the 1990's, studies on quiet standing have shown that muscle fatigue (mainly the ankle or knee muscles) results in increased COP sway displacement (measured by the area, range or amplitude of the COP) and/or an increase in COP sway corrections (measured by the velocity and median frequency of the COP) (see Table 1-3).

Lundin and colleagues (1993) first suggested that the effect of fatigue on postural control results from a delay in force-generating capabilities and proprioceptive deficits, and several studies have since also implicated these two mechanisms (Corbeil *et al.*, 2003; Gribble & Hertel, 2004a; Gribble & Hertel, 2004b; Harkins *et al.*, 2005; Ledin *et al.*, 2004; Vuillerme *et al.*, 2001; Vuillerme *et al.*, 2002b; Vuillerme *et al.*, 2002a; Vuillerme *et al.*,

2002c; Vuillerme & Nougier, 2003; Vuillerme *et al.*, 2006b). Other studies have suggested that an increase in joint stiffness (Caron, 2003; Caron, 2004; Corbeil *et al.*, 2003) and an increase in attentional demands (Vuillerme *et al.*, 2002b; Simoneau *et al.*, 2006) could also play a role. However, the respective role of these mechanisms in relation to postural control remains unclear. The disparity of results in the literature due to different muscle groups targeted, fatigue and/or postural task used, and COP sway variables reported make it difficult to understand the mechanisms responsible for the postural control alterations due to muscle fatigue.

Since the effect of aging on postural control (Redfern *et al.*, 2001a; Woollacott *et al.*, 1986) and on muscle fatigue (Allman & Rice, 2002) have both shown task-dependency, the different methodological procedures between studies needs to be taken into account to clearly understand the mechanisms involved. Thus, the objective of the following sections is to examine to what extent the task-dependent nature of muscle fatigue has an impact on postural control. Findings from studies with similar fatigue protocols are grouped into two categories (dynamic and isometric contractions) and are summarized in three tables (see Table 1 to 3) with an emphasis on the similarities or differences of the findings due to fatigue task and postural task differences.

Although some studies have shown changes in COP variables when fatiguing muscle groups other than those of the lower limb (i.e. trunk and neck) (Davidson *et al.*, 2004; Gosselin *et al.*, 2004; Vuillerme *et al.*, 2005), with non-specific exercise (Ageberg *et al.*, 2003; Erkmen *et al.*, 2009; Lepers *et al.*, 1997; Nardone *et al.*, 1997) or studying responses to perturbations (Vuillerme *et al.*, 2002c; Strang & Berg, 2007), the following section will

focus on studies that have documented the effect of localized muscle fatigue of the lower limb on postural control during quiet standing.

### *2.2.1. Dynamic fatigue protocols*

Dynamic fatigue protocols refer to all types of fatigue tasks that include movement (concentric, eccentric or isotonic contractions). Studies that used this type of protocol have generally shown an increase in numerous COP sway variables when fatiguing muscles using either a dynamometer or a functional task. Table 1 and Table 2 summarize both types of protocols, respectively, and their effects on COP sway displacement variables (i.e., area, range, amplitude) and COP sway correction variables (i.e., velocity, median frequency).

The isokinetic dynamometer has been widely-used to fatigue different muscle groups with the advantage of controlling numerous parameters such as the type of contractions (concentric only or concentric/eccentric contractions), the speed of contractions, and the force produced per contractions (percentage of MVC). On the other hand, this fatigue task restrains researchers to fatiguing only one joint (in one limb) at a time. Thus, of those studies that used the dynamometer to examine the effect of fatigue of different muscle groups on postural control, most reported the effect on a single-leg stance task (see Table 1). With the exception of one study (Rozzi *et al.*, 1999), all those using an isokinetic dynamometer found some postural control alterations with muscle fatigue despite differences in the type and intensity of contractions (Gribble & Hertel, 2004a; Lundin *et al.*, 1993; Yaggie & McGreggor, 2002; Harkins *et al.*, 2005; Surenkok *et al.*, 2006; Salavati *et al.*, 2007; Dickin & Doan, 2008; Lin *et al.*, 2009; Gribble & Hertel, 2004b). Regardless of differences between studies in terms of the COP sway variables measured, three main findings can be retained: 1)

when standing on a firm surface, COP sway in the ML plane appears to be more altered due to fatigue than COP sway in the AP plane; 2) fatigue of proximal muscles creates more postural control alterations compared to fatigue of distal muscles when standing on a firm or a compliant surface; and 3) increased COP sway due to muscle fatigue is found regardless of the availability of vision. However, vision may attenuate ankle muscle fatigue during a unipedal stance (Boyas *et al.*, 2011).

COP sway displacement during a single-leg stance on a firm surface increases in the ML plane only following an intermittent concentric/eccentric ankle muscle fatigue protocol targeting sagittal plane movers (Lundin *et al.*, 1993) or both sagittal and frontal plane movers (Yaggie & McGregor, 2002). The lack of significant results in the AP COP sway displacement on a firm surface in these two studies may be due to the specificity of the task (reduced base of support) or the first muscle group fatigued may have recovered during an intermittent protocol, reducing the effect of fatigue. Both studies concluded that the possible mechanisms contributing to the increased displacement are delays in force-generating capabilities of the ankle musculature and alterations in ankle joint proprioception. Interestingly, Lundin and colleagues (1993) support this last mechanism by showing an anterior shift of the mean COP. These authors suggested a re-weighting of proprioceptive information from the ankle muscles to the big toe muscles of the foot. An alternative interpretation could be that leaning forward in more risky situations, like muscle fatigue, is mechanically more stable.

**Table 1. Dynamic fatigue protocol using a dynamometer.**

Paper	n (M/F)	Muscles <sup>a</sup>	Fatigue Task <sup>b</sup>	Postural Task <sup>c</sup>	Postural Displacement <sup>d</sup>	Postural Corrections <sup>d</sup>	Comments
Lundin et al. 1993	8/0	PF, DF	intermittent CON/ECC	SL-EO	↑ML	n/a	
Johnston et al. 1998	12/8	multijoint	closed kinetic chain 10 1-min sets at different speed	SL-EO, FA-EO, FA- chasing task	n/a	↑total	Not significant for the FA chasing task (balance master index score).
Rozzi et al. 1999	17/17	KE, KF	CON/CON 180deg/s, 2 sets of 40 and a third set until 25%MVC	SL-EO, sway-referenced platform	ns	n/a	The lack of significance may be due to the population (athletes).
Yaggie & Mcgreggor. 2002	24/0	PF, DF AI, AE	CON/ECC 60 deg/s until 50% MVC	SL-EO, leaning forward	↑ML, ↑total	n/a	
Gribble & Hertel. 2004a	4/10	PF, DF KE, KF HE, HF	CON/CON 60deg/s until 50% MVC	SL-EO	n/a	↑AP, ↑ML	Fatigue effects were greater for knee and hip muscle fatigue than ankle muscle fatigue.
Gribble & Hertel. 2004b	4/9	AI, AE HAD, HAB	CON/CON 60deg/s until 50% MVC	SL-EO	n/a	↑ML	Fatigue effects were only significant for the hip muscle fatigue.
Harkins et al. 2005	10/10	PF, DF	CON/CON 60/120 deg/s until 30% or 50% MVC	SL-EC	n/a	↑total	Longer alterations with 30% fatigue protocol.
Surenkok et al. 2006	16/0	KE, KF	CON/CON 60deg/s until 25% MVC	SL-EO, sway-referenced platform	↑Stability Index Score	n/a	
Salvati et al. 2007	10/0	PF, DF AI, AE HE, HF HAD, HAB	ankle: CON/CON, 60/120 deg/s hip: CON/CON, 60/90 deg/s until 50% MVC	SL-EC, sway-referenced platform	↑AP, ↑ML, ↑total	n/a	Fatigue effects were greater for hip muscle fatigue than ankle muscle fatigue.
Dickin & Doan. 2008	9/7	PF, DF KF, KE whole leg	CON/CON ? deg/s until 70% MVC squat jumps until 80% max jump	SL-EO, firm & sway referenced platform	↑AP	n/a	No difference between firm and sway-referenced platform or between fatigue locations.
Lin et al. 2009	16	PF, KE	Isotonic, 12reps/min at 60% MVC	FT-EO	↑total	ns	Fatigue effects were only significant for ankle muscle fatigue (Unilateral fatigue with a bilateral postural task).
Boyas et al. 2011	8/8	PF, DF	PF: CON 30 deg/s DF: CON 120 deg/s PF-DF: CON/CON 30/120 deg/s Each until 50% MVC	SL-EO SL-EC	↑total	↑AP	Fatigue effects were only significant for EC with PF-DF fatigue.

<sup>a</sup> PF: plantarflexors, DF: dorsiflexor, KE, knee extensors, KF: knee flexors, HE: hip extensors, HF: hip flexors, AI: ankle invertors, AE: ankle evertors, HAD: hip adductors, HAB: hip abductors

<sup>b</sup> MVC: maximal voluntary contraction, CON: concentric contractions, ECC: eccentric contractions. IK: isokinetic, IM: isometric

<sup>c</sup> FA: feet apart, SL: single-leg stance, EO: eyes opened, EC: eyes closed, n/a: not reported or applicable

<sup>d</sup> AP: antero-posterior plane, ML: medio-lateral plane

Following a concentric/concentric ankle muscle fatigue protocol, Gribble & Hertel (2004a; 2004b) have demonstrated little (Gribble & Hertel, 2004b) or no changes (Gribble & Hertel, 2004a) in COP sway velocity when targeting sagittal or frontal plane movers, respectively. Although, in both studies, the fatigue of more proximal muscle groups did lead to a greater, albeit small, increase in COP sway velocity than distal muscle groups. These authors suggested that a hip strategy was preferred during the single-leg stance control. They

posit that hip muscle fatigue significantly increases COP sway velocity by creating gross corrective contractions, whereas, ankle muscle fatigue creates only small corrective contractions at the ankle joint, resulting in little impact on COP sway. This hypothesis is not consistent with other studies where an increase in COP sway displacement was found during ankle muscle fatigue (Boyas *et al.*, 2011; Lundin *et al.*, 1993; Yaggie & McGregor, 2002).

Similarly, Lin *et al.* showed an increase in COP sway displacement when fatiguing the ankle (but not when fatiguing the knee), which contradicts the findings of Gribble & Hertel (Gribble & Hertel, 2004a; Gribble & Hertel, 2004b). This study was different in that it used a unilateral muscle fatigue protocol, although, the authors tested postural stability in bilateral stance. Thus, the hypothesis that proximal muscle fatigue induces greater COP sway compared to distal muscle fatigue may only be true for the one-leg stance. Since distal muscles are the main muscle groups for postural stability in a bilateral stance, ankle muscle fatigue may have more effects on postural control than hip muscle fatigue. Nonetheless, fatiguing only one leg and testing postural control using a bilateral task might have reduced the effect of fatigue. Future studies need to explore the differences in effects between proximal vs. distal muscle fatigue.

Other studies have used different types of sway-referenced platforms to reduce the proprioceptive contribution to postural control while investigating the effect of fatigue on postural control (Salavati *et al.*, 2007; Surenkok *et al.*, 2006; Johnston *et al.*, 1998; Rozzi *et al.*, 1999). Stability index scores have been shown to increase (meaning more COP sway) when fatiguing the knee (Surenkok *et al.*, 2006), the ankle, and the hip (Salavati *et al.*, 2007), and when fatiguing the whole leg (Johnston *et al.*, 1998). These similar results were

significant despite different postural tasks (eyes open, eyes closed), different contraction types and speeds in the fatigue protocol, and different fatigue criteria. In contrast, Rozzi and colleagues (1999) did not show any changes in COP sway displacement after fatiguing the knee muscles despite a decrease in kinesthesia (movement detection threshold) at the knee. However, AP and ML COP sway changes were not reported separately; thus, the effect on COP sway displacement in the plane (AP) where the knee is the main effector was not verified. Salavati and colleagues (2007) have shown a greater increase in COP sway displacement when fatiguing the hip muscle compared to fatiguing the ankle muscle, which supports the finding of Gribble & Hertel (2004b). On the other hand, these studies (Salavati *et al.*, 2007; Surenkok *et al.*, 2006; Johnston *et al.*, 1998; Rozzi *et al.*, 1999) did not attempt to determine whether muscle fatigue led to a greater COP sway displacement when standing on a sway-referenced surface compared to a stable surface. Although COP sway displacement was greater when standing on the sway-referenced surface, Dickin & Doan, (2008) have shown no greater increase in COP sway displacement between firm and sway-referenced surfaces when fatiguing ankle, knee, or whole leg. It is difficult to draw general conclusions from this study due to methodological flaws i.e., only one 10-s trial was completed per postural task conditions when others have recommended to use at least 30 seconds to get a reliable measure of COP sway (Pinsault & Vuillerme, 2009).

A limitation that is recurrent in almost all studies, despite the ability to control for all fatigue parameters with the dynamometer, is that these studies do not report a decrease in force due to fatigue and the reader is assuming that a fatigue criterion (e.g., 50% MVC) was reached. Even if it was, the ratio of fatigue percentage reached between muscle groups (plantarflexors vs. dorsiflexors) could be different between studies, and could explain some

differences between studies. Furthermore, most of these studies omitted to report the time to fatigue, which may also explain differences in the results (e.g., peripheral vs. central fatigue may be different). In fact, Harkins and colleagues (2005) demonstrated an increased COP sway velocity with a more vigorous ankle muscle fatigue protocol (concentric/concentric contractions until 30% MVC compared to 50% MVC).

It may be argued that muscle fatigue induced with a dynamometer is not truly relevant to functional behavior and a functional fatigue task should be used instead. A summary of the studies that used a (more) functional task as a dynamic fatigue protocol are shown in Table 2. Most of these studies (Adlerton & Moritz, 1996; Adlerton *et al.*, 2003; Ledin *et al.*, 2004; Springer & Pincivero, 2009; Vuillerme *et al.*, 2006b; Laudani *et al.*, 2009) have fatigued the plantarflexor muscles by asking the subjects to perform heel raises until exhaustion (by following the beat of a metronome). This fatigue protocol generally results in an increase in COP sway displacement in the AP plane (Ledin *et al.*, 2004; Springer & Pincivero, 2009; Vuillerme *et al.*, 2006b; Laudani *et al.*, 2009) and in the ML plane (Springer & Pincivero, 2009; Vuillerme *et al.*, 2006b), despite differences in the postural task. However, two studies showed that vision attenuated the effect of muscle fatigue when subjects stared at a target (black cross at eye level) at 1m (Ledin *et al.*, 2004; Vuillerme *et al.*, 2006b).

Although some studies have reported the number of heel raises and exertion score after the fatigue task, the amount of fatigue induced by this type of protocol is difficult to interpret since it is relative to the weight of the subject, and therefore, work as a percentage of the MVC is variable between subjects. This might explain why two studies have shown no

**Table 2. Dynamic fatigue protocol using a functional task.**

Paper	n (M/F)	Muscles <sup>a</sup>	Fatigue Task <sup>b</sup>	Postural Task <sup>c</sup>	Postural Displacement <sup>d</sup>	Postural Corrections <sup>d</sup>
Alderton & Moritz 1996	2/11	PF	heel raises until exhaustion	SL-EO	n/a	ns
Alderton et al. 2003	0/23	PF	heel raises until exhaustion	SL-EO	↑AP, ↑ML	↓AP, ↓ML
Corbeil et al. 2003	11/0	PF	100 heel raises drop sets starting at 75%MVC	FT-EO, FT-EC	ns	↑AP, ↑ML
Caron. 2004	10/0	SOL	60% MVC seated heel raises until exhaustion	FA-EO, FA-EC	ns	↑total
Ledin et al. 2004	5/6	PF	heel raises until exhaustion	FA-EO, FA-EC	↑AP	n/a
Vuilleme et al. 2006	12	PF	heel raises until exhaustion	FA-EO, FA-EC	↑AP, ↑ML	n/a
Pinsault & Vuilleme	15/0	PF	heel raises until exhaustion	FA-EC	↑AP, ↑ML more with head tilt and less with improved neck somatosensory info	n/a
Laudani et al. 2009	5/5	PF	heel raises until exhaustion	FA-EO	↑AP	n/a
Springer & Pincivero 2009	10/10	PF cardio	heel raises, rowing until exhaustion	SL-EO	↑AP, ↑ML	n/a
Reimer & Wikstrom 2009	9/9	PF HE	SL squat, SL heel raise until 65% of 1RM	SL-EC, sway-referenced platform	↑AP, ↑ML	n/a
Vuilleme et al. 2009	24/0	HAB	lateral leg raises with 1kg load	FT-EC	↑ML	n/a
Vuilleme & boigontier 2010	8/0	PF	unipodal heel raises until exhaustion	FT-EC	↑area	↑mean; non-fatigued leg only
Hlavackova 2011	12	PF Fingers	heel raises until exhaustion	FA-EC	↑mean; PF only	↑mean; PF only
Roerdink 2011	16/0	PF	heel raises until exhaustion	FA-EC	↑AP	↓ Sample entropy
Theдон 2011	7/1	PF	heel raises until exhaustion	FA-EC with and without kintape	↑AP (path), less with kintape	n/a
Gimmon et al. 2011	3/7	PF	heel raises until exhaustion	FT-EC, foam surface	↑AP	↑AP, ↑ML

<sup>a</sup> PF: plantarflexors, SOL: soleus, HE: hip extensors, HAB: hip abductors

<sup>b</sup> MVC: maximal voluntary contraction, RM: maximal repetition

<sup>c</sup> SL: single-leg stance, FA: feet apart, FT: feet together, EO: eyes opened, EC: eyes closed, ns: not significant, n/a: not reported or applicable

<sup>d</sup> AP: antero-posterior plane, ML: medio-lateral plane

(Alderton & Moritz, 1996) or minimally (Alderton et al., 2003) significant results (increase of only 1 mm of COP sway amplitude). When normalizing the fatigue task to the weight of subjects, Laudani and colleagues (Laudani et al., 2009) and Ledin and colleagues (2004) have shown a significant increase in COP sway displacement during two different postural tasks; normal stance (feet apart) and single-leg stance, respectively. This suggests that postural control alterations due to ankle muscle fatigue are not dependent on the postural task performed. Interestingly, two studies using a load relative to the subjects' MVC, have shown an increase in COP sway velocity but not COP sway displacement when standing with feet

apart after seated heel raises (Caron, 2004), or when standing with feet together after standing heel raises (Corbeil et al., 2003). This increase in COP sway velocity was found with eyes closed and eyes open staring at a target (black cross at eye level) at 4m (Corbeil et al., 2003) and at 1m (Caron, 2004), contradicting the findings of Vuillerme and colleagues (Vuillerme *et al.*, 2001; Vuillerme *et al.*, 2006b). This suggests that vision does not necessarily attenuate the effect of fatigue on postural control.

Moreover, Reimer III & Wikstrom (2009) have demonstrated an increase in the stability index score when standing single-leg on a sway-referenced platform with the eyes open after fatiguing the ankle and the hip muscles to 65% MVC. The authors concluded that their functional task could not isolate muscle group (squats and standing heel raises), which could explain the lack of significant differences in COP sway displacements when different muscle groups were fatigued. Only one other study (Vuillerme *et al.*, 2006b) has looked at the effect of hip muscle fatigue on bilateral standing. After fatiguing the hip abductors of the right leg (lateral leg raises), they showed, using two force platforms, an increase of ML COP sway displacement of the left non-fatigued leg. However, no comparison with ankle muscle fatigue was made. Thus, differences between hip muscle and ankle muscle fatigue should be further examined during dynamic functional fatigue tasks.

As mentioned above, the time to fatigue might explain differing results between studies using a functional task. By asking the subject to lift a load relative to their MVC adjusted for their body weight, the work load is greater, thus, fatigue arises sooner, possibly explaining the differences in effects on postural control. However, none of these studies

reported the time to fatigue. Therefore, more studies are needed to examine this hypothesis and the mechanisms involved.

### *2.2.2. Static contractions fatigue protocol*

As shown in Table 3, studies using fatigue protocols involving static or isometric contractions have mainly examined the effect of fatigue of the plantarflexor muscles with consistent results. COP sway displacement and COP sway corrections appear to increase when subjects are asked to stand on their tip-toes for as long as possible until exhaustion, independent of the postural task performed (Mello *et al.*, 2007; Bisson *et al.*, 2010; Vuillerme *et al.*, 2001; Vuillerme *et al.*, 2002a; Vuillerme *et al.*, 2002b; Vuillerme & Nougier, 2003). The extent of the COP sway increase due to muscle fatigue does not seem to depend on the difficulty of the task unless postural control is highly threatened (eyes closed and on one-leg) (Bisson *et al.*, 2010).

As all fatigue protocols used a functional task, the fatigue task in these studies is relative to the weight of the subject. The fact that postural control alterations due to fatigue are consistent throughout these studies may show the importance of the specificity of the fatigue task in relation to the postural system. The fatigue task using quasi-isometric contractions might induce greater instability in the postural system because of the similarities with the postural task (mainly isometric contractions). This hypothesis is further supported by Freitas and colleagues (2005) who showed an increase in COP sway displacement and corrections when standing with feet apart and eyes open after a prolonged period (30 min.) of standing. In contrast, studies using isometric contractions at high intensity with a fatigue criterion relative to the strength of the subject have reported changes in COP sway

corrections but no increase in COP sway displacement when fatiguing the soleus (Caron, 2003) and the quadriceps (Bizid et al., 2009). In addition, in this last study (Bizid et al., 2009), ankle muscle fatigue failed to increase COP sway during a unipedal stance with eyes closed.

Apart from the consistency of observed significant changes in COP sway displacement and corrections, studies using isometric contractions with the subject's own weight as a load have supported two main mechanisms to explain the changes in COP sway during standing in a fatigued state. First, by showing an increase in the lag between muscle activity and COP sway during muscle fatigue, Mello and colleagues (2007) provide support for the effect of a delay of force generating capacity on postural control. Second, the possible effect of reduced proprioception due to a decline of the muscle spindle sensitivity has been supported by studies demonstrating no greater increase in COP sway when the fatigued muscle is vibrated (Vuillerme *et al.*, 2002a; Ledin *et al.*, 2004). Also due to impaired proprioception, re-weighting the sensory information has been supported by studies demonstrating an attenuation of the effect of fatigue by increasing haptic cues with light touch (Vuillerme & Nougier, 2003). Although Vuillerme and colleagues (2001) have shown an attenuation of the effect of fatigue by adding visual information, the incremental reliance on visual information when the muscle is fatigued is still debatable, especially when the COP measurement was made only on 4 s of data.

Future studies should concentrate on validating the hypothesis that postural control alterations due to muscle fatigue may differ depending on the mode of contractions (dynamic or isometric) used to fatigue the muscles. Also, the effect of fatigue on COP sway with

reduced proprioception (sway-referenced platform or foam surface) should be investigated using isometric contractions.

**Table 3. Static contractions fatigue protocol.**

Paper	n (M/F)	Muscles <sup>a</sup>	Fatigue Task <sup>b</sup>	Postural Task <sup>c</sup>	Postural Displacement <sup>d</sup>	Postural Corrections <sup>d</sup>	Comments
Vuillerme et al. 2001	10/0	PF	stand on toes until exhaustion	SL-EO to EC, SL-EC to EO	↑EC	↑EC	Vision attenuated fatigue effects.
Vuillerme et al. 2002a	10	PF	stand on toes until exhaustion	FA-EC / vibration	↑EC	↑EC	No additional increase with vibration.
Vuillerme et al. 2002b	9	PF	stand on toes until exhaustion	FT-EC / RT	↑total	↑total	Fatigue increased attentional demands (RT).
Vuillerme et al. 2003	9	PF	stand on toes until exhaustion	FT-EC / light touch	↑total	↑total	Light touch attenuated fatigue effects.
Caron 2003	10/0	SOL	60% MIVC until exhaustion	narrow FA-EO	n/a	↑total	
Mello et al. 2007	15/7	PF	stand on toes until exhaustion	FT	↑total	↑AP, ↑ML	Fatigue increased lag between muscle latency and COP sway.
Bizid et al. 2009	8/0	PF, KE	MIVC 5-2 sec cycle until exhaustion	SL-EC	n/a	↑ML	Fatigue effects were only significant for knee muscle fatigue.
Bisson et al. 2010	12/12	PF	stand on toes until exhaustion	SL-EO, SL-EC ST-EO, ST-EC FT-EO, FT-EC	↑AP, ↑ML	↑AP, ↑ML	Fatigue effects were greater in SL and FT, and greater with EC.

<sup>a</sup> PF: plantarflexors, SOL: soleus, KE, knee extensors

<sup>b</sup> MIVC: maximal isometric voluntary contraction

<sup>c</sup> SL: single-leg stance, FA: feet apart, FT: feet together, ST: semi-tandem stance, EO: eyes opened, EC: eyes closed, n/a: not reported or applicable

<sup>d</sup> AP: antero-posterior plane, ML: medio-lateral plane

### 2.3. Muscle fatigue mechanisms altering postural control

As previously mentioned, by definition, fatigue creates an acute impairment in the ability to exert (maximal) force or power, regardless of whether or not the task itself can still be performed successfully (Enoka & Stuart, 1992; Bigland-Ritchie & Woods, 1984). This reduction in force can be caused by several central or peripheral physiological mechanisms. In addition, fatigue can also affect sensory processes and integration leading to changes in motor coordination (Forestier & Nougier, 1998; Hufnagel *et al.*, 2006). The impact of these mechanisms on postural control can be grouped into four categories: delay of force-

generating capabilities, changes in joint stiffness, alterations of the proprioceptive information, and changes in central processing.

### *2.3.1. Delay of force-generating capabilities*

It is well known that muscle fatigue induces a reduction in contractile speed (See Nordstrom et al., 2007 for a review). This reduction can create a delay between the central motor command and the movement execution by the muscle. From a postural control perspective, increasing the delay of the muscle command to action could seriously impair the neuromuscular loop. Recently, Mello and colleagues (2007) showed that for quiet standing, muscle activity precedes COP sway displacement with a latency of around 1 second. This confirms that postural muscle activity is anti-phase with COP sway (catch-and-release strategy). These authors also found an increase in the latency between muscle activity and COP sway displacement after fatigue (Mello et al., 2007).

An increase in the delay between the muscle action and the COP displacement results in an increased COP sway area and velocity (Mello et al., 2007). Numerous studies have also shown an increase in COP sway displacement with continuous or intermittent submaximal fatigue (Adlerton *et al.*, 2003; Caron, 2003; Johnston *et al.*, 1998; Ledin *et al.*, 2004; Lepers *et al.*, 1997; Nardone *et al.*, 1997; Vuillerme *et al.*, 2001; Vuillerme *et al.*, 2002a; Vuillerme *et al.*, 2002b; Vuillerme & Nougier, 2003; Vuillerme *et al.*, 2006b; Lundin *et al.*, 1993); and a delay in muscle force production could be responsible. Yaggie & McGregor (2002) have proposed this mechanism to explain the increased medio-lateral and total sway found during a leaning task after fatiguing the ankle sagittal movers. On the other hand, two studies (Vuillerme *et al.*, 2002b; Lundin *et al.*, 1993) have shown that the increase in COP sway area

observed when fatiguing the calf muscles (primary postural muscles in quiet standing) is a result of an anterior shift of the COP mean position that is closer to the limit of stability. These authors (Vuillerme *et al.*, 2002b; Lundin *et al.*, 1993) suggest that the CNS adapts to the muscle delay in the fatigued muscle in favor of the use of toe muscle (not affected by fatigue). An alternative interpretation could be that leaning forward in more risky situations, like muscle fatigue, is mechanically more stable.

### 2.3.2. *Changes in joint stiffness*

The reduction in contractile speed creating the delay between muscle command and mechanical action has a reverse effect on posture. As stated above, studies have demonstrated an increase in COP sway velocity with a high intensity dynamic fatigue protocol (Corbeil *et al.*, 2003; Gribble & Hertel, 2004a; Gribble & Hertel, 2004b) but also with low intensity isometric contractions fatigue protocols (Caron, 2003; Caron, 2004; Mello *et al.*, 2007; Vuillerme *et al.*, 2001; Vuillerme *et al.*, 2002a; Vuillerme *et al.*, 2002b; Vuillerme & Nougier, 2003). A possible explanation for this effect suggested by some authors is increased joint stiffness in the inverse pendulum strategy (more activation in the agonist and antagonist muscle); thus, increasing the frequency of corrections made to body sway (Caron, 2003; Caron, 2004; Corbeil *et al.*, 2003; Gribble & Hertel, 2004a; Gribble & Hertel, 2004b). Corbeil and colleagues (2003) demonstrated an increased COP sway velocity and increased COP sway median frequency after fatiguing the plantarflexors. Using stabilogram diffusion analysis developed by Collins & DeLuca (Collins & De Luca, 1993), an increased anti-persistent (less stochastic) behavior to control upright stance during ankle muscle fatigue was also found, thus, postural control was more tightly regulated (i.e., increase the amount of corrections made by the postural control system). These authors

concluded that a) a “stiffening strategy” (by increasing the activation of the antagonist) was used in order to better resist perturbations induced by fatigue, and b) the increase in the frequency of corrections was needed in order to compensate for the reduction in the rate of force created by muscle fatigue.

As described previously, a decrease in force is unlikely to have a direct impact on postural control; however, a decrease in cross-bridge function, due to an increase in the concentration of metabolic intracellular substrates, leads to increased muscle activity to maintain posture (Laughton et al., 2003). This is likely due to an increase in motor unit (MU) recruitment and an increase in MU firing rates during submaximal effort. Thus, metabolic intracellular substrates might contribute to the increased stiffness of active muscle (co-contraction) observed in postural control during fatigue. It has to be noted that intrinsic muscle stiffness may be affected by muscle fatigue (Gajdosik, 2001; Zhang & Rymer, 2001) and may contribute to the increased activation of non-fatigued muscle to maintain joint stiffness during standing.

Along the same lines, Caron (2000) has used a COG/COP amplitude ratio as an index of active joint stiffness (Caron, 2000). The relationship between these two variables in the frequency domain is an indicator of the performance of the postural control system. Caron (2003) showed that the increased COP sway velocity observed during fatigue is due to an increase in high frequency of the COP, with no accompanying changes in the body COG, indicating greater joint stiffness. Caron duplicated these results in a second study (Caron, 2004); when they additionally removed vision, fatigue did not induce additional joint stiffness.

### 2.3.3. *Alteration to proprioceptive information*

During muscle fatigue, changes in the discharge patterns of muscle afferents have been observed leading to potential altered perceptions and effects on the efferent pathways (Gandevia, 2001; Taylor *et al.*, 2000). Animal experiments have provided evidence of muscle fatigue altering the information provided by muscle receptors, but the link between these changes and human performance remains controversial (Proske & Gandevia, 2012). Nonetheless, muscle fatigue has been shown to alter the ability of participants to sense position and force (Proske & Gandevia, 2012). Recent research suggests that the main mechanism underlying fatigue-induced effects is a change in the central mapping of limb representation due to a decrease in force level (Tsay *et al.*, 2012). The following section summarizes the studies on muscle fatigue and position sense, movement sense and force sense at the ankle; presents a hypothesis about the mechanisms involved; and finally, discusses studies providing evidence of reduced proprioception as a possible factor for postural control alterations due to muscle fatigue.

#### 2.3.3.1. *Position sense.*

Evidence of a decrease in joint position sense (JPS) has been found after fatiguing the shoulder (Lee *et al.*, 2003; Myers *et al.*, 1999), the elbow (Allen & Proske, 2006; Saxton *et al.*, 1995; Walsh *et al.*, 2004), the knee (Givoni *et al.*, 2007; Skinner *et al.*, 1986; Lattanzio & Petrella, 1998) and the ankle (Forestier *et al.*, 2002; Sandrey & Kent, 2008; Vuillerme *et al.*, 2007). In summary, regardless of the type of contractions, muscle fatigue with a level of force reduction of 20% or more, will induce significant errors in JPS (Proske & Gandevia, 2012). In relation to JPS at the ankle, studies examining the effect of muscle fatigue on JPS of the sagittal (Forestier *et al.*, 2002; Gurney B *et al.*, 2000; Huston *et al.*, 2005; Shields *et*

*al.*, 2005; Vuillerme *et al.*, 2007; Vuillerme & Boisgontier, 2008) and frontal (Lin *et al.*, 2008; Sandrey & Kent, 2008; South & George, 2007) movers have shown mixed results. When fatiguing the sagittal plane movers, Gurney and colleagues (2000) did not find a decrease in passive JPS after fatiguing both plantar and dorsiflexor muscles. However, active JPS (matching task; when the ankle is unsupported) was found to be significantly reduced after fatiguing the dorsiflexor muscles at 20° in dorsiflexion (DF) and 10° in plantarflexion (PF) (Forestier *et al.*, 2002) and after fatiguing the plantarflexor muscles at 10° in plantarflexion (Vuillerme *et al.*, 2007). Interestingly, Forestier and colleagues (2002) found no differences at 20° PF and 10° DF, in line with the results found by Gurney and colleagues (2000) and Huston and colleagues (2005). Thus, with regards to ankle position sense, muscle fatigue seems to have an effect only on active JPS. Additionally, no studies on ankle muscle fatigue have shown a decrease in the bias of limb positioning (constant error), only a bias in JPS accuracy (absolute error). Forestier *et al.* (2002) suggested that a decrease in muscle spindle discharge and increased activity of the fusimotor system, which adds noise to the system, could explain the alteration in JPS accuracy. It has to be noted, though, that these studies did not perform a conditioning contraction prior to JPS testing, which may explain the lack of significant results for the constant error (Proske & Gandevia, 2012). More studies on the effect of muscle fatigue on ankle JPS are needed to clarify these findings.

Recent work from Proske and colleagues (Tsay *et al.*, 2012; Givoni *et al.*, 2007; Allen *et al.*, 2010; Allen & Proske, 2006) provides new insights as to how muscle fatigue impairs position sense by testing JPS in supported and unsupported conditions. They recently showed that fatigue of the extensors or the flexors creates the same directional errors; that is, in extension when testing the elbow and in flexion when testing the knee (Allen *et al.*, 2010).

This contradicts the “fatigued muscle always feels longer” hypothesis. This group has observed that repetitive movements without apparent muscle fatigue (6% force reduction) does not create changes in position sense, suggesting that skin joint receptors and muscle spindle discharge rate may not be responsible for the position errors during muscle fatigue (Tsay *et al.*, 2012). They have also found that, muscle fatigue with limited movement (isometric contractions) created changes in position sense, suggesting that the decrease in force is important for generating position errors, not the pattern of afferent activity (Tsay *et al.*, 2012). And finally, they noted that a reduced position sense was maintained after eccentric muscle fatigue with accompanied force reduction 24h later, which suggests that the decrease in force is the principal factor determining position errors after all forms of exercise (Tsay *et al.*, 2012). This group hypothesizes that a decrease in force produces a shift of the body map in the direction of a gravity-neutral posture of the limb (arm more extended, knee more flexed), regardless of the muscle fatigue (agonist vs. antagonist). This hypothesis needs to be further tested by inverting the position of the subjects during the JPS testing (e.g., supine face down vs. seated position during knee JPS).

#### 2.3.3.2. *Movement sense.*

Although studies are limited, it seems that the effect of fatigue on movement sense is small. Allen and Proske (2006) showed no effect of fatigue on movement sense during a movement tracking task at different speeds. As for motion detection threshold, Skinner and colleagues (1986) have found no differences with knee muscle fatigue, whereas ankle muscle fatigue has been shown to increase motion detection threshold by 1.53° in one study (Rozzi *et al.*, 1999), and by 0.18° in another study (Roberts *et al.*, 2003). Given the limited number

of studies, it would be premature at present to conclude that movement detection is affected by fatigue.

#### 2.3.3.3. *Force sense.*

The sensation of muscle force is provided through the sense of tension generated from the GTO and from the sense of effort (Gandevia, 2001). The sense of effort is defined as the judgment of the effort required to generate a force rather than the absolute magnitude of the force that is exerted (Enoka & Stuart, 1992). In contrast to movement and position sense that can arise from a passive limb, force sense is always associated with motor commands, and arises from re-afferent inputs (Proske & Gandevia, 2012). Thus, muscle fatigue, through alteration of force production, is likely to alter force sense. Indeed, studies on force sense of elbow flexors have demonstrated that the magnitude of perceived force increases with muscle fatigue (Brockett *et al.*, 1997; Weerakkody *et al.*, 2003; Jones & Hunter, 1983). In line with these studies, Vuillerme & Boisgontier (Vuillerme & Boisgontier, 2008) demonstrated a decrease in force sense accuracy and consistency regardless of the target force (50N and 150N) after fatiguing the plantarflexor muscles. However, they did not report the constant error; therefore, more studies are needed to confirm whether the level of force in fatigued ankle muscles is also overestimated, similar to what has been shown in the elbow muscles.

Irrespective of the controversies regarding the impact of muscle fatigue on proprioceptive abilities, numerous studies in the postural control literature still refer to reduced proprioception as a factor that can explain increased COP sway after muscle fatigue (Caron, 2003; Johnston *et al.*, 1998; Ledin *et al.*, 2004; Lepers *et al.*, 1997; Nardone *et al.*,

1997; Vuillerme *et al.*, 2001; Vuillerme *et al.*, 2002a; Vuillerme *et al.*, 2002b; Vuillerme & Nougier, 2003; Vuillerme *et al.*, 2006b; Yaggie & McGregor, 2002; Lundin *et al.*, 1993). Two studies have observed a possible contribution of muscle spindles in altering the proprioception system when vibrating a fatigued muscle (Ledin *et al.*, 2004; Vuillerme *et al.*, 2002a). Vuillerme and colleagues (2002a) showed no additional COP sway (amplitude and velocity) when introducing vibration to a fatigued ankle during a quiet standing task without vision. Although these authors reported intervals of 5-s COP data only, they suggested that the muscle spindles could not respond to the vibration because of their low sensitivity caused by metabolites and inflammatory substances, and/or by the modulation of the reflex pathways from the III and IV afferent groups. They also suggested that the CNS re-weights proprioceptive inputs because of impaired ankle proprioception, thus relying more on inputs from other joints or on the vestibular system. This hypothesis has been tested by increasing sensory information during fatigue conditions (Lepers *et al.*, 1997; Vuillerme *et al.*, 2001; Vuillerme & Nougier, 2003; Vuillerme *et al.*, 2006b). For example, the effect of fatigue on COP sway can be eliminated when visual cues are relatively close (target on the wall at 1m) (Lepers *et al.*, 1997; Vuillerme *et al.*, 2001; Vuillerme & Nougier, 2003; Vuillerme *et al.*, 2006b), by increasing neck somatosensory information using an adhesive bandage (Pinsault & Vuillerme, 2008) or haptic cues using light finger touch (Lepers *et al.*, 1997; Vuillerme *et al.*, 2001; Vuillerme & Nougier, 2003; Vuillerme *et al.*, 2006b).

#### *2.3.4. Changes in central processing*

##### *2.3.4.1. The attentional cost of muscle fatigue*

It is well known that static and dynamic postural control requires attention (Lajoie *et al.*, 1993), and that the amount of attention utilized depends on the difficulty of the postural

task (Woollacott & Shumway-Cook, 2002). Fatigue to any postural muscle could result in decreased arousal due largely to fatigue-related changes in central processes, and/or in an increasing task demand mainly caused by peripheral fatigue (increased allocation of attention for the postural task itself). Thus, according to the Wickens Multiple Limited Resources Theory (1984), the attentional demands of postural control could increase when one postural muscle or more are fatigued. However, there are not enough studies on this topic to support this hypothesis. Only one study (Vuillerme *et al.*, 2002b) assessed the attentional cost of localized muscle fatigue during quiet standing. Vuillerme and colleagues (2002b) found that: a) upright standing increased simple reaction time compared to a seated task, confirming findings from previous studies (Lajoie *et al.*, 1993; Lajoie *et al.*, 1996; Teasdale *et al.*, 1993; Teasdale & Simoneau, 2001); and b) muscle fatigue in the calves increased COP sway displacement and velocity, as shown in other studies (Caron, 2003; Johnston *et al.*, 1998; Ledin *et al.*, 2004; Vuillerme *et al.*, 2001; Vuillerme *et al.*, 2002a; Vuillerme *et al.*, 2002b; Vuillerme & Nougier, 2003; Vuillerme *et al.*, 2006b; Lundin *et al.*, 1993). In addition, Vuillerme and colleagues (2002b) found that the increased reaction time during standing was more pronounced after fatiguing the calves. These authors suggested that motor processing requires additional attention to compensate for the decrease in force, and that sensory processing requires additional attention to compensate for the impairment in proprioceptive information. Since this is the first study of its kind, more studies are needed to confirm these conclusions. Besides the increase in attentional demand associated with postural control with muscle fatigue, the postural task may also be more difficult when performing a cognitive task simultaneously; thus, the effect of muscle fatigue on postural control may be more pronounced during a dual-task.

#### 2.3.4.2. Sensory re-weighting abilities

As mentioned earlier, sensory information is redundant and by integrating this information, the CNS re-calibrates the body schema based on the available or most reliable information. The ability to re-weight sensory information from the visual, vestibular and somatosensory systems when one or more systems are altered has been examined (see Horak & MacPherson, 1996 for review), and comparisons between different populations have been conducted (e.g., aging, vestibular, Parkinson's). As a result of muscle fatigue, there is evidence, as mentioned earlier, of increasing reliance on non-fatigued muscle or sensory information other than proprioception to compensate for the possible sensory alteration in the fatigued muscle(s) (Ledin *et al.*, 2004; Pinsault & Vuillerme, 2008; Lundin *et al.*, 1993; Vuillerme *et al.*, 2002b; Vuillerme *et al.*, 2001; Vuillerme & Nougier, 2003; Vuillerme *et al.*, 2002a). Because there are changes in central processes associated with fatigue, the ability to perform this efficiently could be reduced.

Studies examining postural control alterations due to muscle fatigue with and without vision did not show a greater effect of fatigue when the eyes were closed (Caron, 2004; Corbeil *et al.*, 2003; Ledin *et al.*, 2004; Vuillerme *et al.*, 2006b; Bisson *et al.*, 2010), suggesting that the re-weighting ability to compensate for muscle fatigue does not necessarily depend on vision. On the other hand, it seems that when subjects are close to a wall (1m), they are able to rely more on vision, eliminating the effect of fatigue (Vuillerme *et al.*, 2001; Vuillerme *et al.*, 2006b). Pinsault and Vuillerme (2008) have demonstrated an increased reliance on neck somatosensory and vestibular information when the ankle muscles were fatigued. However, the ability to re-weight sensory information due to altered proprioception at the ankle has not been compared before and after a fatigue protocol. It

would be interesting to document whether the effect of fatigue is greater when the somatosensory information at the ankle joint is altered. Unfortunately, studies using a compliant surface (CS: foam surface or sway-referenced platform) have not compared the effect of fatigue with a postural task on a firm surface (FS) (Salavati *et al.*, 2007; Gimmon *et al.*, 2011; Reimer III & Wikstrom, 2009; Rozzi *et al.*, 1999).

#### **2.4. The influence of normal aging**

Normal aging is accompanied by well-known gradual deteriorations of the musculoskeletal, neuromuscular and sensory systems. In addition to decreases in visual acuity (Lord *et al.*, 2007) and in proprioception (Shaffer & Harrison, 2007; Goble *et al.*, 2009), muscle strength is reduced considerably with aging due to muscle morphological changes (Frontera *et al.*, 2000), and it has been shown that physiological mechanisms of muscle fatigue can vary with age (Allman & Rice, 2002). Age-related differences in central and peripheral fatigue have been documented extensively, and have been found to be highly dependent on the type of task and muscle groups (see Allman & Rice, 2002 for a review).

Older adults may have less muscle mass, and fewer motor units (MU) and muscle fibers, but because of the motor unit remodeling that can be observed with aging, the proportion of type I versus type II fibers is greater compared to young adults (see Vandervoort, 2002 for a review). Since both endurance time and recovery period depend on the ratio of type I/II fibers in the muscle (Allen *et al.*, 2008), older adults have the same endurance (Laforest *et al.*, 1990; Lindström *et al.*, 1997; Stackhouse *et al.*, 2001) or tend to have more endurance (Hunter *et al.*, 2005; Lanza *et al.*, 2004; Smolander *et al.*, 1998) in

their lower limb compared with young adults for fatiguing activities involving a relative level of force. However, for fatigue tasks involving absolute force levels (absolute muscle strength), older adults have less endurance compared to younger adults because they need a greater proportion of their maximal strength, or power, to perform the same task (Allman & Rice, 2002).

It is possible that quiet standing could be more challenging for older adults when fatigued compared to younger adults, particularly in frail older adults, as strength decreases as we age. Furthermore, possible mechanisms involved in the reduction in postural control due to muscle fatigue (i.e. delay in force-generating capacities, reduction of proprioceptive information, increase in joint stiffness, increase of central processing) have been shown to decrease with normal aging. However, there is a lack of studies examining the effect of muscle fatigue on postural control in older adults. The following section describes the effect of normal aging on muscle fatigue mechanisms related to postural control as discussed above.

#### *2.4.1. Increased delay of force-generation capacities*

The changes in muscle composition with aging leads to a general slowing of contractile properties, and consequently, a delay in force-generation capacities (Roos, 1997; Bilodeau *et al.*, 2001b; Bilodeau *et al.*, 2001a). However, it is not clear whether older adults experience a greater delay in force generation than young adults with muscle fatigue (Allman & Rice, 2002). Moore and colleagues (2005) suggested that such a delay in force-generating capacities could, in part, explain the increase in COP sway seen in older adults after exercising the quadriceps. These authors showed a longer time in the open-loop control after

muscle fatigue, suggesting a delay in postural corrections according to the Open-Closed Loop Theory (Collins & De Luca, 1993). In contrast, their results could also suggest a delay in the sensory processing. It is important to note that these authors did not have a control group of young adults. Thus, comparison between age groups was not possible.

#### *2.4.2. Increased joint stiffness*

Some studies have suggested an increase in joint stiffness during quiet standing with aging (Collins *et al.*, 1995; Laughton *et al.*, 2003). This increase seems to be explained, at least in part, by an increase in muscle activity (co-contraction) (Collins *et al.*, 1995; Laughton *et al.*, 2003). In terms of muscle fatigue, only one study has included an indirect measure of stiffness (Lin *et al.*, 2009). In this study, the effect of localized muscle fatigue at four different joints on COP sway was compared between young and older adults. The authors found no differences in ankle stiffness, as measured with the Winter estimation method (Winter *et al.*, 2001), between young and older adults; and muscle fatigue did not increase ankle stiffness in either group. In addition, contrary to young adults, older adults in this study did not increase their COP sway displacement after muscle fatigue to any of the joints tested. This result was not expected. The authors tried to explain their results by suggesting that older adults were more efficient in using a hip strategy (muscle group not fatigued in the study) or that they were less fatigued due to a lack of motivation or tolerance of discomfort.

#### *2.4.3. Proprioception deficit*

It is well known that the efficacy of the somatosensory system declines with age (Shaffer & Harrison, 2007). Age-related changes in proprioception have been shown for JPS

(You, 2005; Tsang & Hui-Chan, 2003; Barrack *et al.*, 1983; Petrella *et al.*, 1997; Bullock-Saxton *et al.*, 2001), movement sense (Barrack *et al.*, 1983; Skinner *et al.*, 1986; Westlake & Culham, 2007) and dynamic position sense (Verschueren *et al.*, 2002; Madhavan & Shields, 2005). Almost unanimously, studies comparing older and young adults have indicated a significant deterioration of position sense at the knee and ankle for older adults as compared to young adults (Goble *et al.*, 2009). However, hip position sense was not found to differ between older and young adults in both passive and active JPS (Pickard *et al.*, 2003). Westlake *et al.* (2007) found that the motion detection threshold of the ankle was significantly greater for older adults ( $2.0^{\circ}$ ) compared to young adults ( $0.83^{\circ}$ ) at a speed of  $0.25^{\circ}/s$ . They also found that velocity discrimination (reference at  $5^{\circ}/s$ ) was greater for older adults ( $1.28^{\circ}/s$ ) compared with young adults ( $0.46^{\circ}/s$ ). Two studies have demonstrated a greater decrease in passive dynamic joint position sense of older compared to young adults (Verschueren *et al.*, 2002; Madhavan & Shields, 2005), and this was associated with single-leg stance time (Madhavan & Shields, 2005).

Bellew & Fenter (2006) suggested that a decline in proprioception could explain their results, where the effect of fatigue of the knee on different balance tests was not the same when compared to the effect of fatigue of the ankle. The authors have demonstrated a greater effect of ankle muscle fatigue on a test that required more motion at the ankle, compared to a test that required more knee motion (and vice-versa with knee muscle fatigue). Again, these results were not compared to a younger control group; therefore, the effect of age cannot be discussed.

#### 2.4.4. Slower central processing

The attentional cost of aging on postural control is well-documented (see Fraizer & Mitra, 2008; Woollacott & Shumway-Cook, 2002 for reviews). In summary, postural control during quiet standing requires more attention for older adults compared to younger adults, and this is more pronounced as the complexity of the postural task or the secondary task increases. However, as detailed by Fraizer and colleagues (2008), the effect of a secondary task on postural control is not clear. Some studies examining this relationship showed a decrease in COP sway, while others showed no differences or even an increase in COP sway. As suggested by Egerton and colleagues (2009), although changes to standing balance due to fatigue may not be sufficient to detrimentally affect fall risk in older adults, the attentional demands could be greater during muscle fatigue, and the sum of the two effects could increase the risk of falls. This hypothesis is worthy of investigation since attentional demands have been shown to increase with muscle fatigue (Vuillerme *et al.*, 2002b).

As all sensory systems required for postural control are impaired with normal aging, the weighting of sensory information by the CNS may be modified, and consequently re-weighting efficiency altered. It has been shown that postural control in older adults is affected to a greater extent by optical illusions (Borger *et al.*, 1999), by a visual secondary task (Maylor & Wing, 1996) and by reintegration of the visual information (Teasdale *et al.*, 1991b); and it is generally accepted that older adults rely more on vision to maintain stability. Furthermore, postural control decreases even more when two sensory systems are altered (Woollacott *et al.*, 1986; Redfern *et al.*, 2001b), suggesting that the reliance on only one system is far more difficult in this older population compared to the younger population. By analyzing COP sway data during transition between different sensory conditions (eyes

open-closed, with and without ankle vibration), Teasdale and colleagues (Teasdale & Simoneau, 2001) found that re-integrating somatosensory information increases COP sway in older adults, suggesting that re-weighting sensory information is less efficient in this age group.

Since muscle fatigue impairs proprioceptive information, older adults could have greater difficulty in coping with muscle fatigue when vision is not available. As no studies have examined the effect of muscle fatigue during standing on an altered surface, it is not clear if the effect of muscle fatigue would be greater in older adults compared to young adults.

## **2.5. Summary**

Studies on postural control and muscle fatigue provide evidence that the mechanisms involved in postural alterations reported during muscle fatigue could include: 1) delay in force-generating capacities, 2) alteration of proprioceptive information, 3) changes in joint stiffness, 4) an increase in attentional demands and, 5) alterations in sensory re-weighting abilities. The latter two mechanisms have not been studied extensively in young adults and no comparison between young and older adults exists. Thus, the main goal of this thesis was to determine whether muscle fatigue negatively affects COP sway and associated central processes (attentional demands and sensory re-weighting) differently in young and older adults. Evidence described in the last section of this review suggests that older adults may be more affected by fatigue compared to young adults. However, no studies have shown this difference at the moment.

## CHAPTER 3. RESEARCH QUESTIONS AND HYPOTHESES

This thesis includes four different studies with objectives to examine: a) how the effect of muscle fatigue on COP sway during quiet standing differs between older adults (60 years of age and older) and younger adults (18 to 35 years of age); and b) how changes in central processing (attentional demands and sensory re-weighting) could increase the effect of muscle fatigue on COP sway in older compared to young adults.

### 3.1. Research questions and hypotheses for manuscript 1

Numerous studies have demonstrated postural control alterations across several tasks (e.g., unipedal stance, bipedal stance, eyes open, eyes closed) by fatiguing the ankle (Vuillerme *et al.*, 2001; Vuillerme *et al.*, 2002b; Lundin *et al.*, 1993; Corbeil *et al.*, 2003), knee (Gribble & Hertel, 2004b), hip (Gribble & Hertel, 2004a; Salavati *et al.*, 2007), back (Davidson *et al.*, 2004) and neck (Gosselin *et al.*, 2004) muscle groups. Furthermore, several studies have shown that fatigue to proximal (hip) muscles increases COP sway to a greater extent than more distal (ankle) muscles (Gribble & Hertel, 2004a; Gribble & Hertel, 2004b; Salavati *et al.*, 2007). However, there is a lack of studies looking at changes to posture-related central processes with muscle fatigue. Only one study (Vuillerme *et al.*, 2002b) demonstrated an increase in the attentional demands required for a postural task performance due to localized muscle fatigue.

Thus, the first manuscript involved testing the effect of ankle and hip muscle fatigue on COP sway during a dual-task paradigm. The study aimed to determine whether attentional

demands were associated with the differential postural control alterations of hip and ankle muscle fatigue found in prior studies on young adults (Paillard, 2012). The study was based on a study performed by Gribble & Hertel (2004b), where ankle, knee and hip muscles of young adults were fatigued with concentric/concentric continuous contractions. However, the present study tested postural control following ankle and hip muscle fatigue only and included a dual-task paradigm. Two main questions were addressed by conducting this study in young adults. The first involved determining whether the effect of fatigue of hip muscles on COP sway was different compared to fatigue of ankle muscles. Secondly, we tested whether the attentional demands associated with a postural task were increased with hip compared to ankle muscle fatigue. Based on previous results (Salavati *et al.*, 2007; Gribble & Hertel, 2004b), we hypothesized that fatigue of hip muscles would lead to greater postural control alterations and this would be associated with a greater increase in attentional demands, compared with fatigue of ankle muscles.

### **3.2. Research questions and hypotheses for manuscript 2**

In contrast to young adults, little is known about the effect of muscle fatigue on postural control in older adults. An age-related difference in the effects of fatigue on postural control is possible, as physiological mechanisms involved in fatigue can vary with age (Allman & Rice, 2002). Furthermore, the effects of muscle fatigue on the attentional demands of postural control have never been investigated in older adults. Thus, the second study examined the possible differential effects of muscle fatigue of the ankle on postural control and attentional demands in older adults compared to young adults using the same dual-task paradigm as the first manuscript. Two main questions were addressed by

conducting this second study: 1) are older adults more susceptible to postural changes due to ankle muscle fatigue compared with young adults? 2) Is the attentional cost of ankle muscle fatigue on postural changes greater in older compared with young adults?

Since older adults have greater joint stiffness (Collins *et al.*, 1995; Laughton *et al.*, 2003) and more difficulty in re-weighting their sensory information (Woollacott *et al.*, 1986; Redfern *et al.*, 2001b), we hypothesized that the postural control alterations due to fatigue would be greater in this population. It is well known that attentional demands increase as age increase, and more so with more difficult tasks. Thus, as we expected that standing on one leg would be more difficult after ankle muscle fatigue (Lundin *et al.*, 1993; Yaggie & McGregor, 2002), we hypothesized a greater increase in attentional demands with fatigue in older compared with young adults.

### **3.3. Research questions and hypotheses for manuscript 3**

The findings from studies examining the effect of ankle muscle fatigue on postural control vary significantly. This is possibly due to methodological differences across studies (e.g., fatigue protocols, postural stances used and/or amount of visual information available). Thus, in an attempt to elucidate factors contributing to the different reports regarding postural control alterations due to muscle fatigue, the first objective of the third study was to compare the effects of isometric and concentric isokinetic fatiguing exercises on COP sway during quiet stance in young adults.

Numerous studies examining the effect of ankle muscle fatigue on postural control have suggested a direct link between a reduction in proprioception and an increase in COP sway with fatigue (Salavati *et al.*, 2007; Gribble & Hertel, 2004a). Consequently re-weighting of sensory information is required to maintain stability. In fact, Vuillerme and colleagues (2002a) demonstrated that fatigue of the ankle induced the same increase in COP sway displacement and COP sway velocity as when vibrating the ankle. The authors concluded that because the sensitivity of the muscle spindles was reduced with fatigue, vibration was not able to induce greater COP sway when applied to the fatigued muscle. However, the evidence of greater postural control alterations due to muscle fatigue when standing on a CS compared to a FS is still unexplored. Thus, the second objective of the third study was to assess whether the magnitude of the postural control alterations due to muscle fatigue is dependent on the amount of proprioceptive information available (i.e., by comparing postural tasks performed on a FS and a CS). It was hypothesized that an isometric fatiguing exercise would induce greater alterations in postural control compared to an isokinetic concentric fatiguing exercise, likely due to a greater increase in metabolite concentration (Babault *et al.*, 2006). It was further hypothesized that postural control on a CS would be impaired to a greater extent after fatigue compared to a FS because standing on a CS requires more proprioceptive information and greater control by the neuromuscular system.

#### **3.4. Research questions and hypotheses for manuscript 4**

The impact of muscle fatigue on postural control in older adults may be more pronounced than in young adults since their proprioceptive and neuromuscular systems are

less efficient. Interestingly, Egerton and colleagues (2009) have shown greater COP sway during quiet standing in older compared to young adults, but failed to show greater COP sway displacement or velocity in older compared with young adults following fatigue. Furthermore, manuscript 2 of the present thesis suggests that attentional demands of a unipedal stance are not changed after fatiguing the ankle muscles in young and older adults. However, these studies were conducted on a FS. It is known that age differences in postural control are evidenced when inputs from two of the three sensory systems are not available/reliable (e.g., vision blocked and proprioception altered). However, no study has examined the effect of fatigue on postural control in this condition in older adults. Older adults may be at greater risk in this situation since they have more difficulty re-weighting less-to-more reliable sensory information (Woollacott et al., 1986; Redfern et al., 2001).

Thus, the objective of the fourth study was to examine the effect of ankle muscle fatigue on COP sway and attentional demands of young and older adults with different surface conditions (FS and CS), in order to induce a natural re-weighting of sensory information before and after muscle fatigue. This allowed for the comparison of the ability to re-weight sensory information between groups after muscle fatigue. As for study three, we expected to see a greater increase in COP sway after fatigue during tasks on a CS due to the decreased reliability of the proprioceptive system for both groups.

Since attentional demands are known to increase with the difficulty of the task, we expected to see a decrease in performance of the secondary task with fatigue for both groups, and more so when performed on the CS. Additionally, as older adults have been shown to have more difficulty re-weighting less reliable to more reliable sensory information

(Woollacott *et al.*, 1986; Redfern *et al.*, 2001b), we hypothesized an increase in COP sway with fatigue for all conditions in this age group, and that the associated increase in attentional demands would be greater compared to the younger group.

## **CHAPTER 4. MANUSCRIPT 1**

Effects of Ankle and Hip Muscle Fatigue on Postural Sway and Attentional Demands During Unipedal Stance.

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**Title:**

**Effects of Ankle and Hip Muscle Fatigue on Postural Sway and Attentional Demands During Unipedal Stance.**

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## **Abstract**

The effect of muscle fatigue on quiet standing is equivocal, including its duration/recovery and whether it leads to an increase in attentional demands. The purpose of this study was to assess the effects of ankle and hip muscle fatigue on postural sway and simple reaction time during a unipedal task. Two groups of fourteen young adults (mean age =  $22.50 \pm 3.23$ ) had to stand on their dominant leg for 30-s trials before and after fatigue of hip or ankle flexors and extensors. Half of the unipedal trials were performed in a dual-task condition where subjects, in addition to standing, had to respond verbally to an auditory stimulus. Sway area, and sway variability and velocity in the AP and ML planes were calculated using center of pressure data obtained from a force platform. Voice reaction time was recorded seated and during the dual-task condition to assess attentional demands. A main effect of fatigue was found for AP sway variability ( $p=0.027$ ), AP sway velocity ( $p=0.017$ ) and ML sway velocity ( $p=0.004$ ). Both groups showed increased sway velocity in both directions and in reaction time during the dual-task condition ( $p<0.001$ ), but reaction time did not increase with fatigue. A group by fatigue interaction was found significant for ML sway velocity ( $p=0.043$ ). Results suggest that hip and ankle fatigue affected postural control in the fatigued plane (AP) but only hip fatigue affected postural control in the non-fatigued plane (ML sway velocity). However, fatigue did not lead to an increase in attentional demands and increased AP and ML sway velocity had recovered within 30 min.

**Keywords:** muscle fatigue, postural stability, attention, lower extremity

## 1. Introduction

The ability to maintain a stable, upright stance is an essential component of daily activities. In order to maintain an upright stance, the CNS must integrate and (re-)weight information from different sensory systems (vision, vestibular and somatosensation) and modulate commands to the neuromuscular systems continuously. Even though this is an automated process, numerous studies using the dual-task paradigm have shown that tasks like standing or walking require some attentional resources<sup>1</sup>. An increase in attentional demands can be inferred from a reduction in the performance of a secondary task (usually a cognitive task) while the performance on the primary (postural) task remains the same. It is well known that the attentional demands for postural sway regulation increase with the difficulty of the task<sup>2-4</sup>, aging<sup>5-7</sup> and pathology<sup>8, 9</sup>, particularly when proprioceptive information is reduced due to environmental constraints<sup>3-6</sup>. This is not surprising since ankle proprioception is one of the primary regulatory mechanisms for stabilization of the body<sup>10, 11</sup>.

Muscle fatigue, defined as an acute impairment in the ability to produce maximum force, regardless of whether or not the task itself can still be performed successfully<sup>12</sup>, has been shown to impair the mechanical properties of the muscle<sup>13</sup> and the proprioceptive system<sup>14, 15</sup> required for postural stability. The proprioceptive impairment due to muscle fatigue could be caused by changes in the discharge patterns of muscle afferents due to metabolite build up leading to potential altered muscle spindles information<sup>15</sup>, altered central processing of proprioception via group III and IV afferents<sup>14</sup> and effects on the efferent pathways<sup>16</sup>. However, the relative contribution of fatigue-related changes in mechanical properties and proprioception for postural stability remains to be clarified. Studies on the effect of muscle fatigue and postural stability have repeatedly suggested that proprioception

could be the primary mechanism explaining changes in postural sway observed after fatigue<sup>17-23</sup>. The work of Vuillerme and colleagues<sup>21-23</sup> supports this by showing that the increase in postural sway due to muscle fatigue is not accentuated with vibration<sup>21</sup>, is eliminated with light touch<sup>22</sup>, and is attenuated with augmented visual feedback<sup>23</sup>. If muscle fatigue induces deficiencies in proprioception resulting in reduced stability of the body, the attentional resources needed to perform the task are likely to increase. However, only one study at present has shown an increase in attentional demands after fatiguing a targeted muscle group (localized fatigue of the plantar flexors)<sup>20</sup>. Since several studies have shown an increase in postural sway after fatiguing various muscle groups<sup>18, 24, 25</sup>, it is reasonable to expect an increase in attentional demands when fatiguing such muscle groups. Although the effect of exercise on cognitive performance is complex<sup>26</sup>, and because fatigue of certain muscle groups may have a more pronounced effect on postural control (e.g., hip or knee versus ankle<sup>18</sup>), it could be hypothesized that an increase in attentional demands with fatigue may be specific to the muscle group fatigued.

The purpose of this study was thus to compare the extent to which fatigue of ankle extensor (plantarflexor) and flexor (dorsiflexor) muscles versus fatigue of hip extensor and flexor muscles: a) increases postural sway in unipedal stance and b) leads to an increase in attentional demands during a dual-task paradigm. Based on previous results<sup>18, 25</sup>, it was hypothesized that fatigue of hip muscles would have a greater effect on posture control compared with fatigue of ankle muscles, and this would be associated with a greater increase in attentional demands with fatigue of the hip compared with ankle muscles.

## **2. Methodology**

### *2.1. Subjects*

Two groups, each comprised of 14 young adults between 19 and 30 years of age with no known orthopaedic, cardiovascular or neurological conditions were recruited for this study through convenience sampling. The cognitive status of subjects was assessed using the Mini Mental State Exam<sup>27</sup>. The study was approved by the University of Ottawa and the Bruyère Continuing Care research ethics boards and written informed consent was obtained from each subject prior to their participation in the study.

### *2.2. Procedures*

Subjects were asked to maintain a unipedal stance on their dominant leg, as steadily as possible, while standing on a force platform without their shoes. The leg which the subject would use to kick a ball was considered the dominant leg. Subjects were asked to fixate a black cross placed on the wall at eye level, 2.5 m in front of them. Their arms had to hang by their sides and support from the elevated leg was not permitted. Each subject completed eight 30-s trials for each of the following time points: pre-fatigue, post-fatigue and after 30 min of recovery. For each time point, trials were alternated between a single-task condition (quiet standing alone) and a dual-task condition (quiet standing with the addition of a simple reaction time task). The order of trials was counterbalance between subjects. Simple reaction time (SRT) consisted of responding verbally with the word “top” after hearing an auditory stimulus (1000Hz, 100ms) which was randomly dispersed four times throughout the 30-s trial. Subjects were asked to respond to each auditory stimulus as quickly as possible while maintaining their focus on the primary (postural) task (i.e., to be as steady as possible). Prior

to pre-fatigue trials, each subject was familiarized with the tasks and three trials of seated SRT were recorded.

### *2.3. Fatigue protocol*

For each group respectively, the ankle or hip flexor and extensor muscle groups were fatigued using a BIODEX system III (Shirley, NY). Starting position for the ankle fatigue protocol was seated with the hip, knee and ankle joints at 90°, 35° and 80°, respectively; whereas the hip fatigue protocol was performed in a supine position with the hip, knee and ankle joints at 180°, 35° and 90°, respectively. For both protocols, knee angle was kept constant and total range of motion was set at 35° for the ankle and 40° for the hip. The non-dominant leg was left hanging free without support to limit its use during the fatigue protocol. The arms were crossed in front of the subject with the waist, knee and ankle securely strapped to eliminate potential compensations. Prior to the fatigue protocol, the peak torque output was measured during three maximal voluntary concentric contractions (MVCs) at 30°/s for the extension direction and 120°/s for flexion. The fatigue protocol consisted of alternating maximal isokinetic contractions in extension and flexion (same speeds as for the MVCs) for as many repetitions as possible, i.e., until the torque for three consecutive sets of contractions decreased below 50% MVC for both muscle groups. The chosen contraction speeds (30°/s and 120°/s) were selected based on preliminary testing of the fatigue protocol, to allow reaching the criteria to end the fatigue protocol (50% MVC) relatively simultaneously with both muscle groups. To avoid the effect of an initial recovery during the post-fatigue trials, the fatigue protocol was repeated (re-fatigue) once after the first two trials of each task (single-task and dual-task) were completed. The time elapsed between the end of the fatigue protocol and the start of the postural data collection was 40 s on average.

#### *2.4. Data Analysis*

Postural data was collected using an AMTI Acu-Gait force platform (Watertown, MA). Three center of pressure (COP) variables were calculated using BioAnalysis 2.1 software (Watertown, MA): sway area, represented by the area of the 95% confidence ellipse (EA in  $\text{cm}^2$ ; which is an ellipse that encloses 95% of the center of pressure data for a given trial (AMTI, Watertown, MA)); sway variability, represented by the standard deviation of the COP around the mean position (SD in cm); and sway velocity, represented by the total COP displacement divided by time (cm/s). The last 2 variables were obtained for both antero-posterior (AP) and medio-lateral (ML) directions. SRT data was collected with an MP3 recorder fixated to the subject's arm to gather both the start of the auditory stimulus and the verbal response from the subject. The mean of all trials in each condition were calculated and used for statistical analyses. Only 1% of the trials were not used for analyses because of steps taken by the subjects.

Three-way analyses of variance (ANOVAs) were used to assess the effects of group (ankle or hip; independent factor), fatigue (PRE, POST, REC; repeated measures) and tasks (single-task or dual-task; repeated measures) for each of the dependent postural variables (EA, AP and ML SD, AP and ML velocity). A two-way ANOVA was used to assess the effects of group (ankle or hip; independent factor) and condition (seated, PRE, POST, REC; repeated measures) on SRT. All statistical analyses were completed using PASW statistics 18 (IBM, Chicago, IL) with a p-value of 0.05. Post hoc analyses were used when appropriate using a Bonferoni adjustment.

### **3. Results**

Table 1 depicts the characteristics of each group. Independent t-tests showed no differences between groups ( $p > 0.05$ ), except for the time to re-fatigue which was longer for the hip fatigue group ( $p = 0.03$ ). Results for all the postural variables are provided in Table 2.

#### *3.1. Postural sway area*

EA results revealed no significant main effect of fatigue ( $F = 1.930$ ,  $p = 0.155$ ), task ( $F = 0.002$ ,  $p = 0.968$ ) or group ( $F = 0.151$ ,  $p = 0.701$ ). All interaction effects were also not significant ( $p > 0.05$ ).

#### *3.2. Postural sway variability*

SD AP results showed a significant main effect of fatigue ( $F = 3.856$ ,  $p = 0.027$ ). The main effects of task ( $F = 0.457$ ,  $p = 0.505$ ) and group ( $F = 0.052$ ,  $p = 0.822$ ) and all interaction effects ( $p > 0.05$ ) were found not significant. SD AP increased after fatigue, however, pairwise comparisons showed that a significant difference was found only between pre-fatigue and recovery (mean difference = 0.056,  $p = 0.011$ ). SD ML results revealed no significant main effect of fatigue ( $F = 0.902$ ,  $p = 0.412$ ), task ( $F = 4.112$ ,  $p = 0.053$ ) or group ( $F = 0.962$ ,  $p = 0.336$ ). All interaction effects were also not significant ( $p > 0.05$ ).

#### *3.2. Postural sway velocity*

AP sway velocity results revealed a significant main effect of fatigue ( $F = 4.666$ ,  $p = 0.017$ ) and task ( $F = 27.697$ ,  $p = 0.000$ ). The main effect of group ( $F = 0.322$ ,  $p = 0.575$ ) and all interaction effects were found not significant ( $p > 0.05$ ). ML sway velocity results revealed a

significant main effect of fatigue ( $F=6.057$ ,  $p=0.004$ ) and task (ML;  $F=23.399$ ,  $p=0.000$ ). The main effect of group was found not significant ( $F=0.826$ ,  $p=0.372$ ). Interaction effects were found not significant ( $p>0.05$ ), except for the fatigue by group interaction effect ( $F=3.340$ ,  $p=0.043$ ). Pairwise comparisons did not show any significant differences between groups in ML velocity for a particular time point (pre, post, rec). However, pairwise comparison showed a significant increase in ML sway velocity after fatigue (post-fatigue) for the hip group (mean difference= 0.283,  $p=0.011$ ) but not for the ankle group (mean difference= 0.003  $p=1.000$ ). Furthermore, the mean difference in ML sway velocity between pre-fatigue and 30 min recovery was non significant (mean difference= 0.005,  $p=1.000$ ). Figure 1 shows the percent change in sway velocity for the ankle group and for the hip group.

### *3.3. Simple Reaction Time*

SRT results are shown in Figure 2. Results of the ANOVA showed a significant main effect of condition ( $F= 17.275$ ,  $p=0.000$ ), but no main effect of group ( $F=0.0213$ ,  $p=0.648$ ). The condition by group interaction effect was also found not significant ( $F=0.079$ ,  $p=0.975$ ). Pairwise comparisons showed only a significant difference between seated SRT and all standing SRTs for both the ankle and hip fatigue groups ( $p<0.05$ ).

## **4. Discussion**

Our main results showed that ankle and hip fatigue increased sway variability and sway velocity in young healthy adults during a unipedal stance in the fatigued plane (AP), whereas sway velocity in the non-fatigued plane (ML) increased only after hip fatigue, suggesting a greater decline in postural control with fatigue for this muscle group. When a

secondary task was performed simultaneously with the postural task, AP and ML sway velocity increased significantly. However, this effect was the same after fatigue (ankle or hip), and fatigue did not affect SRT, suggesting that the present fatigue protocols did not increase the attentional demands associated with a unipedal stance.

#### *4.1. Effect of fatigue*

Our study and several others<sup>18, 24, 25</sup> show that fatiguing proximal muscles (hip and/or knee) has a greater effect on postural control than distal (ankle) muscles, confirming our first hypothesis. Our results on a unipedal stance task with the eyes open showed that proximal and distal muscle fatigue increased sway velocity in the fatigued plane (AP), but only proximal muscle fatigue increased sway velocity in the non-fatigued plane (ML), as previously documented<sup>18</sup>. When looking at percent change (figure 1), fatigue of the hip flexors/extensors increased ML sway velocity by 13% and AP sway velocity by 12%, whereas fatigue of the ankle plantar/dorsiflexors barely increased sway velocity in either direction (2%). A common explanation in the literature for this joint-specific fatigue effect resides in the compensatory mechanisms available after fatigue<sup>18, 24, 25</sup>. The ankle strategy is predominantly used during quiet standing but the use of the hip strategy increases with the difficulty of the task<sup>28</sup>. Thus, the unipedal stance is controlled by a combination of ankle and hip strategy<sup>29</sup>. Others<sup>18, 24</sup> have suggested that when the ankle is fatigued, the decrease in ankle control (due to impaired ankle proprioception<sup>14, 15</sup>) can be compensated by an increase reliance on the hip strategy. In fact, the reliance on more proximal muscles to maintain upright stance has been shown to increase (increased corrective actions at the knee and hip) when proprioceptive information at the ankle is reduced (foam surface and multiaxial platform)<sup>29</sup>. However, impaired proprioception following fatigue of hip muscles may have

compelled subjects to rely primarily on an ankle strategy, leading to an increase sway velocity to maintain stability.

Vuillerme et al.<sup>19</sup> have demonstrated that vision alone could attenuate the postural deficits associated with fatigue of the ankle plantarflexors. It should also be noted that with the absence of vision, both ankle and hip fatigue have been shown to increase postural sway<sup>25</sup>. In the present study, subjects were tested with eyes opened, thus reliance on visual information was possible. Consequently, the decrease in ankle proprioception may not have been sufficient to affect sway velocity when vision was available. However, the presence of visual information was not sufficient to compensate for the effect of fatigue induced at the hip on the control of a unipedal stance.

Nonetheless, the effect of fatigue was short-lived since sway velocity decreased to pre-fatigue values after 30 min of recovery. Others<sup>30</sup> have also found a rapid recovery of postural control variables following fatigue. Interestingly, AP sway variability was significantly increased after 30 min of recovery. However, this increase in AP sway variability was minimal and did not lead to a greater sway area (which combines information from both the AP and ML planes).

#### *4.2. Dual-task*

In this study, subjects were asked to focus on standing as still as possible during all conditions (primary task). According to such dual-task instructions, it was expected that no differences would be observed in sway area and sway variability between the single-task and dual-tasks, which was confirmed. In contrast, a significant increase in AP and ML sway

velocity during the dual-task condition was noted. When the difficulty of a task increases, more activity of the supporting musculature may be needed to remain in a stable posture. Because subjects did not sway more (EA, AP and ML SD did not change), the increase in sway velocity during the dual-task condition suggests an increase in corrective actions<sup>18, 31</sup>. Although the articulation of words may cause an increase in sway<sup>32</sup>, the time to articulate the SRT used in our study rounds up to only a fraction of the 30-s trial over which each sway parameter was computed. Thus, it is more likely that the increase in sway velocity was due to an increase in attentional demands when subjects were required to respond to the auditory stimulus. In a recent review, Fraizer & Mitra<sup>1</sup> explained that attentional demands were shown to increase during a dual-task, resulting in compensatory activity (increase sway velocity) for the primary task and a decrease in performance of the secondary task. In the present study, this decreased performance was reflected in the increased SRT from sitting when compared to standing.

Contrary to our initial hypothesis, performing a unipedal stance did not require more attention following muscle fatigue, as reflected by the absence of a change in SRT, regardless of the muscle groups fatigued. Also, the increase in sway velocity during the dual-task compared with the single-task was not greater after fatigue. Although this is the first study investigating the attentional cost of fatigue at the hip joint, our results are in contrast with two other studies investigating the attentional cost of muscle fatigue<sup>20, 33</sup>. Vuillerme and colleagues<sup>20</sup> found an increase in SRT during quiet standing with feet together and eyes closed after fatiguing the plantarflexor muscles. Simoneau and colleagues<sup>33</sup> also demonstrated an increase in SRT during a dynamical task (target tracking) after bouts of treadmill walking. Considering that the postural task used in this study was relatively

difficult, we expected an increase in attentional demands due to fatigue. There are two possible explanations for the lack of change in attentional demands of postural control with our fatigue protocols. First, fatiguing the hip or ankle muscles using concentric contractions may not have caused enough deficits in proprioception and postural control to increase the attentional demands of unipedal stance. Other than the relatively modest increase (less than 15%) in sway velocity, sway area and sway variability did not change immediately after fatigue. In comparison, the increase in attentional demands to maintain a static bipedal stance found in Vuillerme and colleagues<sup>20</sup> study was accompanied by an increase in postural sway range and greater increase in sway velocity (65% increase) due to an isometric fatigue protocol. Second, the fact that our subjects could rely on visual information may have attenuated the increase in attentional demands due to fatigue and could explain the lack of significance in this study. Nonetheless, further research is needed to thoroughly document the attentional cost of fatigue on postural control.

## **5. Conclusion**

Fatigue in proximal (hip) muscles decreased postural control of a unipedal stance to a greater extent compared with fatigue of distal (ankle) muscles, possibly because the former muscles are more important in this specific task. The increase in attentional demands observed during the dual-task was not greater when subjects' ankle or hip muscles were fatigued. This suggests the presence of sufficient attentional resources to perform both tasks simultaneously after an isokinetic fatigue protocol.

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Table 1 - Group characteristics

	mean (SD) <sup>a</sup>	
	Ankle (n=14)	Hip (n=14)
Gender, # female (%)	10 (67)	9 (60)
Age, yrs	22.4 (3.0)	23.7 (3.1)
Height, cm	168 (7.6)	169 (10.0)
Weight, kg	66.1 (12.7)	67.0 (10.1)
MMSE score, /30	29.6 (0.6)	29.7 (0.5)
Time to fatigue, s	123 (159.1)	159 (133.4)
Time to re-fatigue <sup>b</sup> , s	67.9 (37.8)	127 (85.0)

<sup>a</sup> unless otherwise stated

<sup>b</sup> time of the second fatigue protocol (re-fatigue). t-tests < 0.05

Table 2 - Mean and standard deviation (SD) of each postural variable during the single (ST) and dual task (DT).

variables	task	ANKLE group			HIP group		
		pre	post	rec	pre	post	rec
95% ellipse area	ST	8.21 (2.18)	8.73 (2.20)	8.33 (2.83)	7.55 (2.37)	7.98 (1.64)	8.94 (3.12)
	DT	8.04 (1.93)	8.96 (2.70)	8.39 (2.19)	8.00 (2.56)	8.21 (2.04)	8.18 (2.43)
SD AP <sup>a</sup>	ST	0.75 (0.15)	0.82 (0.14)	0.79 (0.17)	0.75 (0.17)	0.80 (0.10)	0.87 (0.18)
	DT	0.75 (0.13)	0.82 (0.15)	0.79 (0.11)	0.78 (0.18)	0.77 (0.15)	0.80 (0.14)
SD ML	ST	0.58 (0.07)	0.57 (0.07)	0.56 (0.07)	0.54 (0.06)	0.53 (0.07)	0.54 (0.09)
	DT	0.58 (0.07)	0.58 (0.09)	0.57 (0.08)	0.56 (0.08)	0.57 (0.08)	0.55 (0.09)
Velocity AP <sup>a,b</sup>	ST	2.53 (0.63)	2.53 (0.56)	2.47 (0.64)	2.24 (0.54)	2.53 (0.70)	2.35 (0.65)
	DT	2.65 (0.75)	2.68 (0.73)	2.57 (0.69)	2.38 (0.54)	2.70 (0.79)	2.42 (0.59)
Velocity ML <sup>a,b,c</sup>	ST	2.71 (0.48)	2.76 (0.52)	2.59 (0.59)	2.43 (0.43)	2.70 (0.54)	2.46 (0.50)
	DT	2.90 (0.61)	2.85 (0.53)	2.82 (0.63)	2.58 (0.48)	2.88 (0.64)	2.56 (0.44)

<sup>a</sup> main effect of fatigue (p<0.05)

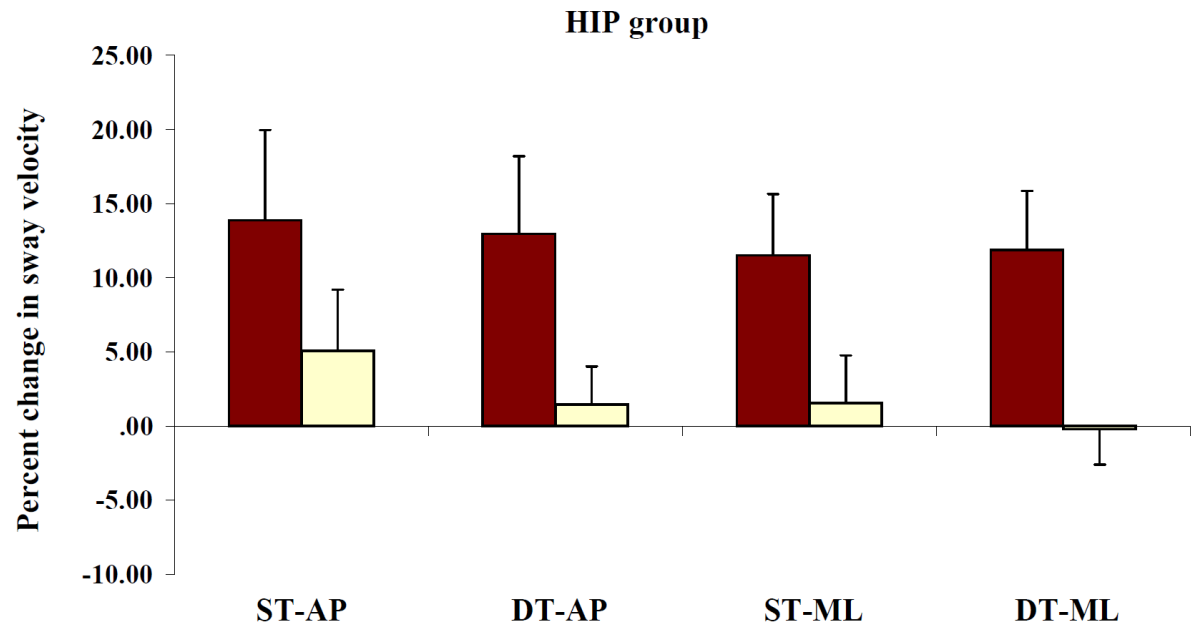
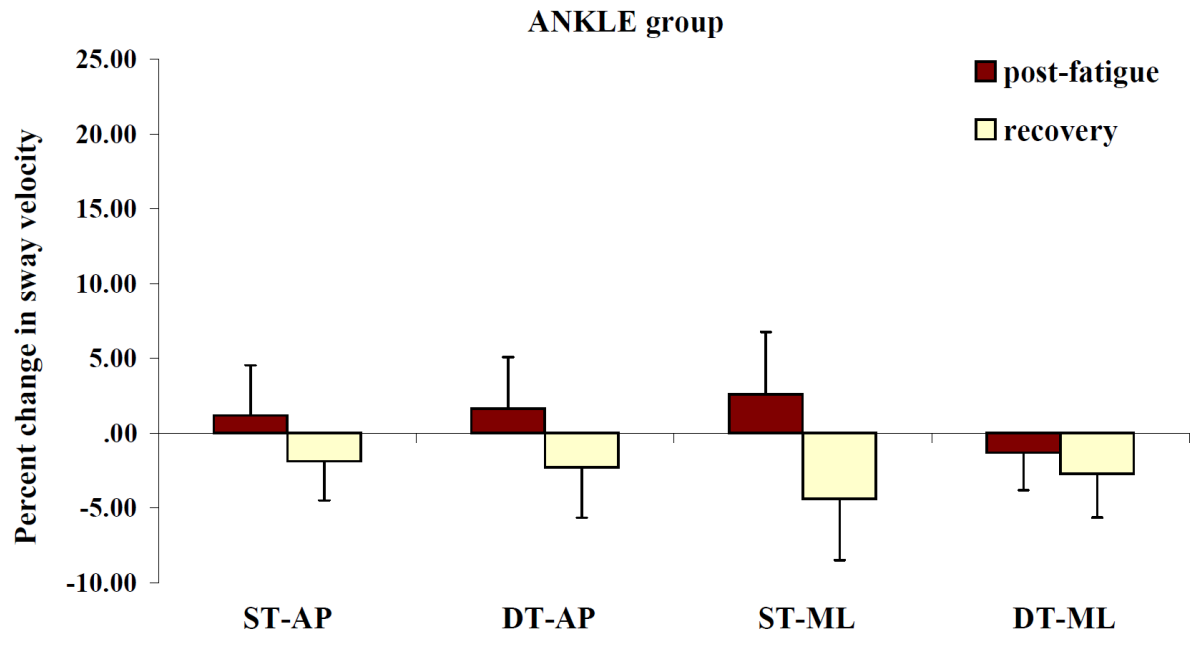
<sup>b</sup> main effect of task (p<0.05)

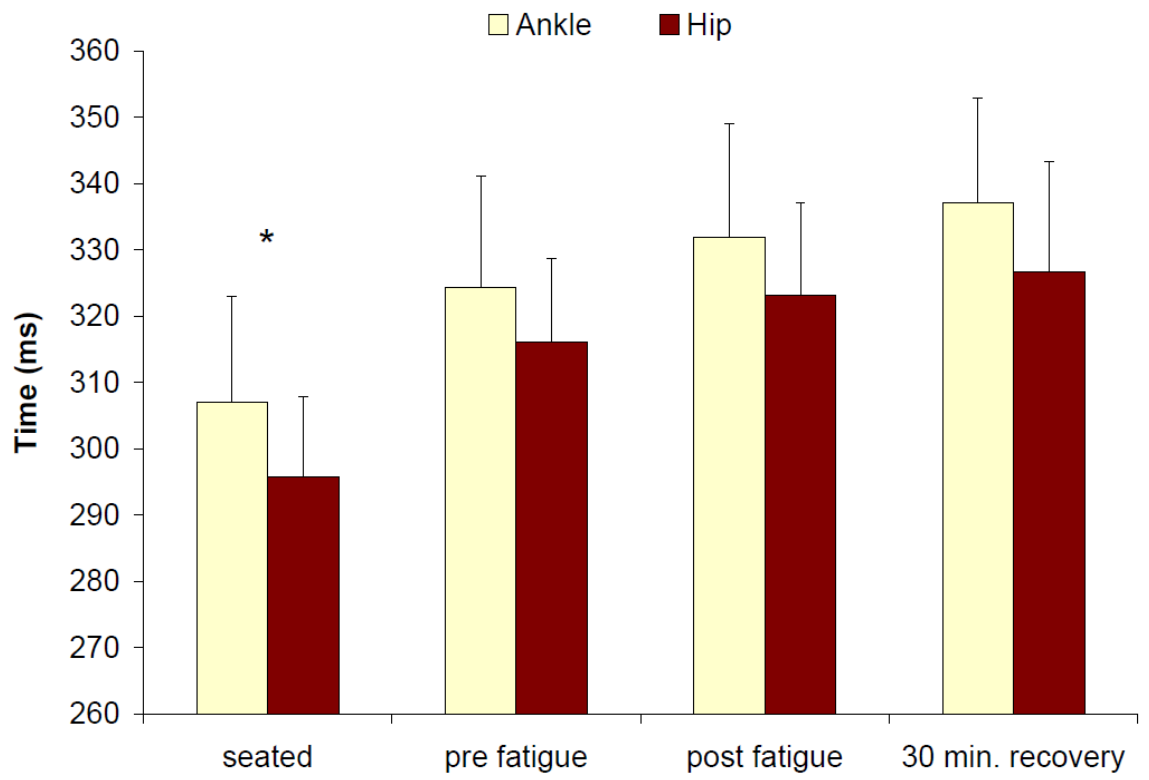
<sup>c</sup> group x time interaction (p<0.05)

## Figure captions

**Figure 1.** Percent change in sway velocity (mean and standard error) in AP and ML directions for the ankle fatigue group (top panel) and for the hip fatigue group (bottom panel). ML sway velocity increased significantly immediately after fatiguing the hip muscles only ( $p=0.011$ ). ST= single-task, DT= dual-task.

**Figure 2.** Simple reaction time (mean and standard error) at each time point for the ankle fatigue group (light bars) and for the hip fatigue group (dark bars). Simple reaction time was significantly different between seated and standing before fatigue (pre-fatigue), standing immediately after fatigue (post-fatigue) and standing 30 min after fatigue (30 min recovery) for both groups (\*  $p \leq 0.05$ ).





## **CHAPTER 5. MANUSCRIPT 2**

Changes in postural sway and attentional demands due to ankle neuromuscular fatigue with aging.

Submitted to *PLOS ONE*

**Changes in postural sway and attentional demands due to ankle neuromuscular fatigue  
with aging**

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## **ABSTRACT:**

**Purpose.** The purpose of this study was to compare the effects of ankle muscle fatigue on postural sway and concurrent attentional demands during a unipedal stance task between healthy older and younger adults. **Methods.** Seventeen older adults (mean age =  $65 \pm 4$  years) and 14 young adults (mean age =  $22 \pm 3$  years) were asked to stand on their dominant leg for 30-s trials before and after ankle muscle fatigue. Half of the trials were carried-out while performing a voice reaction time task (dual-task). The fatigue task included alternating plantar and dorsiflexion maximal contractions on a dynamometer until the torque decreased below 50% of the pre-fatigue maximal torque in both directions. Sway variables were calculated using center of pressure (COP) data obtained from a force platform. Voice reaction time was recorded seated and during the dual-task trials to assess attentional demands. **Results.** Fatigue led to a significant posterior displacement of the COP mean position for the older group, and an increase in AP sway variability for both groups. In contrast, fatigue had no effect on AP and ML sway velocity in either group. However, an increase in ML sway velocity was seen with the presence of a dual-task compared with a single task for the older group only. Simple reaction time increased from sitting to all standing trials, illustrating an increase in attentional demands during unipedal stance. However, fatigue had no effect on simple reaction time for either group. **Conclusion.** The postural task was more difficult for older adults, but the alterations in sway induced by the fatiguing activity were not more pronounced than those observed for young adults. The addition of a secondary task made unipedal standing more challenging to control for older adults, but this was not affected by fatigue.

**Key words:** muscle fatigue, postural stability, attention, lower extremity

## **Introduction**

Aging is accompanied by well-known gradual deteriorations of the musculoskeletal, neuromuscular and sensory systems. As a consequence, older adults generally present with greater postural sway compared to their younger counterparts [1]. The increase in postural sway has been found to correlate with decreased visual acuity [2], reduced proprioception [3,4], and reduced muscle strength due to muscle morphological changes with aging [5]. Although the long-term benefits of physical activity are obvious for older adults [6], acute muscle fatigue following physical activity could be problematic as it has been widely shown to increase postural sway in young adults [7–14]. Muscle fatigue, defined as an acute impairment in the ability to produce maximum force, regardless of whether or not the task itself can still be performed successfully [15], has been shown to impair the mechanical properties of muscles [16] and the proprioceptive system [17,18] required for postural control. In fact, numerous studies on young adults have attributed the change in postural control with fatigue to a decrease in proprioceptive information [9,14] and/or a slowing in force-generating capabilities of muscles [12]. Such decrease in postural control with fatigue could be more pronounced in older compared with young adults since their proprioceptive and neuromuscular systems are less efficient. However, a few recent studies have failed to show greater fatigue-related impairments in posture control for older compared with young adults [19,20]. Interestingly, Elgerton and colleagues [19] have suggested that even with the observation of similar postural sway after fatigue in young and older adults, the amount of attention allocated to postural control may be increased in older adults.

Indeed, in addition to muscle capacity and proprioceptive declines, muscle fatigue may alter the central processing of information required for postural control [13,21]. This could lead to an increase in attentional demands associated with postural control. Only two studies on young adults showed an increase in attentional demands following ankle muscle fatigue [13] or treadmill walking [21]; this, in contrast to one study where no effect of ankle muscle fatigue was found [7]. The attentional cost of postural control has been shown to increase with aging [22,23] and with the difficulty of the task [24,25], particularly when proprioceptive information is reduced due to environmental constraints [22,23,25]. Thus, it can be hypothesized that fatigue may significantly affect the attentional cost of postural control in older adults.

The objectives of this study were: a) to compare changes in postural sway during a unipedal stance due to fatigue of ankle extensor (plantarflexor) and flexor (dorsiflexor) muscles between young and older adults; and b) to examine whether such fatigue would lead to an increase in attentional demands during a dual-task paradigm. It was hypothesized that older adults would show a greater increase in postural sway due to ankle muscle fatigue compared to young adults, and that this would be associated with a corresponding increase in attentional demands.

## **Methods**

### **Subjects**

Seventeen older adults (10 females, mean  $\pm$  SD for age =  $65 \pm 4$  years, height =  $164.2 \pm 10.7$  cm, weight =  $63.2 \pm 13.8$  kg) and 14 young adults (10 females, mean  $\pm$  SD for age =

22 ± 3 years, height = 168.4 ± 7.6 cm, weight = 66.7 ± 11.1 kg) were recruited for this study through convenience sampling. Subjects were free of orthopaedic, cardiovascular or neurological conditions known to influence postural control. The cognitive status of young and older subjects was assessed using the Mini Mental State Exam (MMSE) [26]. No subject scored below a 25 on the MMSE (mean score = 29.6 ± 0.6 and 28.9 ± 1.7, for both groups, respectively). The study was approved by the University of Ottawa and the Bruyère Continuing Care Research Ethics Boards and written informed consent was obtained from each subject prior to their participation in the study.

## **Procedures**

Similar procedures to those found in our recent study with young adults were used for the present study [7]. Subjects were asked to stand barefoot on a force platform on their dominant leg. The leg which the subject would use to kick a ball was considered the dominant leg. Subjects were asked to maintain their balance as steadily as possible for 30 s with eyes open, fixating a black cross placed on the wall at eye level, 2 m in front of them. Their arms had to hang by their sides and support from the elevated leg was not permitted. Each subject completed eight trials (four in single-task, four in dual-task) before and immediately after a fatigue task (pre-fatigue, post-fatigue, respectively). For each time point, trials were alternated between a single-task condition consisting of quiet standing alone and a dual-task condition consisting of quiet standing with the addition of a simple reaction time task (SRT). The SRT task consisted of responding verbally with the word “top” after hearing an auditory stimulus (1000Hz, 100ms) which was randomly dispersed four times throughout each dual-task trial. Subjects were asked to respond to each auditory stimulus as quickly as

possible while maintaining their focus on the postural task (primary task). Prior to pre-fatigue trials, each subject was familiarized with the tasks and three trials of seated SRT were recorded in order to determine the attentional demands of the primary tasks. The order of the standing tasks was counterbalanced between subjects.

### **Fatigue task**

The ankle plantarflexor and dorsiflexor muscles were fatigued using a BIODEX system III (Shirley, NY) dynamometer. Starting position was seated with the hip, knee and ankle joints flexed at 90°, 35° and 80°, respectively. Knee angle was kept constant and ankle range of motion was set at 35° (10° of dorsiflexion to 25° of plantarflexion). The non-dominant leg was left hanging free without support to limit its use during the fatigue task. Both arms were crossed in front of the subject with the waist, shank and foot securely strapped to eliminate potential compensations. Before the fatigue task, peak torque output was measured during three maximal voluntary concentric contractions (MVCs) at 30°/s in plantarflexion and 120°/s in dorsiflexion. The fatigue task consisted of alternating maximal isokinetic contractions in plantarflexion and dorsiflexion (same speeds as for the MVCs) for as many repetitions as possible, until the torque decreased below 50% MVC for three consecutive contractions for both muscle groups. Different velocities were chosen for isokinetic contractions of plantarflexors and dorsiflexors in order to achieve similar time to fatigue for both muscle groups as done previously [7,11]. Subjects were given strong verbal encouragement during maximal contractions and all fatigue bouts. To avoid the effect of an initial recovery during the post-fatigue trials, the fatigue task was repeated once after the first two trials of each postural task (single-task and dual-task). For both fatigue protocols

(fatigue and re-fatigue), the fatigue time (time between the first and last contractions) was measured.

### **Data Analysis**

Postural data were collected using an AMTI AccuGait force platform (Watertown, MA). Four center of pressure (COP) variables were calculated using BioAnalysis 2.1 software (Watertown, MA): sway area, represented by the area of the 95% confidence ellipse (in  $\text{cm}^2$ ); mean COP position, represented by the mean position of the COP from the center of the force plate (cm); sway variability, represented by the standard deviation of the COP around the mean position (cm); and sway velocity, represented by the total COP displacement divided by time (cm/s). The last three variables were obtained for both antero-posterior (AP) and medio-lateral (ML) directions. SRT data were collected with an MP3 recorder secured to the subject's arm to gather both the start of the auditory stimulus and the verbal response from the subject. The mean of all trials for each pre-fatigue condition was calculated and used for statistical analyses. Because the effects of muscle fatigue on postural sway have been shown to recover quickly [9,11], the mean of the first two trials of each condition after the fatigue task (immediate post-fatigue) and the mean of the two subsequent trials (late post-fatigue) were calculated and used separately for statistical analyses. When a step occurred during a postural trial, the trial was removed from data analysis only if the step affected the sway parameters (trials greater than two standard deviations from the mean for sway area). All steps occurred in the older group (equally before and after fatigue). This represented 7% of the total number of trials (i.e., 29 trials out of a total of 408 trials) performed by this group.

A two way mixed-model ANOVA was used to compare the fatigue time of each fatigue protocol (repeated measure; fatigue protocol, re-fatigue protocol) between groups (between factor: young, older). Three-way mixed-model ANOVAs were used to assess the effects of fatigue (repeated measure; pre-fatigue, immediate post-fatigue, late post-fatigue), task (repeated measure; single-task or dual-task), and group (between factor; young, older) on each dependent postural variable (sway area, AP and ML mean COP position, AP and ML sway variability, AP and ML sway velocity). A two-way mixed-model ANOVA was used to assess the effects of condition (repeated measure; seated, pre-fatigue, immediate post-fatigue, late post-fatigue) and group (between factor; young, older) on SRT. All statistical analyses were completed using PASW statistics 18 (IBM, Chicago, IL) with a significance level set at  $p \leq 0.05$ . Post hoc analyses were used when appropriate using a Bonferroni adjustment.

## **Results**

### **Fatigue Time**

Fatigue time was not significantly different between the fatigue and the re-fatigue protocol ( $F = 3.16$ ,  $p = 0.087$ ) but was significantly longer for the older adults ( $F = 6.75$ ,  $p = 0.015$ ). The fatigue protocol by group interaction ( $F = 0.429$ ,  $p = 0.518$ ) was found not significant. Young and older adults took on average (both fatigue protocols combined)  $71 \pm 16$  s and  $131 \pm 82$  s, respectively to reach 50% of the MVC in both plantarflexors and dorsiflexors.

### **Mean COP position**

ML mean COP position was not affected by fatigue or task for either group. In contrast, AP mean COP position results revealed a significant main effect of fatigue ( $F = 3.86$ ,  $p = 0.027$ ). There was no significant effect of task ( $F = 1.76$ ,  $p = 0.194$ ) or group ( $F = 1.88$ ,  $p = 0.180$ ), but a fatigue by task interaction ( $F = 3.41$ ,  $p = 0.040$ ) and a fatigue by group interaction ( $F = 7.04$ ,  $p = 0.002$ ) were statistically significant. As shown in Figure 1, pairwise comparisons showed a significant posterior shift of the AP mean COP position for the older adults during the immediate post-fatigue ( $p = 0.003$ ), but no difference with the late post-fatigue ( $p = 0.30$ ), whereas AP mean COP position for both immediate and late post-fatigue trials did not differ from pre-fatigue values for young adults ( $p > 0.05$ ). Interestingly, a posterior shift in COP was statistically significant after fatigue for the single task (immediate post-fatigue:  $p = 0.015$ ; late post-fatigue:  $p = 0.037$ ), but not the dual task ( $p > 0.05$ ). Although the fatigue by task by group interaction was found not significant ( $F = 0.563$ ,  $p = 0.573$ ), Figure 1 clearly shows that the posterior shift is only apparent in older adults.

### **Postural sway area and variability**

Sway area and ML sway variability results (Table 1) revealed no significant main effects of fatigue (sway area:  $F = 2.69$ ,  $p = 0.08$ ; ML sway variability:  $F = 0.434$ ,  $p = 0.650$ ) or task (sway area:  $F = 1.14$ ,  $p = 0.295$ ; ML sway variability:  $F = 1.62$ ,  $p = 0.214$ ), but a significant main effect of group (sway area:  $F = 10.16$ ,  $p = 0.003$ ; ML sway variability:  $F = 32.53$ ,  $p < 0.001$ ). Additionally, all interactions were not significant ( $p > 0.05$ ). Compared to

young adults, older adults had greater ML sway variability ( $0.77 \pm 0.12$  vs.  $0.58 \pm 0.08$ ) and greater sway area ( $11.60 \pm 3.60$  vs.  $8.61 \pm 2.54$ ).

AP sway variability results (Table 1) revealed significant main effects of fatigue ( $F = 3.75$ ,  $p = 0.029$ ), but not task ( $F = 0.293$ ,  $p = 0.593$ ) or group ( $F = 0.005$ ,  $p = 0.946$ ). All interactions were not significant ( $p > 0.05$ ). Pairwise comparisons showed that AP sway variability increased significantly immediately after fatigue compared to pre-fatigue ( $p = 0.028$ ), but not during the late post-fatigue trials ( $p = 0.115$ ).

### **Postural sway velocity**

AP and ML sway velocity results (Table 1) revealed no significant main effects of fatigue (AP sway velocity,  $F = 2.50$ ,  $p = 0.098$ ; ML sway velocity,  $F = 1.84$ ,  $p = 0.176$ ), but main effects of task (AP sway velocity,  $F = 19.16$ ,  $p < 0.001$ ; ML sway velocity,  $F = 22.44$ ,  $p < 0.001$ ) and group (AP sway velocity,  $F = 10.96$ ,  $p = 0.002$ ; ML sway velocity,  $F = 26.66$ ,  $p < 0.001$ ). Fatigue by task interaction was not found to be significant ( $p > 0.05$ ). A task by group interaction was found to be significant for ML sway velocity ( $F = 4.95$ ,  $p = 0.034$ ), but did not reach significance for AP sway velocity ( $F = 3.21$ ,  $p = 0.08$ ). Older adults had greater sway velocity compared with younger adults. When standing during a dual task, older adults showed a significant increase in ML sway velocity (DT =  $4.74 \pm 1.25$  vs. ST =  $4.42 \pm 1.24$ ;  $p < 0.001$ ) compared with standing during a single task. No such differences were apparent for the younger group.

## **Simple Reaction Time**

SRT results are shown in Figure 2. Results showed a significant main effect of condition ( $F = 13.96$ ,  $p < 0.001$ ), but no group effect ( $F = 0.134$ ,  $p = 0.717$ ) and no condition by group interaction ( $F = 1.27$ ,  $p = 2.89$ ). Pairwise comparisons showed only a significant difference between seated SRT and all standing SRTs ( $p < 0.001$ ).

## **Discussion**

Our results show that young and older adults increased their sway amplitude (AP sway variability) similarly when standing on one leg immediately following ankle muscle fatigue compared with pre-fatigue, refuting our first hypothesis stating that older adults would present with greater postural control alterations. However, it was found that older adults had a posterior shift in AP mean COP position, suggesting a change in strategy to compensate for a loss of proprioceptive information or use of non-fatigued muscles (change in the way force is generated) to maintain stability that was not observed in the young adults. Nevertheless, the increase in attentional demands seen during a dual-task was not greater when young and older adults were fatigued.

## **Effect of fatigue**

As previously shown in the literature [7–14], ankle muscle fatigue increases postural sway (AP sway variability) in young adults. In the present study, this increase was modest and older adults had a similar increase due to fatigue compared with young adults. Egerton and colleagues [19] found similar results where groups of 31 young adults, 33 healthy older adults and 22 balance-impaired older adults had greater mean COP displacement and

variability (SD), but no increase in COP velocity after a moderate physical activity session. In their study, differences in the changes of COP parameters due to fatigue between the groups were not significant. These authors suggested investigating the effect of fatigue on a task more challenging than a bipedal task with eyes open to identify the true risk of falls during a fatigue state. The fact that the present study found no differences between young and older adults using a difficult task (one-leg stance) was not expected. As shown by Egerton and colleagues [19], older adults had greater postural sway (sway area, ML sway variability and greater AP and ML sway velocity) compared with young adults, which suggests that they had more difficulty with the task compared to their younger counterparts. Moreover, most of the older adults had to step during some trials (before and after fatigue), whereas none of the younger adults made a single step during the whole testing session. Thus, even if the task was more difficult, older adults were able to compensate for muscle fatigue similarly to young adults. One explanation may be that the older adults recruited in the present study were relatively active and highly functional (able to stand on one-leg for multiple bouts of 30 s). Alternatively, older adults may have increased their reliance on visual information to compensate for proprioceptive alteration due to ankle muscle fatigue.

We found a posterior shift in mean COP position after ankle muscle fatigue, suggesting a change in strategy to control posture in older adults which was not observed in young adults. The ankle strategy is predominantly used during quiet standing, but the unipedal stance is controlled by a combination of ankle and hip strategies [27]. Although kinematic data on muscle activity would further support this hypothesis, it has been shown that a posterior shift of the COP is associated with a change in ankle, knee and/or hip angles,

which could reduce the demands or reliance placed on the muscle group fatigued to optimize postural control [28]. For example it has been suggested that when the ankle musculature is fatigued, the decrease in ankle control can be compensated by an increased reliance on the hip strategy [8,10].

Nonetheless, the effect of fatigue was short-lived since AP sway variability decreased as early as the second set of post-fatigue trials. Others [9,11] have also found a rapid recovery of postural control variables following fatigue in young adults. Our results suggest that older adults are able to recover quickly just like their younger counterparts.

### **Dual-task**

In a recent review, Fraizer & Mitra [29] explained that attentional demands are shown to increase during a dual-task, resulting in compensatory activity (increase sway velocity) for the primary task, and a decrease in performance of the secondary task. In the present study, the performance on the secondary task (SRT) decreased from sitting to standing on one-foot suggesting an increase in attentional demands for both groups. Furthermore, despite no difference in sway area and sway variability, a significant increase in ML sway velocity during the dual-task condition was noted for the older adults, suggesting that this group may have adopted a stiffening strategy to remain stable when attention was divided. This was not observed in the young adults.

As suggested by Egerton and colleagues [19], for a similar increase in postural sway due to fatigue, older adults may need more attention than young adults to maintain postural

control. However, the increase in attentional demand was not greater following ankle muscle fatigue, as reflected by the absence of a change in SRT and in compensatory activity (sway velocity). This suggests the presence of sufficient attentional resources to perform a unipedal stance task and an auditory SRT task simultaneously after the present fatigue protocol, for both groups. There are two possible explanations for the lack of change in attentional demands associated with postural control following our fatigue protocol. First, fatiguing ankle muscles using concentric contractions may not have caused enough postural control alterations to increase the attentional demands of unipedal stance. Our fatigue protocol led to a modest increase (less than 15%) in AP sway variability after fatigue. In comparison, the increase in attentional demands to maintain a static bipedal stance found by Vuillerme and colleagues [13] was accompanied by a more substantial increase in postural sway range, and an increase in sway velocity (65% increase) due to an isometric fatigue protocol. Second, the fact that our subjects could rely on visual information may have attenuated the increase in attentional demands due to fatigue and could explain the lack of significance in this study. Nonetheless, further research is needed to thoroughly document the attentional cost of fatigue on postural control, particularly in older adults.

## **Conclusion**

In the present study, ankle muscle fatigue induced a modest increase in AP sway variability in both young and older adults. This suggests that even if the task was more difficult for the older adults, they were able to compensate for muscle fatigue similarly to young adults. However, ankle muscle fatigue appeared to modify the strategy used to control unipedal stance (a posterior shift of the body) in older but not young adults. Although the

addition of a dual-task made unipedal standing more challenging to control, this increase in attentional demand was not greater when ankle muscles were fatigued. This suggests the presence of sufficient attentional resources to perform a unipedal stance task and an auditory SRT task simultaneously after the present fatigue protocol, for both groups.

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**Table 1. Comparison of the COP parameters between young and older adults during a single and dual task before and after fatigue**

COP parameter	Single Task			Dual Task		
	pre-fatigue	immediate post-fatigue	late post-fatigue	pre-fatigue	immediate post-fatigue	late post-fatigue
Sway Area, cm <sup>2</sup> (SD)						
young	8.21 (2.18)	8.36 (2.40)	9.16 (2.93)	8.04 (1.93)	9.42 (2.99)	8.50 (2.82)
older <sup>a</sup>	11.15 (3.31)	11.42 (2.66)	11.08 (3.26)	11.24 (3.65)	12.68 (4.73)	12.02 (3.97)
AP sway variability, mm(SD) <sup>b</sup>						
young	75.1 (14.8)	78.8 (16.4)	84.7 (20.6)	74.8 (12.5)	85.8 (19.7)	79.0 (15.2)
older	78.5 (12.8)	81.2 (14.4)	76.9 (9.5)	77.5 (14.1)	83.8 (19.4)	82.0 (19.1)
ML sway variability, mm (SD)						
young	57.6 (6.6)	56.3 (7.6)	58.6 (8.5)	58.1 (7.1)	58.6 (8.5)	87.8 (10.7)
older <sup>a</sup>	75.1 (12.1)	76.3 (10.1)	77.2 (14.1)	76.9 (13.1)	79.7 (13.3)	77.9 (12.2)
AP sway velocity, cm/s (SD) <sup>c</sup>						
young	2.53 (0.63)	2.50 (0.60)	2.56 (0.56)	2.65 (0.75)	2.71 (0.75)	2.64 (0.75)
older <sup>a</sup>	3.95 (1.52)	3.72 (1.44)	3.82 (1.34)	4.23 (1.75)	4.09 (1.55)	3.78 (1.05)
ML sway velocity, cm/s (SD) <sup>d</sup>						
young	2.71 (0.48)	2.77 (0.51)	2.75 (0.60)	2.90 (0.61)	2.83 (0.53)	2.85 (0.61)
older <sup>a</sup>	4.48 (1.28)	4.32 (1.26)	4.47 (1.18)	4.83 (1.38)	4.74 (1.18)	4.66 (1.20)

<sup>a</sup> Older had greater sway area, ML sway variability, AP and ML sway velocity compared with young adults (p<0.01).

<sup>b</sup> AP sway variability was greater immediately after fatigue compared to pre-fatigue (p = 0.028).

<sup>c</sup> AP sway velocity was greater during dual task trials compared with single task trials (p<0.001).

<sup>d</sup> ML sway velocity was greater during dual task trials compared with single task trials for older adults only (p<0.001).

## Figure Legends

**Figure 1. AP COP mean position (cm) comparison between groups at each time point.** For the older adults, there was a significant posterior shift of the AP COP mean position from baseline to the immediate post-fatigue during the dual task (\*\*  $p = 0.003$ ) but no difference with the late post-fatigue ( $p = 0.30$ ). For the young adults, AP COP mean position during both post-fatigue did not differ from pre-fatigue values ( $p > 0.05$ ). COP: centre of pressure, SD: standard deviation, AP: antero-posterior, ML: medio-lateral, ST: single-task, DT: Dual-task.

**Figure 2. Simple reaction time (mean and standard deviation) at each time point.** Simple reaction time was significantly different between seated and baseline, immediate post-fatigue and late post-fatigue for the young adults (young) and the older adults (older). \*\*\*  $p < 0.001$

Figure 1.

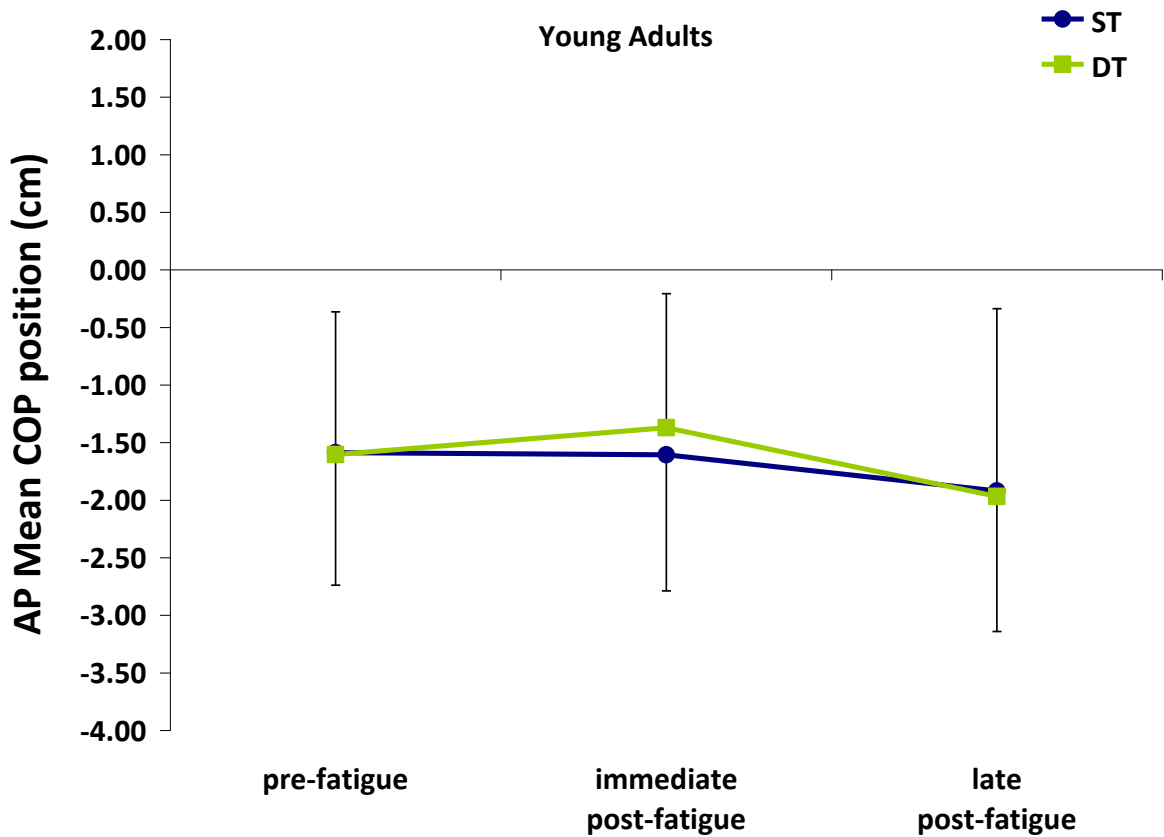
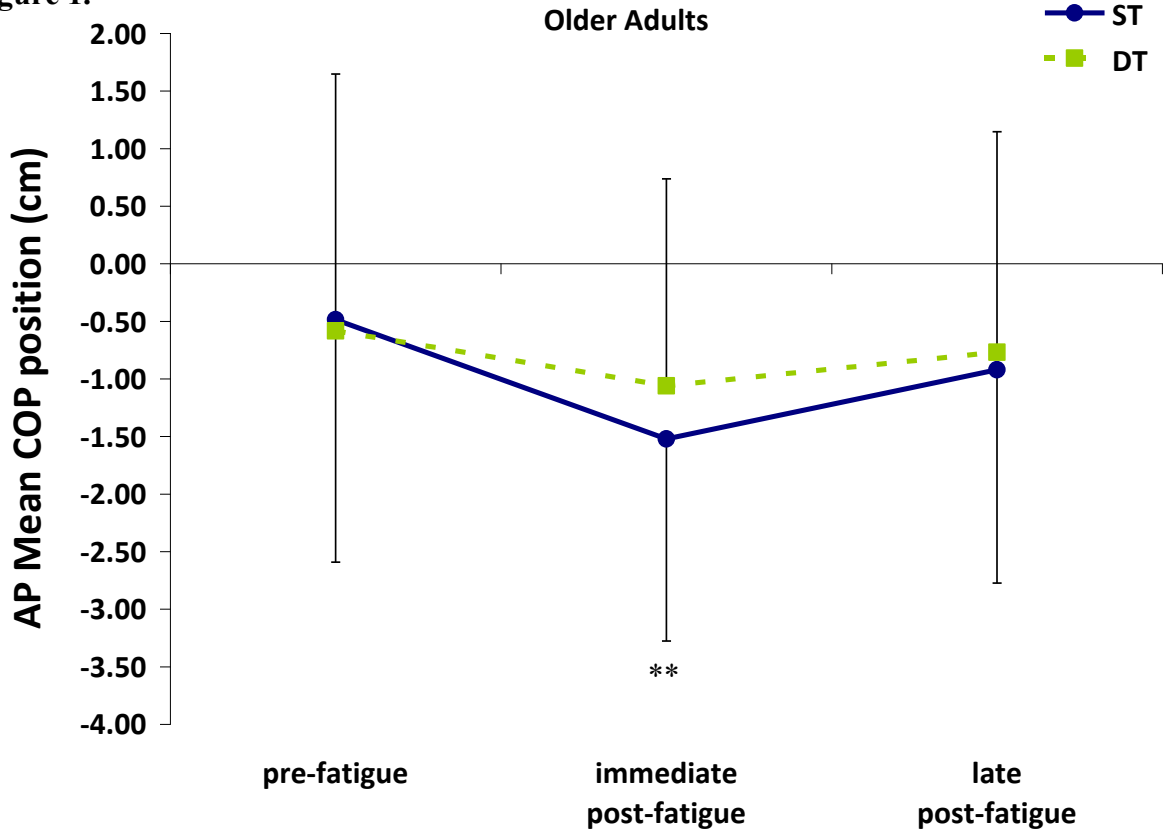
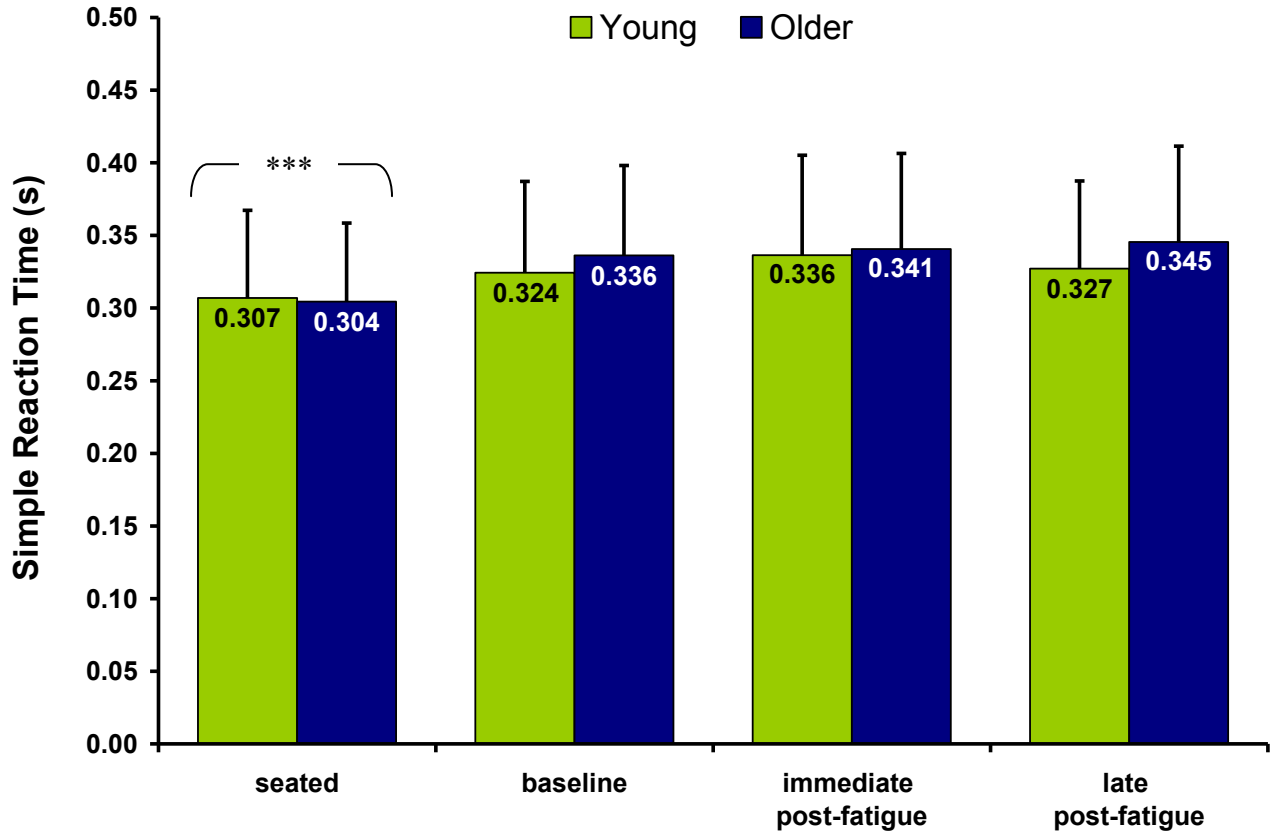


Figure 2.



## **CHAPTER 6. MANUSCRIPT 3**

Effects of fatiguing isometric and isokinetic ankle exercises on postural control while standing on firm and compliant surfaces.

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# **Effects of fatiguing isometric and isokinetic ankle exercises on postural control while standing on firm and compliant surfaces**

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# **Abstract**

## **Background**

Fatiguing exercises used across studies to induce alterations in postural control are diverse and may explain the different findings reported. This study aimed to compare the effects of two types of fatiguing plantarflexion exercises on postural control on a firm and a compliant surface. Ten healthy young men ( $29 \pm 4$  years) were asked to stand as steadily as possible for 30 s, blindfolded with feet together, on a firm and a compliant surface before and immediately after an isometric and an isokinetic fatiguing exercise.

## **Results**

Maximal force reduction due to fatigue was found significant but similar between exercises. No significant difference was found between the fatiguing exercises on all Center of Pressure (CoP) parameters. Both fatiguing exercises induced increases in CoP excursion area, CoP variability and CoP velocity in both planes (antero-posterior, mediolateral) on the compliant surface. On the firm surface, both fatiguing exercises only induced increases in CoP variability and CoP velocity in the fatigued plane (antero-posterior).

## **Conclusions**

Isometric and isokinetic fatiguing exercises, when producing a similar level of force reduction, induce similar decreases in postural control. The effects of fatigue on postural control in healthy young men are more pronounced when standing on a compliant surface, i.e., when proprioceptive information at the ankle is altered.

## **Keywords**

Neuromuscular Fatigue, Posturography, Centre of Pressure, Contraction Mode, Plantarflexor Muscles

## Background

The ability to perform a multitude of physical activities and most daily living activities requires adequate postural control. In order to maintain postural control, the central nervous system must integrate and (re-)weight information from the visual, vestibular and somatosensory systems and modulate commands to the neuromuscular system continuously [1]. Not surprisingly, numerous studies [2-11] have demonstrated an impairment in postural control in different postural tasks after neuromuscular fatigue. Since the plantarflexor muscles constitute the main controllers in quiet standing [12], the effect of fatigue of these muscles on postural control have been largely examined. The findings, however, vary significantly possibly due to methodological differences (i.e., fatigue protocols, postural stances used and/or amount of visual information available) across studies. In a recent study [4], we found that an isometric fatiguing exercise (standing on tip-toes until exhaustion) increased Center of Pressure (CoP) excursion area, CoP variability and CoP velocity in both antero-posterior (AP) and medio-lateral (ML) planes. This increase was found independent of the difficulty of the postural task (unipedal, tandem, bipedal), except for a more pronounced effect for the most challenging postural task (i.e., unipedal stance with eyes closed). Our results were consistent with other studies using a similar isometric fatiguing exercise [5,8-11]. In contrast, when the ankle musculature was fatigued with an isokinetic exercise in a different study [2], an increase in CoP velocity was found only in the AP plane, i.e., the plane in which the fatigued plantarflexor muscles act as prime mover muscles. Again, these results were consistent with studies that have used a similar fatiguing exercise [3,6,13]. In addition to the different modes of contraction (isometric vs. isokinetic), other parameters specific to a given fatiguing exercise (intensity, duration) can explain why results

vary across studies. Thus, it can be questioned if the impairment of postural control is really influenced by the mode of contraction or if it is only a factor of intensity and/or duration of the fatigue task.

Intense or prolonged exercise inevitably induces neuromuscular fatigue through various mechanisms, i.e., alterations in the activation of the primary motor cortex, reduction of motor unit discharge rates, alterations of excitation-contraction coupling, and slowing of the contractile apparatus [14,15]. Furthermore, muscle fatigue due to intense or prolonged exercise also affects the proprioceptive system [16,17]. This could be explained by the accumulation of metabolites leading to altered muscle spindle function [17], as well as altered central processing of proprioception via group III and IV afferents [16]. However, it has been shown that the mechanisms involved in muscle fatigue are dependent on the exercise performed to fatigue the muscles (task dependency) [18]. Sustained isometric activities have been suggested to induce greater central fatigue compared to concentric intermittent contractions due to greater metabolite by-products accumulation with the limited blood flow, causing in turn an inhibition of the supraspinal descending drive possibly via small-diameter afferents [14,15,19]. However, the impact of these different modes of contraction on postural control has yet to be compared.

Compliant surfaces (such as temper foams and sway-referenced platforms) are commonly used in postural studies to examine the reliance on proprioceptive information in the control of postural tasks [1,20-25]. They are also used in clinical settings to assess balance [26]. By comparing CoP parameters on a firm and a compliant surface, the latter condition has been shown to be more sensitive to balance problems observed with old age

[22,25], pathologies such as vestibular disorders [1] and injuries [20,21]. Since a reduction in proprioception and the re-weighting of this information have been proposed to be the main causes of decreased postural control with fatigue [27], one may expect the effect of fatigue to be different on a firm versus a compliant surface. Several studies [7,28-30] have shown an impairment in postural control when standing on a compliant surface (sway-referenced platform) after fatigue. However, only one study [30] compared fatigue-related changes of CoP parameters between a compliant and a firm surface. The authors found an impairment in postural control after ankle, knee and global fatigue. This effect was not greater on a sway-referenced platform. Since the results of this study may be limited because of methodological issues (i.e., duration and number of trials), more research is needed to clarify these findings.

Thus, in an attempt to elucidate factors contributing to the different reports regarding the effect of fatigue on postural control, the objectives of the present study were: a) to compare the effects of isometric and concentric isokinetic fatiguing exercises on postural control during quiet stance, and b) to assess whether the magnitude of these effects are dependent on the amount of proprioceptive information available (i.e., by comparing postural tasks performed on a firm surface and a compliant surface). It was hypothesized that an isometric fatiguing exercise would induce greater alterations in postural control compared to an isokinetic concentric fatiguing exercise, likely due to a greater increase in metabolite concentration [19]. It was further hypothesized that postural control on a compliant surface would be impaired to a greater extent after fatigue compared to a firm surface because standing on a compliant surface requires more proprioceptive information and greater control by the neuromuscular system.

## Methods

### Subjects.

Ten healthy young men ( $29 \pm 4$  years,  $178.6 \pm 7.5$  cm,  $73.6 \pm 9.6$  kg) were recruited to participate in this study. Subjects had no neurological problems and no history of falls or ankle injury in the past year. The study was approved by the University of Ottawa and the Bruyère Continuing Care research ethics boards, and written informed consent was obtained from each subject prior to their participation in the study.

### Procedures.

Subjects took part in two identical sessions, performed one week apart, where postural control was assessed before and immediately after an isometric (IM) or isokinetic (IK) plantarflexion fatiguing exercise. For both sessions (IM session and IK session), postural control was assessed under two surface conditions (firm versus compliant surface), where three 30-s trials of standing as still as possible with feet together and blindfolded (opaque ski goggles) were collected before and after fatigue. This postural task (feet together) without vision was shown to be more sensitive to fatigue on a firm surface compared to the same task with vision [4,8]. Thus, 3 postural trials  $\times$  2 types of surface (firm and compliant)  $\times$  2 time points (before and after fatigue) for a total of 12 trials were performed per session. A medium density temper foam ( $41 \times 47 \times 8$  cm; density =  $108 \text{ kg/m}^3$ ) was used for the compliant surface condition. When standing on this type of foam, subjects were unable to feel the floor surface, thus, proprioceptive information from the feet and ankles was less reliable. Subjects practiced each postural task prior to the pre-fatigue

trials. Subjects were asked to position their hands on their hips at the beginning of the trials and were allowed to use them to maintain their balance if necessary.

After completing a first bout of fatiguing exercise (IM or IK depending on session), subjects performed the post-fatigue postural trials in one condition (firm or compliant). Then, after completing the same fatiguing exercise a second time (second bout), subjects performed the post-fatigue postural trials in the other condition (compliant or firm). The fatiguing task was repeated between the two post-fatigue postural conditions in order to ensure the maintenance of an equivalent fatigue state for both conditions. The time elapsed between the end of the fatiguing exercise and the start of the first post-fatigue postural trial for each condition was 40 s on average. The order of the sessions (IM and IK session) and postural conditions (firm, compliant) were counterbalanced between subjects.

### **Fatiguing exercises.**

Both fatiguing exercises were completed using a Biodex system 3 dynamometer (Shirley, NY, USA) and a custom attachment allowing the production of force using plantarflexor muscles from both ankles simultaneously (Figure 1). During both sessions, subjects were first secured on the dynamometer in the initial position (Figure 1) where legs were horizontal, the trunk elevated to form a 25° angle, and the angle between the legs and the feet fixed at 90°. Subjects performed 10 submaximal isokinetic contractions ( $30^{\circ}\cdot\text{s}^{-1}$ ) and five submaximal isometric contractions of increasing intensities as a warm-up and to be familiarized with the dynamometer. Subsequently, for both IM and IK session, subjects performed three maximal isometric voluntary contractions ( $\text{MVC}_{\text{IM}}$ ) where the highest peak torque output was considered the subject's pre-fatigue  $\text{MVC}_{\text{IM}}$ . The same procedure was

used to calculate the maximal voluntary isokinetic concentric contraction ( $MVC_{IK}$ ) before the IK fatiguing exercise (IK session only).

The fatiguing exercise for the IM session consisted of maintaining 50% of pre-fatigue  $MVC_{IM}$  until exhaustion (i.e., subjects unable to maintain the force target for 3 s). The fatiguing exercise for the IK session consisted of performing continuous maximal concentric IK contractions of the plantarflexors. Angular velocity was set at  $30^{\circ}\cdot s^{-1}$  with a total range of motion of  $35^{\circ}$  (from  $10^{\circ}$  dorsiflexion to  $25^{\circ}$  plantarflexion, with  $0^{\circ}$  = initial position). The isokinetic fatiguing exercise ended when the torque decreased below 50% of  $MVC_{IK}$  for three consecutive contractions. To avoid any muscle fatigue of dorsiflexor muscles, after each plantarflexion contraction through the  $35^{\circ}$  range of motion, an experimenter quickly pulled back the attachment to the starting position ( $10^{\circ}$  dorsiflexion) and subjects were instructed to relax during that time. After completion of the first and second bouts of fatiguing exercise for both IM and IK session, subjects were asked to perform a  $MVC_{IM}$  (post-fatigue 1, post-fatigue 2) before transferring to the force platform to compare the level of fatigue after both types of exercise. Strong verbal encouragements and visual feedback of the torque output were provided to subjects during the MVC contractions and fatiguing exercises.

### **Data acquisition.**

The torque output from the dynamometer was sampled (5000 Hz) via a 1401Plus analog-to-digital board using Spike2 v.7 (CED, Cambridge, UK). Center of pressure (COP) data were collected using an AMTI AccuGait force-platform (Watertown, MA, USA) at a 50 Hz sampling rate. The changes in CoP variations associated with fatigue were quantified

with three postural variables using BioAnalysis 2.1 software (Watertown, MA, USA): the CoP excursion area ( $\text{cm}^2$ ) represented by the 95% ellipse area [31], CoP variability (cm) represented by the standard deviation of the CoP, and mean CoP velocity ( $\text{cm}\cdot\text{s}^{-1}$ ). CoP variability and velocity variables were computed separately for the ML and AP directions. The mean of the three trials for each surface and fatigue conditions was calculated and used for statistical analyses.

### **Data analysis.**

A two-way analysis of variance (ANOVA) with repeated measures was used to assess the effects of fatigue (pre-fatigue, post-fatigue 1 and post-fatigue 2) and type of fatigue (IM and IK) on  $\text{MVC}_{\text{IM}}$ . A two-way ANOVA with repeated measures was used to assess the effects of fatigue (post-fatigue 1 and post-fatigue 2) and type of fatigue (IM and IK) on time to failure (the time elapsed to reach the fatigue state criterion of each fatiguing exercise). Separate three-way ANOVAs with repeated measures were used to assess the effects of fatigue (pre and post-fatigue), type of fatigue (IM and IK) and type of surface (firm and compliant) for each of the five postural variables (CoP excursion area, ML and AP CoP variability, ML and AP CoP velocity). For all statistical tests, the significance level was set at 0.05. Post hoc analyses were completed when appropriate using Bonferroni adjustments. Normal distribution of the data was confirmed with Kolmogorov-Smirnov tests.

## **Results**

### **Type of fatigue**

$\text{MVC}_{\text{IM}}$ . As shown in Figure 2, results on the  $\text{MVC}_{\text{IM}}$  showed a significant main effect of fatigue ( $F = 94.6$ ,  $p < 0.001$ ,  $\eta^2_p = 0.91$ ). The main effect of type of fatigue ( $F = 2.6$ ,

$p = 0.14$ ,  $\eta^2_p = 0.22$ ) and the fatigue by type interaction ( $F = 1.3$ ,  $p = 0.30$ ,  $\eta^2_p = 0.12$ ) were found not significant.  $MVC_{IM}$  recorded after each fatiguing exercises (Pooled IM and IK mean values for post-fatigue 1 =  $180.3 \pm 34.5$  N·m and for post-fatigue 2 =  $175.8 \pm 32.9$  N·m) were significantly different from pre-fatigue (Pooled IM and IK mean values =  $246.9 \pm 42.0$  N·m;  $p < 0.001$ ). The absence of the effect of the type of fatigue suggests that the level of fatigue was similar between the IM and IK fatiguing exercises (mean % of pre-fatigue  $MVC_{IM} = 73.9 \pm 6.7$  and  $70.9 \pm 8.7$ , respectively).

**Time to failure.** Results showed significant main effects of fatigue ( $F = 11.4$ ,  $p = 0.01$ ,  $\eta^2_p = 0.59$ ), type of fatigue ( $F = 39.5$ ,  $p = 0.001$ ,  $\eta^2_p = 0.83$ ), and a type by fatigue interaction ( $F = 17.1$ ,  $p = 0.003$ ,  $\eta^2_p = 0.68$ ). The time to failure of the plantarflexor muscles was significantly longer during the IM session than during the IK session for the first bout of fatiguing exercise (respectively  $145.3 \pm 34.6$  s vs.  $54.6 \pm 12.1$  s,  $p < 0.001$ ) and for the second bout of fatiguing exercise (respectively  $107.0 \pm 39.9$  s vs.  $56.2 \pm 13.6$  s,  $p = 0.002$ ). In addition, the time to failure of the first bout of fatiguing exercise was longer compared to the second bout of fatiguing exercise for the IM mode ( $p = 0.003$ ), but not for the IK mode ( $p = 0.57$ ).

### **Effect of fatigue on COP parameters**

For all CoP parameters analyzed, the effect of the type of fatigue (IM vs. IK) and all relevant interactions were found non-significant ( $p > 0.05$ ). Thus, data from both types of fatiguing exercises were pooled and the subsequent results only describe the effects of fatigue (pre and post-fatigue) and surface (firm, compliant) on the COP parameters.

**CoP excursion area.** Main effects of fatigue ( $F = 7.9$ ,  $p = 0.02$ ,  $\eta^2_p = 0.47$ ), and surface ( $F = 91.8$ ,  $p < 0.001$ ,  $\eta^2_p = 0.91$ ) were found significant for the 95% ellipse area parameter. A significant fatigue by surface interaction ( $F = 12.6$ ,  $p = 0.006$ ,  $\eta^2_p = 0.58$ ) was also found. As shown in Figure 3, CoP excursion area was significantly greater during the compliant condition compared to the firm condition in both pre and post-fatigue ( $p < 0.001$ ). Also, the effect of fatigue depended on the difficulty of the task (firm vs. compliant surface) since CoP excursion area increased significantly after fatigue when standing on the compliant surface ( $p = 0.011$ ) but not on the firm surface ( $p = 0.108$ ).

**ML postural control.** Figure 4 shows the results for ML CoP velocity (Fig. 4A) and variability (Fig. 4B). A main effect of fatigue ( $F = 12.41$ ,  $p = 0.006$ ,  $\eta^2_p = 0.58$ ) was found significant for ML CoP velocity only. Both CoP velocity and CoP variability showed a significant main effect of surface (velocity:  $F = 154.9$ ,  $p < 0.001$ ,  $\eta^2_p = 0.95$ ; variability:  $F = 379.9$ ,  $p < 0.001$ ,  $\eta^2_p = 0.98$ ) and a fatigue by surface interaction (velocity:  $F = 19.9$ ,  $p = 0.002$ ,  $\eta^2_p = 0.69$ ; variability:  $F = 12.7$ ,  $p = 0.006$ ,  $\eta^2_p = 0.59$ ). As shown in Figure 4, ML CoP velocity and ML CoP variability was significantly greater during the compliant condition compared to the firm condition in both pre and post-fatigue ( $p < 0.001$ ). Also, the effect of fatigue depended on the difficulty of the task (firm vs. compliant surface) since ML CoP velocity and ML CoP variability increased significantly after fatigue when standing on the compliant surface (ML CoP velocity:  $p = 0.003$ ; ML CoP variability:  $p = 0.003$ ) but not on the firm surface (ML CoP velocity:  $p = 0.13$ ; ML CoP variability:  $p = 0.90$ ).

**AP postural control.** Both AP CoP velocity and AP CoP variability showed significant main effects of fatigue (velocity:  $F = 13.5$ ,  $p = 0.005$ ,  $\eta^2_p = 0.60$ ; variability:  $F =$

9.9,  $p = 0.012$ ,  $\eta^2_p = 0.52$ ) and surface (velocity:  $F = 125.8$ ,  $p < 0.001$ ,  $\eta^2_p = 0.93$ ; variability:  $F = 193.3$ ,  $p < 0.001$ ,  $\eta^2_p = 0.96$ ). A significant fatigue by surface interaction was found ( $F = 7.51$ ,  $p = 0.023$ ,  $\eta^2_p = 0.46$ ) for CoP velocity only. AP CoP variability was significantly greater during the compliant condition ( $0.91 \pm 0.07$  cm) compared to the firm condition ( $0.53 \pm 0.05$  cm) and after fatigue ( $0.82 \pm 0.08$  cm) compared to before fatigue ( $0.67 \pm 0.05$  cm). As shown in Figure 5, AP CoP velocity was significantly greater during the compliant condition compared to the firm condition in both pre and post-fatigue ( $p < 0.001$ ). Also, AP CoP velocity increased significantly after fatigue when standing on the compliant surface ( $p = 0.007$ ) and on the firm surface ( $p = 0.005$ ). Thus, the significant interaction suggests that AP CoP velocity was increased to a greater extent after fatigue when standing on the compliant compared to the firm surface.

## Discussion

This study compared the effects of two types of fatiguing exercise on postural control while standing on a firm and a compliant surface. Our results showed similar amounts of force reduction and decreased postural control between the two fatiguing exercises performed (isometric vs. isokinetic). This refutes our first hypothesis that an isometric fatiguing exercise would induce greater alterations in postural control compared to an isokinetic concentric fatiguing exercise. As expected, all CoP parameters increased when standing on a compliant surface compared to a firm surface. In addition, all five CoP parameters increased with fatigue when standing on a compliant surface whereas only two parameters (those specific to the fatigued AP plane) increased with fatigue when standing on a firm surface. Furthermore, subjects seem to have a greater increase in AP CoP velocity

with fatigue when standing on a compliant compared to a firm surface. This confirms our second hypothesis that postural control on a compliant surface with eyes closed is more impaired after fatigue compared to a firm surface.

### **Effects of the type of fatigue.**

Both contraction types induced the same amount of force reduction but the isometric fatiguing exercise was of longer duration. This difference could have led to a different effect on postural control. However, no difference in postural control changes with fatigue was observed between contraction modes in this study.

Specific characteristics of the fatiguing exercises could explain the absence of a difference concerning their effect on postural control. For example, the combination of intensity (moderate) and overall duration (relatively short) of both types of fatiguing exercises may have been too similar to lead to differences in fatigue mechanisms (central or peripheral[15] ) and consequently on postural control. Time to failure has been reported to be faster with higher-intensity exercises [15,32]. This, combined with the fact that the transition time between the end of the fatiguing exercises and the start of the post-fatigue measurements may have allowed subjects to partly recover from fatigue, could have reduced our ability to detect a difference in the fatigue effects of both contraction modes used.

However, the fact that fatigue did have a significant impact on postural control, suggests that recovery was not complete. Considering that the force of the plantarflexors was reduced to 75% of the pre-fatigue  $MVC_{IM}$  and static postural control requires forces of approximately only 10% MVC [33], it becomes apparent that the reduction in force may not

be a major factor explaining the reduction in postural control due to fatigue. Others have suggested that the reduction in postural control due to fatigue may be due to mechanisms other than force-generating capacity, such as altered proprioceptive inputs [8,9,11]. Since the intensity of the fatiguing exercises and their effects on postural control were similar, the proprioceptive deficits might have been equivalent. Our results also suggest that the seemingly different effect of fatigue observed between isometric and isokinetic activities in the literature might be due to methodological factors. Most isometric fatiguing exercises [4,9-11] have typically been of relatively low intensity (lifting body weight) and have been performed directly on the force platform or fairly close to it, leading to minimal recovery between the fatiguing exercise and postural sway acquisition. In contrast, most studies using isokinetic fatiguing exercises [2,6,7] have used a relatively high intensity (50% MVC) and were performed on a dynamometer. Thus, a greater transition time likely occurred and increased the recovery from fatigue prior to the postural testing. Considering the level of intensity (50%) and the use of a dynamometer to induce fatigue, the results (on firm surface) obtained in the present study reflects those reported in studies that used an isokinetic fatiguing exercises. It would be interesting to examine the differences between modes of contraction using a low force fatiguing exercises.

#### **Effects of altered proprioceptive information.**

In a young healthy population, simple postural tasks can be controlled even when some sensory systems are unavailable or altered [1,25,34-37]. According to the sensory reweighting hypothesis [1,35,37], this is possible since all three sensory systems (visual, vestibular and somatosensory) give redundant information and, “the central nervous system dynamically and selectively adjusts the relative contributions of sensory inputs (i.e., the

sensory weights) to maintain upright stance depending not only on the sensory environment, but also on the neuromuscular constraints acting on the subject”[36]. However, these studies showed that postural control decreases considerably when the availability of two sensory systems (somatosensory and vision) are reduced during a standing task [1,25,34-37]. Overall, our results are in line with this sensory reweighting hypothesis [1,35,37]. Subjects were able to maintain their balance, but all CoP parameters tested in this study increased when standing blindfolded on a compliant surface.

However, the original finding in this study is that postural control decreased even more after an ankle fatiguing exercise when the availability of these two sensory systems was reduced. Indeed, both fatiguing exercises increased CoP parameters in both planes (AP and ML) when standing on the compliant surface compared to standing on a firm surface, where CoP parameters increased only in the fatigued plane (AP). In contrast, Dickin and Doan [30] found impairments in postural control due to fatigue (ankle, knee and global fatigue) and type of surface (stable and sway-referenced platform) but no interaction between the two factors. In this latter study, only one trial and one postural parameter (RMS) were used, increasing the variability and potentially decreasing the reliability of the measurements. This may have masked a potential interaction between fatigue and surface type since, according to Ruhe and colleagues [38], at least three trials and parameters in both distance and time-distance domains are needed to accurately characterize postural control.

Vuillerme and colleagues [9] found that vibration of the ankle plantarflexors after fatigue did not show greater effects on postural control compared to fatigue or vibration only. These authors explained their findings by a reduction in sensitivity to the mechanical

vibration due to alteration of ankle proprioception (muscle spindles) during fatigue. Since both muscle fatigue and vibration alter the same postural control elements (somatosensory information from the ankle), a combination of the two would not induce greater postural impairments. Conversely, we found in the present study that when subjects were standing on a compliant surface after a fatiguing exercise, their somatosensory information was less reliable potentially due to two distinct mechanisms. First, standing on a compliant surface alters the somatosensory information at the ankle (joint receptors, Golgi tendon organ, muscle spindles) and the sole of the foot (cutaneous mechanoreceptors) in relation to the environment, thus, increasing reliance on other sensory systems (i.e., vestibular) [34]. Second, after fatiguing exercises, the processing of information concerning joint position is altered [39] and force production of the fatigued muscle(s) may be less accurate and more variable [40]. Thus, in the present study, when the kinesthetic references were altered (compliant condition) and muscle position and force sense were impaired (after fatigue), subjects showed greater postural impairments in both planes compared to either condition taken separately. Furthermore, fatiguing the plantarflexor muscles resulted in a decrease in postural control in the ML plane when standing on a compliant but not a firm surface. This is interesting given that postural control in this plane is thought to involve primarily proximal muscles (i.e., hip and back muscles)[41]. However, it has been shown that the contribution of the ankle musculature for quiet standing is still relatively high when feet are less than 8 cm apart [42]. Although the primary muscle group fatigued was the plantarflexors, some of these muscles can also generate torque in the ML plane. Thus, the role of ankle muscles in maintaining postural control in the ML plane with feet together may have been altered after fatigue. To compensate for this, subjects may have re-weighted their sensory inputs to the

hip musculature. This strategy may have been effective on a firm surface but not on a compliant surface where the ankle musculature is more solicited.

Although this study was limited to young healthy adults, the impact of these results could be important if found with a more vulnerable population (i.e., older adults, diabetic patients with peripheral neuropathy). These populations, with a potentially less reliable somatosensory system, could be more at risk of falls/injuries following muscle fatigue. Future studies should focus on the impact of muscle fatigue in a population with reduced proprioception.

## **Conclusions**

Previous studies on the effect of ankle fatigue on postural control have shown changes in CoP parameters of different magnitude using different types of fatiguing exercises (different mode of contractions, duration, intensities). The present study aimed to compare the effect of two types of exercise (isometric, isokinetic) with a similar intensity on postural control. We found that isometric and isokinetic fatiguing exercises performed until a similar force reduction induce a similar decrease in postural control. This finding suggests that the decrease in postural control due to muscle fatigue is independent of the mode of contraction performed. Thus, differences between studies are likely due to other factors, such as differences in the force reduction induced by the fatiguing activity, and not due to the type of contraction used. Furthermore, the effects of fatigue on postural control were more pronounced when standing on a compliant surface, i.e., when proprioceptive information at the ankle was altered. This finding supports the literature suggesting that postural control

deficits observed after fatigue are largely due to a deficit in proprioception, and suggests that fatigued-related balance impairments leading to falls/injuries could be more frequent in situations where proprioceptive information is reduced (e.g., diabetic or other patient with peripheral neuropathy).

## **Competing Interests**

None of the authors have any financial and non-financial competing interests related to this work.

## **Authors Contributions**

EJB conceptualized the study, carried out the data collection, statistical analyses and drafted the manuscript. AR and SB participated in the design of the study, the data collection, data analyses and the writing of the manuscript. YL participated in the analysis and interpretation of the data, and revised the manuscript. MB participated in the conception and design of the study and revised the manuscript. All authors read and approved the final manuscript.

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## Figures

### Figure 1 - Experimental setup

Initial position for the MVCs and the fatiguing exercises. Also depicted is the custom attachment which allowed the simultaneous assessment of both ankles on the Biodex System 3.

### Figure 2 - Changes in torque output

Mean and standard deviation of MVC<sub>IM</sub> torque output for each fatiguing exercise. Torque significantly decreased with fatigue (\*\* $p < 0.001$ ), similarly for both types of exercise.

### Figure 3 - Changes in CoP excursion area

Mean and standard deviation of sway area (pooled data from isometric and isokinetic fatiguing exercises). CoP area significantly increased with fatigue when standing on the compliant surface only. \*  $p < 0.05$ ; \*\*\*  $p < 0.001$ .

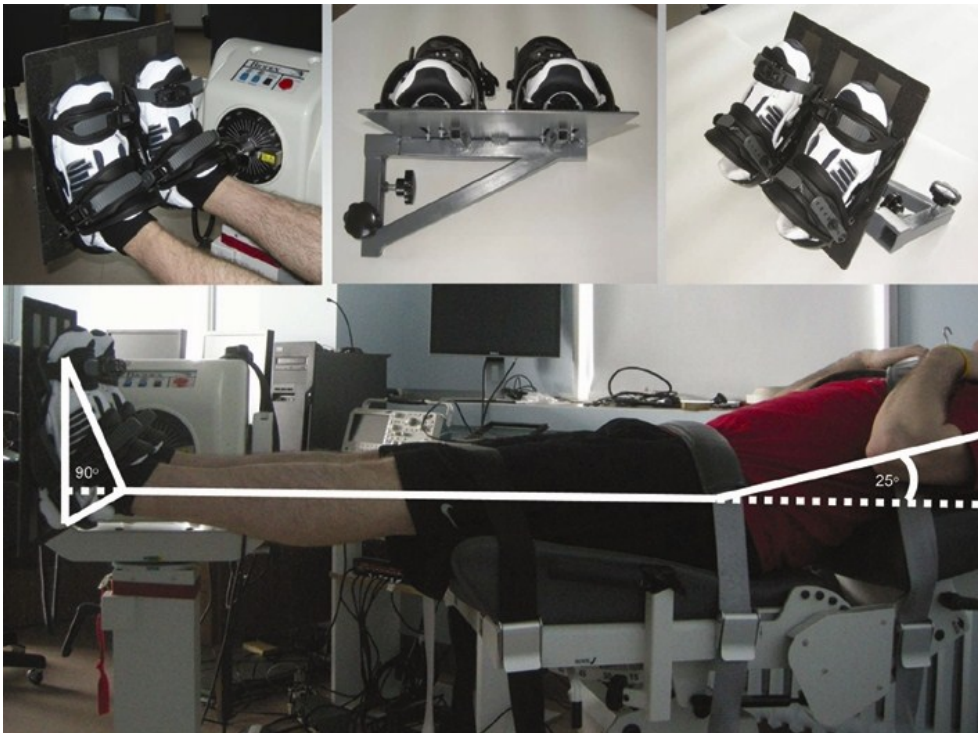
### Figure 4 - Changes in ML CoP velocity and variability

Mean and standard deviation of CoP parameters in ML (pooled data from isometric and isokinetic fatiguing exercises). ML CoP velocity (**A**) and ML CoP variability (**B**) significantly increased with fatigue when standing on the compliant surface only. \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$ .

### **Figure 5 - Changes in AP CoP velocity**

Mean and standard deviation of AP CoP velocity (pooled data from isometric and isokinetic fatiguing exercises). AP CoP velocity significantly increased with fatigue for both surface conditions but appears to be greater when standing on compliant surface. \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$ .

**Figure 1.**



**Figure 2.**

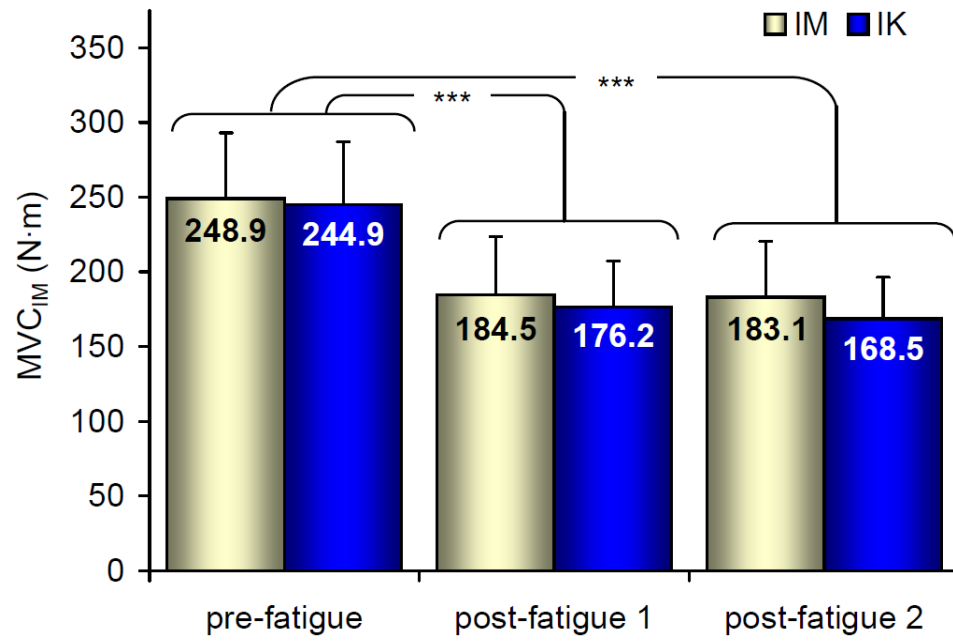


Figure 3.

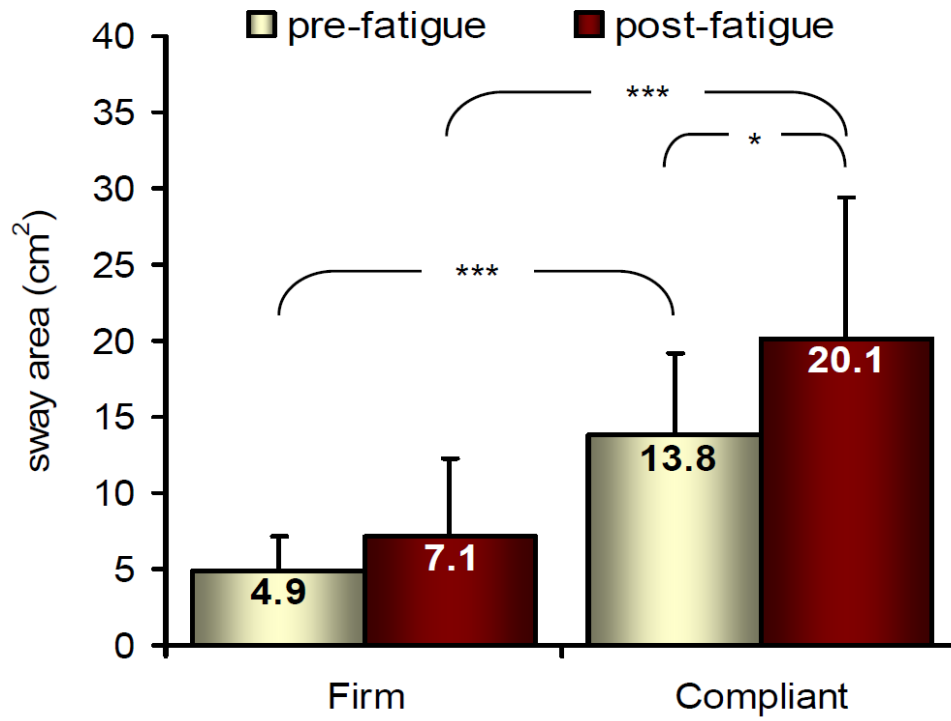


Figure 4.

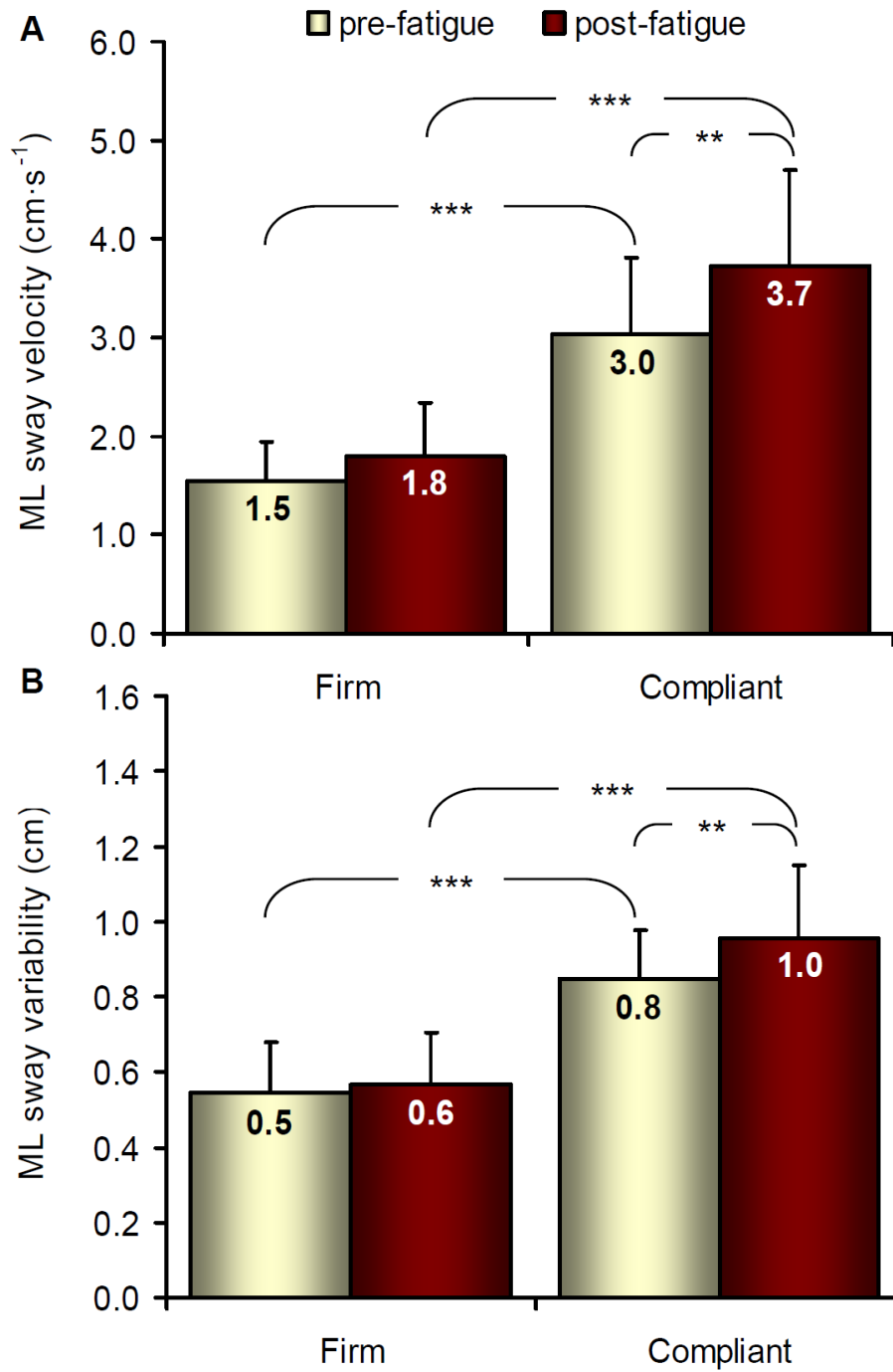
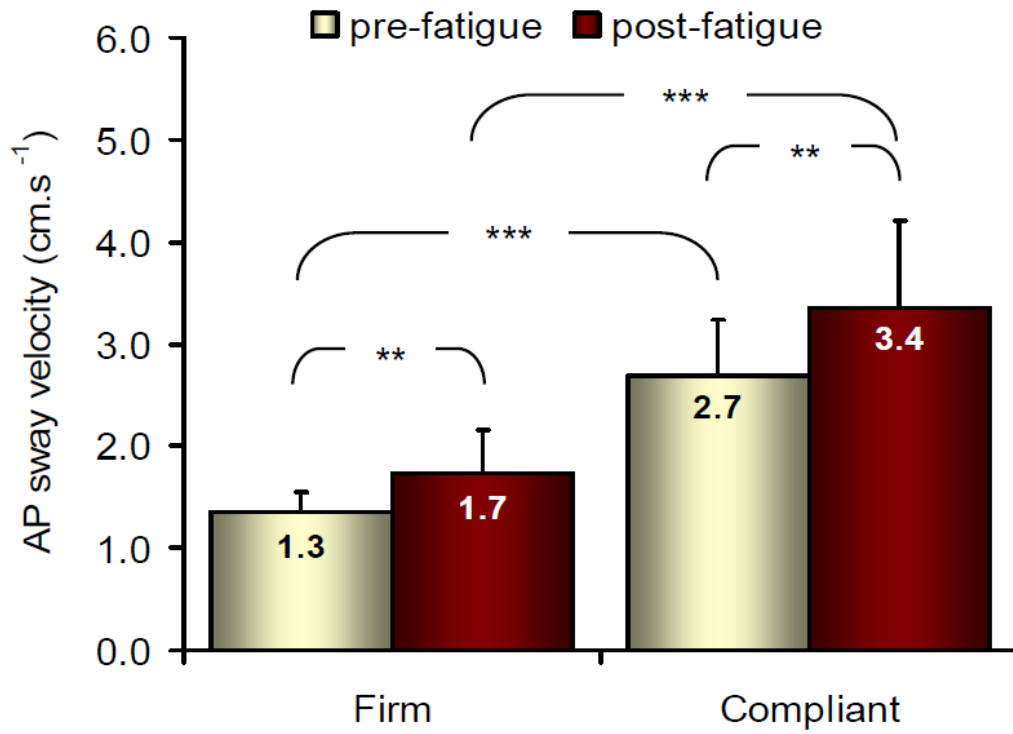


Figure 5.



**CHAPTER 7. MANUSCRIPT 4**

The influence of age and surface compliance on changes in postural control and attention due to ankle neuromuscular fatigue.

To be submitted to the

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**Title:**

The influence of age and surface compliance on changes in postural control and attention due to ankle neuromuscular fatigue.

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**Running Title:**

Postural control and muscle fatigue with aging

## **Abstract**

**Background.** The reduction in the quality and integration of sensory information with aging could potentially increase the impairment in postural control due to muscle fatigue that has been observed in younger adults. This study aimed to compare the changes in postural control and attentional demands due to ankle muscle fatigue with intact, and reduced proprioceptive information at the ankle joint, between young and older adults.

**Methods.** Eleven young men ( $24 \pm 4$  years) and 13 older men ( $65 \pm 4$  years) stood quietly on a force platform, blindfolded with feet together, under four experimental conditions (firm / compliant surface, single / dual task), before and immediately after a fatiguing exercise. The fatiguing exercise consisted of maintaining an isometric contraction of the plantarflexors at 50% of the maximal voluntary contraction (MVC) until exhaustion. The MVC was measured before and immediately after fatigue.

**Results.** MVC force reduction due to the fatiguing exercise was similar between groups. Both COP sway area and COP sway velocity was greater on the compliant surface, and increased significantly with fatigue for both groups in all conditions. COP sway area showed a greater increase with fatigue in older adults when standing on the compliant surface. Reaction time (secondary task) increased significantly after fatigue only for older adults when standing on the compliant surface.

**Conclusions.** The effects of fatigue on postural control are more important when proprioceptive information at the ankle is altered. Particularly, older adults had more difficulty and may have needed more attention to stand quietly, compared with young adults.

## **Introduction**

There is clear evidence in the literature that muscle fatigue can alter postural control. Most studies with young adults have shown an increase in center of pressure (COP) displacement and/or velocity regardless of the muscle group fatigued, the postural task performed, and the fatigue protocol used [1]. Numerous studies examining the effect of ankle muscle fatigue on postural control have suggested a link between an alteration in proprioception and an increase in COP sway with fatigue [2–4]. If proprioceptive information is altered with fatigue, re-weighting of sensory information would be required to maintain stability (re-weighting hypothesis) [5,6]. Young adults are able to use this compensatory strategy effectively, using increased somatosensory information at the neck [7] and ankle [8], and by using light touch [9]. However, when proprioceptive inputs are less reliable, it has been shown that postural control alterations due to ankle muscle fatigue are greater [8,10].

The impact of muscle fatigue on postural control in older adults may be more pronounced than in young adults since their proprioceptive and neuromuscular systems are less efficient. Neuromuscular fatigue can also be influenced by age, and this has been shown to be task-dependent [11]. For a load relative to maximum force capacity, older adults seem to be more resistant to fatigue, likely because of lower maximal motor unit discharge rates, slower contractile properties, and relatively greater reliance on oxidative metabolism [12]. Conversely, for an absolute load, older adults have less endurance compared to younger adults because they need a greater proportion of their maximal strength, or power, to perform the same task [12]. Thus, for a muscle fatigue task involving a relative load, older adults may demonstrate more fatigue resistance compared to young adults, but the associated alterations

on postural control could be greater for older adults. Interestingly, a number of studies have shown greater COP sway during quiet standing in older adults after fatigue [13,14], but no direct comparison has been made with a “control” group of young adults. Furthermore, these studies were conducted on a firm and stable surface. It is known that age-related differences in postural control are evidenced when inputs from two of the three sensory systems controlling posture are not available/reliable (e.g., vision blocked and proprioception altered). No study has examined the effect of fatigue on postural control in this condition in older adults, who may be at greater risk when standing with reduced proprioceptive information since they have more difficulty re-weighting less-to-more reliable sensory information [15,16]. Also, as suggested by Egerton and colleagues [14], even if postural control alterations due to muscle fatigue are similar for older compared with young adults, a greater increase in attentional demands after fatigue may be observed in older compared to young adults. No study has yet to address this hypothesis (except for manuscript 2 of this thesis).

Thus, the goal of this study was to compare changes in postural control and attentional demands due to ankle muscle fatigue on both a firm and a compliant surface, between young and older healthy adults. Our main hypotheses were that: 1) we would observe an increase in COP sway with fatigue in both young and older adults, but this would be more pronounced in the latter group overall and on the compliant surface for both groups [8,10]; and 2) we would also document a decrease in performance of the secondary task with fatigue, which would also be more pronounced on the compliant surface and for older adults.

## **Methods**

### *Participants*

Eleven young ( $24 \pm 3$  years,  $181.9 \pm 6.6$  cm,  $75.2 \pm 9.8$  kg) and 13 older men ( $65 \pm 4$  years,  $175.3 \pm 4.1$  cm,  $78.5 \pm 9.6$  kg) were recruited from the Ottawa (Canada) area to participate in the study. None of the participants had a history of falls in the past year and all were medically healthy. Older men had good cognitive status scoring between 28.5 and 30 / 30 (mean = 29.7) on the Mini Mental State Exam [17]. No participants had diminished protective plantar sensation when tested with the Semmes-Weinstein monofilaments [18]. Both groups included participants with low (3 young, 3 older men), moderate (3 young, 6 older men) and high levels of physical activity (5 young, 4 older men); as assessed with the Godin Leisure-Time Exercise Questionnaire [19]. The study was approved by the University of Ottawa and the Bruyère Continuing Care Research Ethics Boards, and written informed consent was obtained from each participant prior to their participation in the study.

### *Procedures*

A schematic of the procedures is presented in Figure 1. COP sway and attentional demands in a dual task paradigm were tested during two distinct groups of trials: a) baseline trials, and b) post-fatigue trials. To minimize recovery during post-fatigue trials, the force platform was placed within 2 m of the dynamometer where fatigue was induced, and the fatigue protocol was repeated between tested conditions (F1, F2, F3, F4).

Participants were first secured on the dynamometer with both legs horizontal, the trunk elevated to form a  $25^\circ$  angle, and the angle between the legs and the feet fixed at  $90^\circ$ . The feet, shank, waist, and chest were strapped to the dynamometer in order to optimize

ankle muscle contraction and minimize compensation. In this position, participants performed a warm-up followed by three maximal isometric voluntary contractions (MVC) in plantarflexion, where the highest peak torque output was considered the participant's baseline MVC.

### *Postural task*

For the postural task, participants had to stand as still as possible with their feet together, their arms by their sides and blindfolded (opaque ski goggles) in four different conditions: quiet standing alone, and while performing a secondary task (single vs. dual-task conditions), both on a firm (FS) and a compliant surface (CS). Each postural task was performed in blocks of four 30-s trials for a total of 16 trials during a practice period, and then for baseline and post-fatigue periods (for a total of 48 trials). The order of the postural conditions was counterbalanced. For trials with the CS, participants were asked to stand on a medium density temper foam ( $41 \times 47 \times 8$  cm; density =  $108 \text{ kg/m}^3$ ) placed on the force platform to alter proprioceptive information from the feet and ankles.

### *Secondary task*

For dual-task condition trials, participants were instructed to prioritize the postural task (primary task) while responding to a secondary task as best as they could. The secondary task consisted of a Choice Reaction Time (CRT) task, where two different auditory stimuli were presented randomly and two corresponding verbal responses had to be given. Participants needed to respond "TIE" when the auditory cue was a high-pitch sound (3,000Hz, 50ms) and respond "TOE" when the auditory cue was a low-pitch sound (250Hz,

50ms). Six stimuli were presented per trial, for a total of 24 stimuli per dual-task condition presented to the participant. The presentation of the stimuli was quasi-random with at least two stimuli of each sound given to the participant per trial.

In order to determine the attentional cost of the primary tasks, four trials of seated CRT were performed during the practice period and prior to the baseline trials and at the end of the session (following the post-fatigue trials).

### *Fatigue protocol*

The fatigue protocol used in this study has been described in detail elsewhere [5]. Muscle fatigue of the plantar-flexors of both ankles was induced with a custom built attachment to a BIODEX dynamometer (System III, Shirley, NY) in order to fatigue both ankles simultaneously. The fatigue task consisted of a continuous isometric contraction of the plantarflexors at 50% MVC until exhaustion. The fatigue protocol was ended when participants were unable to hold 50% MVC for five consecutive seconds. After completion of each bout of fatiguing exercise, participants were asked to perform a MVC, to document the level of fatigue, before transferring to the postural task. Strong verbal encouragements and visual feedback of the torque output were provided to participants during the MVC contractions and fatigue exercises.

### *Data Acquisition and Statistical Analyses*

**Fatigue index.** The fatigue induced in the plantarflexors was documented by measuring the torque output during the MVC before fatigue (baseline) and after each fatigue protocol (F1, F2, F3, F4). The time to failure was also measured for each fatigue protocol. To

ensure fatigue was induced and maintained during post-fatigue trials, a two-way mixed-model ANOVA was performed on the MVC torque output at each time point (within factor; baseline, F1, F2, F3, F4) for both groups (between factor; young, older). Also, a two-way mixed-model ANOVA was performed on the time to failure for each fatigue protocol (within factor; F1, F2, F3, F4) for both groups (between factor; young, older).

**COP sway parameters.** COP data were collected at a sampling rate of 50 Hz using an AMTI AccuGait force-platform (Watertown, MA). COP sway during the feet together stance was characterized with three time-domain variables using BioAnalysis 2.1 software (Watertown, MA): the 95% ellipse sway area and medio-lateral (ML) and antero-posterior (AP) COP sway velocity. For each condition, the mean of the four pre-fatigue trials (baseline) were calculated for the different variables and compared to each trial after fatigue (T1, T2, T3, T4). Post-fatigue trials were separately considered in the analyses because the effects of muscle fatigue on COP sway have been shown to recover quickly [19,20]. Considering that the effect of fatigue is apparent mainly in the first post-fatigue trial for all COP sway variables (see Figure 2 and 3), statistical analyses were performed only on this trial (T1) compared to the mean of the pre-fatigue trials (baseline). Thus, for each COP sway variable (area, AP and ML velocity), a four-way mixed-model ANOVA was used to analyse the effects of ankle muscle fatigue (within factor; baseline, T1), group (between factor; young, older), task (within factor; single, dual) and surface (within factor; FS, CS) on postural control.

**Choice reaction time.** Both high-pitch (3,000Hz, 50ms) and low-pitch (250Hz, 50ms) auditory cues were generated by a computer using Spike 2 v7 (CED, Cambridge, UK)

through speakers placed at ear level. Verbal responses were recorded using a wireless voice recorder which was connected directly to a PC computer. The response time (referred to as CRT) was considered the time between the start of the auditory cue and the start of the vocal responses. The mean CRT (four trials) was calculated for both auditory cues (high and low-pitch cue) for the seated trials (before baseline trials and after post-fatigue trials), baseline trials, and for each trial after fatigue (T1, T2, T3, T4). First, to examine if there was a general effect of fatigue on the ability to execute the secondary task, a three-way mixed-model ANOVA was performed on the seated CRT before and after fatigue (within factor; baseline, post-fatigue), type of cue (within factor; high-pitch, low-pitch) and group (between factor; young, older). Second, a four-way mixed-model ANOVA was used to analyse the effect of fatigue (within factor; baseline, T1), group (between factor; young, older), type of cue (within factor; high-pitch, low-pitch) and surface (within factor; FS, CS) on CRT.

All statistical analyses were completed using PASW statistics 18 (IBM, Chicago, IL) with a significance level set at  $p \leq 0.05$ . Tests for sphericity were done and values adjusted (using Greenhouse & Geisser adjustment) if found significant. Post hoc analyses were used when appropriate using a Bonferroni adjustment.

## **Results**

### *Fatigue index*

**MVC torque.** Results for MVC torque output showed significant main effects of fatigue ( $F[4,84] = 172.7, p < 0.001$ ), group ( $F[1,21] = 4.73, p = 0.041$ ) and a fatigue by group interaction (adjusted:  $F[2.6,84] = 5.2, p = 0.005$ ). As presented in Table 1, MVC torque recorded after each fatiguing protocol was significantly different from baseline for both

groups ( $p < 0.001$ ). Young men had significantly greater MVC at baseline ( $p = 0.008$ ), and after fatigue protocol 1 ( $p = 0.027$ ) and fatigue protocol 2 ( $p = 0.031$ ) compared to older adults, but not after fatigue protocol 3 and 4. This suggest that older adults maintained the same level of fatigue throughout all four fatigue protocols, whereas young adults had a similar level of fatigue as the older adults for the first two fatigue protocols, but increased their level of fatigue slightly with the last two fatigue protocols. Nonetheless, both groups had a considerable reduction in force output due to ankle muscle fatigue.

**Time to failure.** Results for time to failure showed significant main effects of fatigue ( $F[3,66] = 31.0$ ,  $p < 0.001$ ) and group ( $F[1,22] = 5.79$ ,  $p = 0.025$ ). As shown in Table 1, the time to failure of the plantarflexor muscles was significantly longer during the first bout of fatiguing exercise compared to all other bouts of fatiguing exercises ( $p < 0.001$ ). In addition, the time to failure of older men was longer compared to that of young men.

#### *Effects of fatigue on COP sway parameters*

For all COP parameters analyzed, the effect of the task (single vs. dual task) and all relevant interactions were found to be non-significant ( $p > 0.05$ ), suggesting that participants prioritized the primary (postural) task at all time as instructed. Thus, for clarity purposes, data from both tasks were pooled and the subsequent results describe only the effects of fatigue (baseline, T1), surface (FS, CS) and group (young, older) on the COP parameters.

**COP sway area.** Significant main effects of fatigue ( $F[1,22] = 56.24$ ,  $p < 0.001$ ) and surface ( $F[1,22] = 140.33$ ,  $p < 0.001$ ) were found for the 95% ellipse area parameter. Significant fatigue by surface ( $F[1,22] = 34.15$ ,  $p < 0.001$ ), fatigue by group ( $F[1,22] = 4.62$ ,

$p = 0.047$ ) and fatigue by surface by group interactions ( $F[1,22] = 4.42$ ,  $p = 0.043$ ) were found. As can be seen in Figure 2, pairwise comparisons showed a) significantly greater COP sway area on the CS compared to the FS in both baseline and T1, and for both groups ( $p < 0.001$ ); b) a significant increase in COP sway area with ankle muscle fatigue for each surface and for both groups ( $p < 0.001$ ); and c) a significant difference in COP sway area between groups after fatigue (T1) when standing on the CS ( $p = 0.029$ ) only. This reflects the fact that the increase in COP sway area due to ankle muscle fatigue was more pronounced for the older men when standing on the CS (78% increase) compared to when standing on the FS (46% increase) and compared to their young counterparts when standing on either surfaces (CS: 46% increase; FS: 31% increase). Thus, the difference in COP sway area between groups was significant only when standing on the CS after ankle muscle fatigue.

**COP sway velocity.** For both planes (AP and ML), significant main effects of fatigue (AP:  $F[1,22] = 61.13$ ,  $p < 0.001$ ; ML:  $F[1,22] = 24.35$ ,  $p < 0.001$ ), surface (AP:  $F[1,22] = 186.81$ ,  $p < 0.001$ ; ML:  $F[1,22] = 239.50$ ,  $p < 0.001$ ) and group (AP:  $F[1,22] = 4.44$ ,  $p = 0.047$ ; ML:  $F[1,22] = 8.29$ ,  $p = 0.009$ ) were found for the COP sway velocity parameter. Significant fatigue by surface (AP:  $F[1,22] = 35.47$ ,  $p < 0.001$ ; ML:  $F[1,22] = 14.26$ ,  $p < 0.001$ ) and surface by group interactions (AP:  $F[1,22] = 35.47$ ,  $p < 0.001$ ; ML:  $F[1,22] = 14.26$ ,  $p < 0.001$ ) were also found. As can be seen in Figure 3, pairwise comparisons showed that AP and ML COP sway velocities were significantly greater during the CS condition compared to the FS condition in both baseline and post-fatigue and for both groups ( $p < 0.001$ ). However, older men had greater COP sway velocity compared to young men on the CS ( $p < 0.05$ ), but not the FS. Finally, ankle muscle fatigue significantly increased AP and ML COP sway velocity on each surface (CS and FS) and for both groups ( $p < 0.01$ ). This

increase was more pronounced when standing on the CS (mean of both groups of 37% and 30% increase for AP and ML, respectively) compared to when standing on a FS (mean of both groups of 24% and 21% increase for AP and ML, respectively).

#### *Effects of fatigue on attention*

**Seated CRT.** No main effects of fatigue ( $F[1,20] = 0.021$ ,  $p = 0.886$ ), type of cue ( $F[1,20] = 0.793$ ,  $p = 0.384$ ) or group ( $F[1,20] = 3.15$ ,  $p = 0.091$ ) or interactions were found to be significant ( $p > 0.05$ ) for seated CRT. Both young and older adults were able to maintain their baseline CRT after the post-fatigue trials for the high-pitch cue (young adults = 440ms vs. 431 ms and older adults = 485 ms vs. 497 ms) and for the low-pitch cue (young adults = 424 ms vs. 430 ms and older adults = 488 ms vs. 486 ms, respectively) during the seated CRT.

**Standing CRT.** Significant main effects of the type of cue ( $F[1,22] = 9.41$ ,  $p = 0.006$ ) and surface ( $F[1,22] = 4.73$ ,  $p = 0.042$ ) were found for CRT. Additionally, a significant fatigue by surface by group interaction ( $F[1,22] = 6.79$ ,  $p = 0.017$ ) was found. Participants responded faster for the low-pitch sound (mean CRT of 460 ms) compared to the high-pitch sound (mean CRT of 482 ms). As depicted in Figure 4, pairwise comparisons showed that CRT (both types of cues combined) increased significantly with fatigue in the older men when standing on the CS (mean increase of 54 ms,  $p = 0.004$ ) compared to when standing on a FS, and compared to their young counterparts when standing on either surface ( $p > 0.05$ ). Thus, the differences between groups were significant only when standing on the CS after ankle muscle fatigue.

## **Discussion**

This study examined age-related differences in postural control alterations and possible increased attentional demands caused by ankle muscle fatigue when standing on a FS compared with a CS. After learning the postural task (especially when standing on the CS), all COP sway parameters measured for young and older participants increased after fatiguing the plantarflexors of both ankles, which confirms our first hypothesis. Our second hypothesis was also confirmed, i.e., when standing on the CS, both groups showed a greater COP sway area due to muscle fatigue compared to standing on a FS. We also hypothesized that older adults would be affected to a greater extent by muscle fatigue compared to young adults. This hypothesis was found to be true, but only when standing on a CS. In addition, we expected to see an increase in attentional demands due to fatigue for both groups and more so for the older group. In this regard, only older men showed an increase in CRT with fatigue, and only when standing on the CS.

### *Muscle fatigue effects on postural control in young adults*

As described by Paillard [1], compensatory strategies such as re-weighting the sensory inputs to more reliable sources (i.e., vestibular and peripheral proprioceptive inputs) can help limit postural control alterations due to fatigue. However, during conditions where the proprioceptive inputs at the foot and ankle are altered, the re-weighting of these inputs to more reliable ones has already occurred [5]. Similar to previous findings [8,10,20], our results showed that isometric muscle fatigue creates greater postural control alterations when standing on a CS (5). The fact that there is an additive effect of muscle fatigue on postural control when standing with reduced somatosensory information from the feet and ankles (CS) suggests: a) an even greater reliance on vestibular inputs to limit postural control

alterations when standing on a CS during fatigue [21], and b) that the importance of ankle and foot cutaneous receptors to regulate postural control increases when ankle muscles are fatigued [8]. Also, it is possible that the increased COP sway is part of a compensation strategy to permit the use of the sensory information due to a higher threshold in the fatigued muscles.

Muscle fatigue could increase the central processing associated with postural control as another compensation strategy [22,23]. Vuillerme and colleagues [22] and Simoneau and colleagues [23] have shown changes in attentional demands due to muscle fatigue using a probe reaction time task [22,23]. However, using a voice reaction time task, our findings demonstrated that the attention allocated to the postural task did not increase with fatigue for young adults. This suggests that the attentional demands of postural control during muscle fatigue may be dependent on the secondary task performed. Furthermore, the fact that a CRT task (compared to a simple reaction time task) did not increase with fatigue suggests that this task specificity may not depend on the difficulty of the task, but more so on the type of response used (probe versus vocal response). Future research is needed to compare the use of different reaction time tasks with muscle fatigue to better understand the attentional cost of muscle fatigue on postural control regulation.

#### *Muscle fatigue effects on postural control of older adults*

The effect of fatigue on COP sway of older adults reported in the present study was relatively greater compared to that in previous studies. For example, Egerton and colleagues [14] have shown a modest effect of fatigue on COP sway displacement (5% increase), whereas older adults in the present study increased their COP sway area by 46%. This could simply be explained by the absence of vision since visual information can attenuate the effect

of muscle fatigue on postural control [24–26]. However, as Egerton and colleagues [14] failed to demonstrate, postural control in the group of older adults tested here was no more altered with fatigue than in young adults when standing on a FS. The fact that older adults already prefer a hip strategy may have helped them to limit postural control alterations when ankle muscles were fatigued [27], but this could only be confirmed with kinematic/electromyography data. Furthermore, peripheral proprioceptive inputs were still available on the FS likely providing enough sensory information at the ankle to limit postural control alterations. With similar results, Egerton and colleagues [14] suggested that the attention allocated to postural control could have increased with fatigue, making older adults at greater risk of falls. However, as observed here for young adults, older adults did not require more attention with fatigue on the FS, which suggests that for this condition, the compensatory strategy used by the latter group was as efficient and may not have required increased attention compared to young adults.

On the other hand, postural tasks where two sensory systems are altered (e.g., with eyes closed and standing on a CS) are more sensitive to differences between healthy older and young adults [28]. This is reflected in our results where no differences between groups were found in COP sway velocity when standing on a FS, but a greater COP sway velocity was noted when standing on the CS for the older compared to the young adults. With regards to muscle fatigue, however, the increase in COP sway velocity being similar across groups may suggest that an increase in stiffness due to fatigue was similar. As presented in Figure 2, COP sway area was similar between older ( $20.01 \pm 1.83$  cm) and young ( $17.64 \pm 1.99$  cm) adults before fatigue when standing on a CS, suggesting that the older group was highly functional. Although both groups increased their COP sway area after fatigue on the CS

compared to the FS, older adults showed a greater increase (78%) compared to young adults (46% increase). Thus, with either reduced proprioception at the ankle and foot (CS) or when ankle muscles are fatigued on a FS, older adults are able to limit postural control alterations as well as young adults. However, when both conditions (muscle fatigue and standing on the CS) are combined, older adults seem to be less efficient at compensating than young adults. This could be explained by several factors: a) older adults may not be as able to rely on vestibular inputs to limit postural control alterations compared to young adults due to deterioration of the vestibular system [29]; b) older adults are known to have weaker leg muscles compared to young adults [30], therefore, an increased reliance on the hip strategy, due to the increased reliance on vestibular inputs, may not be effective in controlling stability in this context; and c) older adults may have increased co-contraction at the ankle joint during fatigue [31], a strategy which may be less efficient on the CS. These possible compensation strategies would need to be properly investigated with electromyography and kinematic data to confirm any stated hypotheses.

Furthermore, with proprioceptive inputs potentially perturbed by two different sources (CS and muscle fatigue), older adults may have more difficulties re-weighting the sensory information and recalibrating their body schema [32]. This could lead to a greater increase in cognitive demands with fatigue for older compared with young adults [33]. Our results for the secondary task support this. When standing on a CS with eyes closed, older adults increased their CRT by 50 ms after muscle fatigue, whereas young adults did not increase their CRT. These results contrast with the FS results where peripheral inputs at the foot and ankle were still available to compensate for muscle fatigue at the ankle. This reflects the importance of proprioceptive inputs for postural control, and that older adults could be

less efficient and may need more attention in using other sensory inputs to maintain stability during a complex postural task when their ankle muscles are fatigued.

## **Conclusion**

This study has shown greater postural control alterations due to ankle muscle fatigue when proprioceptive information at the ankle is less reliable (CS). Furthermore, older adults had more difficulty and may have needed more attention to stand quietly when fatigued, compared with young adults, but only in the context of standing on the CS without vision. To our knowledge, this study is the first to show fatigue-related differences between older and young adults on postural control when standing quietly. Considering an increase of 78% in COP sway area and an increase of 50 ms in CRT, older adults may be temporarily at risk of a fall when fatigued and proprioceptive feedback is less reliable. It has to be noted that we found this in a highly active older adult population. The effect of fatigue may be greater with a more frail population (e.g., sedentary older adults, diabetics).

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Table 1. Fatigue index comparison between each fatigue protocol for the young (n=11) and older men (n=13)

	baseline	Fatigue protocol			
		F1	F2	F3	F4
MVC Torque (N) <sup>a</sup>					
Young	266.1 (48.9) <sup>b</sup>	196.4 (39.0) <sup>b</sup>	197.1 (45.9) <sup>b</sup>	183.6 (41.8)	184.0 (39.4)
Older	219.1 (28.6)	165.6 (25.4)	164.6 (22.6)	163.9 (27.3)	159.2 (25.6)
Time to Failure (s)					
Young		126.1 (29.6) <sup>c</sup>	101.8 (25.9)	95.4 (22.0)	90.3 (18.3)
Older		176.2 (65.0) <sup>cd</sup>	138.0 (49.6) <sup>d</sup>	123.6 (44.0) <sup>d</sup>	116.5 (25.7) <sup>d</sup>

<sup>a</sup> MVC torque decreased for both groups from baseline to each fatigue protocol (p<0.001)

<sup>b</sup> MVC torque was significantly greater for young compared with older adults (p<0.05)

<sup>c</sup> Time to failure was longer for the first fatigue protocol (p<0.001)

<sup>d</sup> Older adults had longer time to failure compared to young adults (p<0.05)

## Figure captions

**Figure 1. Schematic of the testing procedures.** Each time point (baseline and post-fatigue) consisted of a total of 16 trials of 30s (4 trials / conditions). MVC= Maximal isometric contraction; FS= firm surface; CS= compliant surface; ST= single task; DT= dual-task; F1-F4 = fatigue protocols performed alternatively with the each postural task.

**Figure 2. Mean and standard deviation of COP sway area during each condition for both groups.** COP sway area was greater when standing on the CS compared to FS at all time points ( $p < 0.001$ ). COP sway area significantly increased with fatigue (T1) for both young and older adults when standing on the FS and the CS (\*  $p < 0.05$ , \*\*  $p < 0.01$ , \*\*\*  $p < 0.001$ ). COP sway area was significantly different ( $p < 0.05$ ) between groups only at T1 when standing on the CS, suggesting a greater increase for the older adults during this condition. For clarity purposes, significance symbols are only shown to depict differences between baseline and T1.

**Figure 3. Mean and standard deviation of COP sway velocity in AP (A) and ML (B) during each condition for both groups.** AP and ML COP sway velocity was greater when standing on the CS compared to FS at all time points ( $p < 0.001$ ). AP and ML COP sway velocity significantly increased with fatigue (T1) when standing on the FS and the CS (\*\*  $p < 0.01$ , \*\*\*  $p < 0.001$ ). This increase was greater when standing on the CS ( $p < 0.001$ ) but similar between groups. COP sway velocity was significantly different ( $p < 0.05$ ) between groups on the CS ( $p < 0.05$ ) but not on the FS. For clarity purposes, significance symbols are only shown to depict differences between baseline and T1.

**Figure 4. Mean and standard deviation for CRT during the dual task conditions.** CRT was significantly different between baseline and immediately after fatigue (T1) for the older adults when standing on the CS only (\*\*  $p < 0.01$ ).

Figure 1

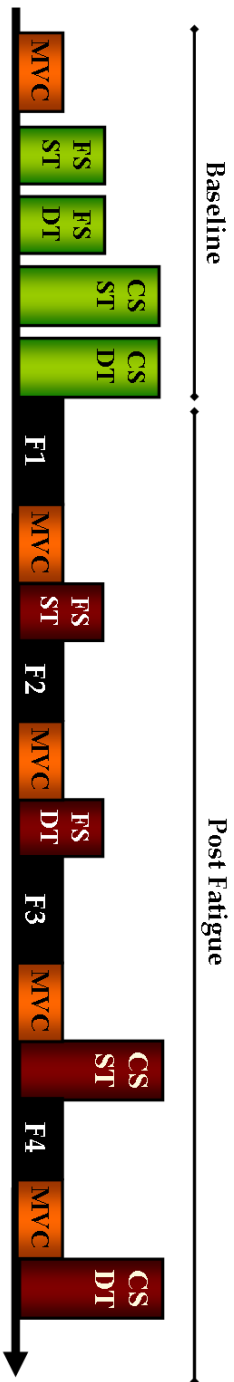


Figure 2

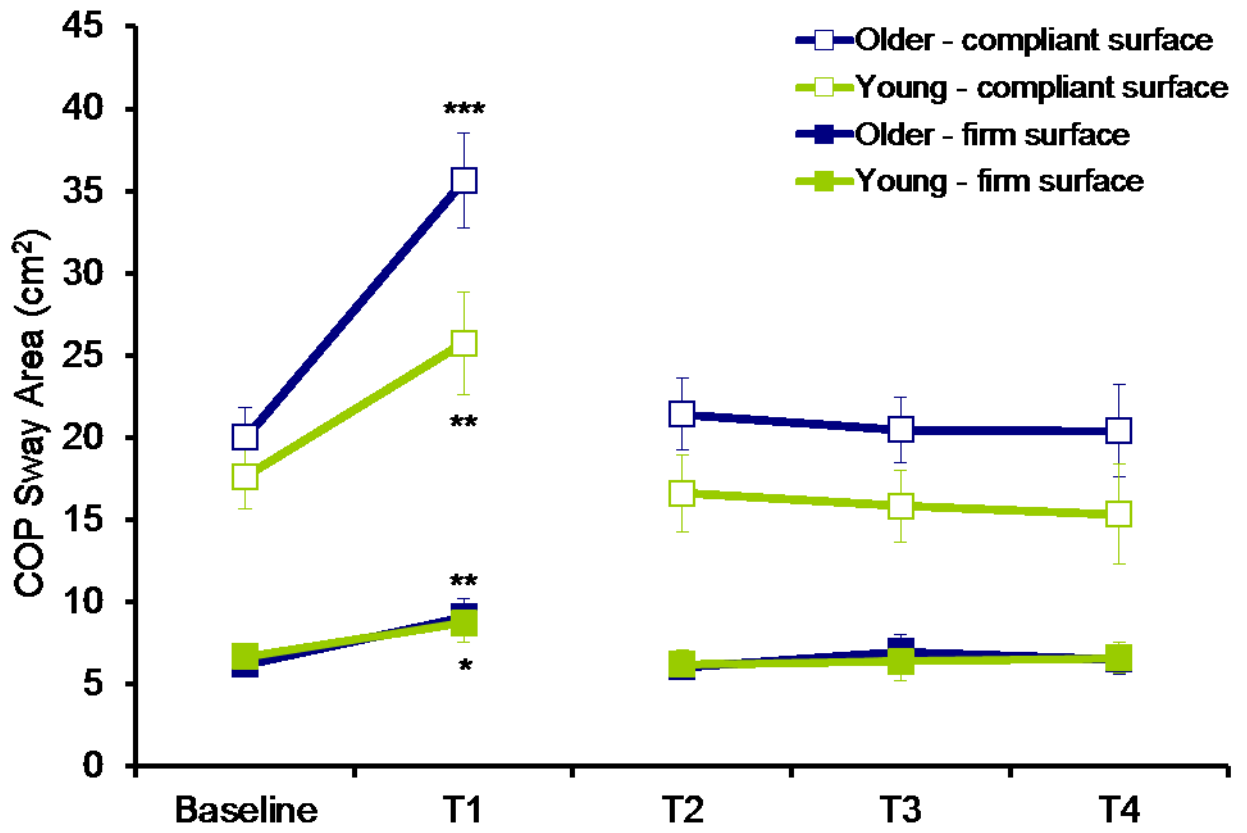


Figure 3

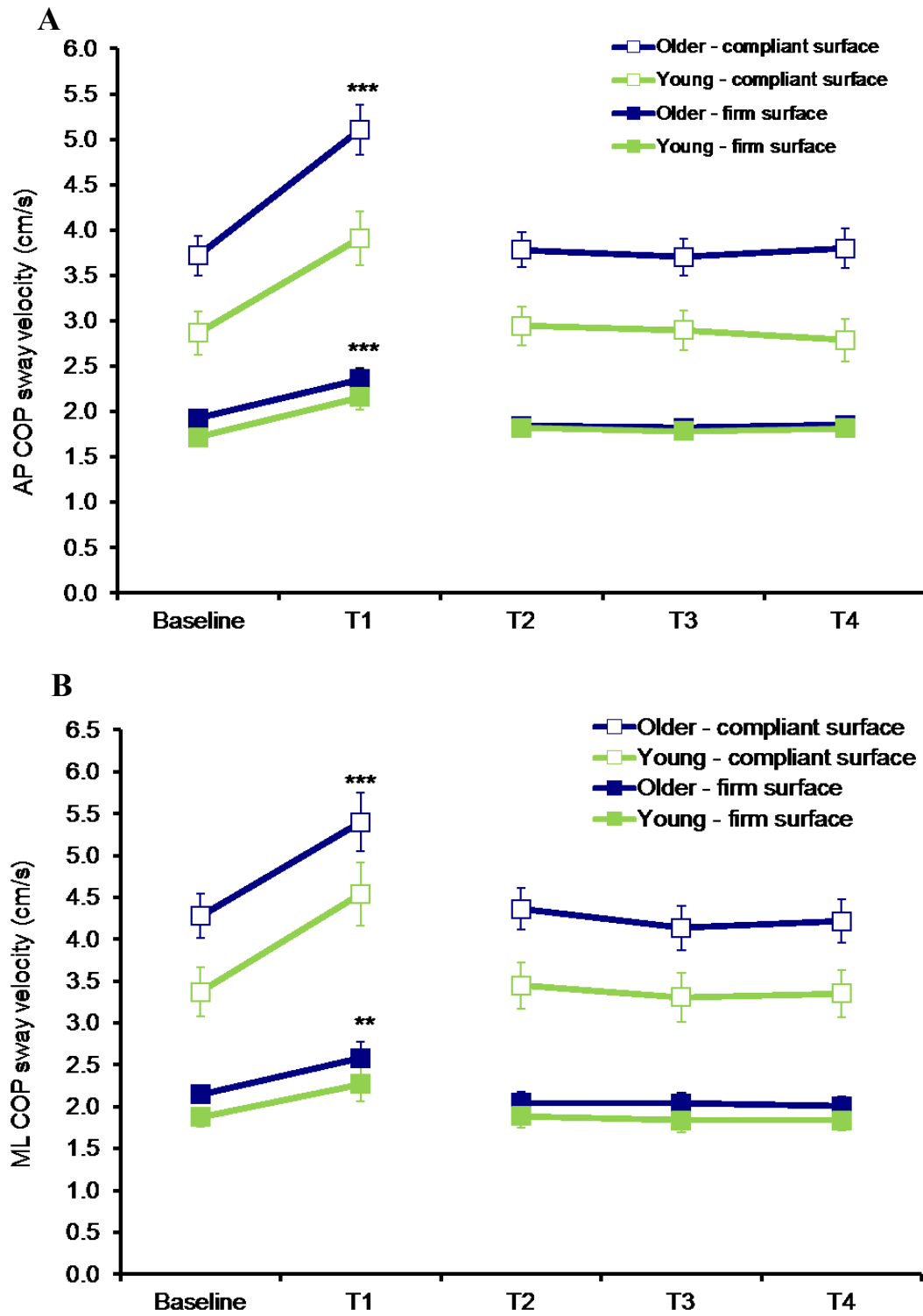
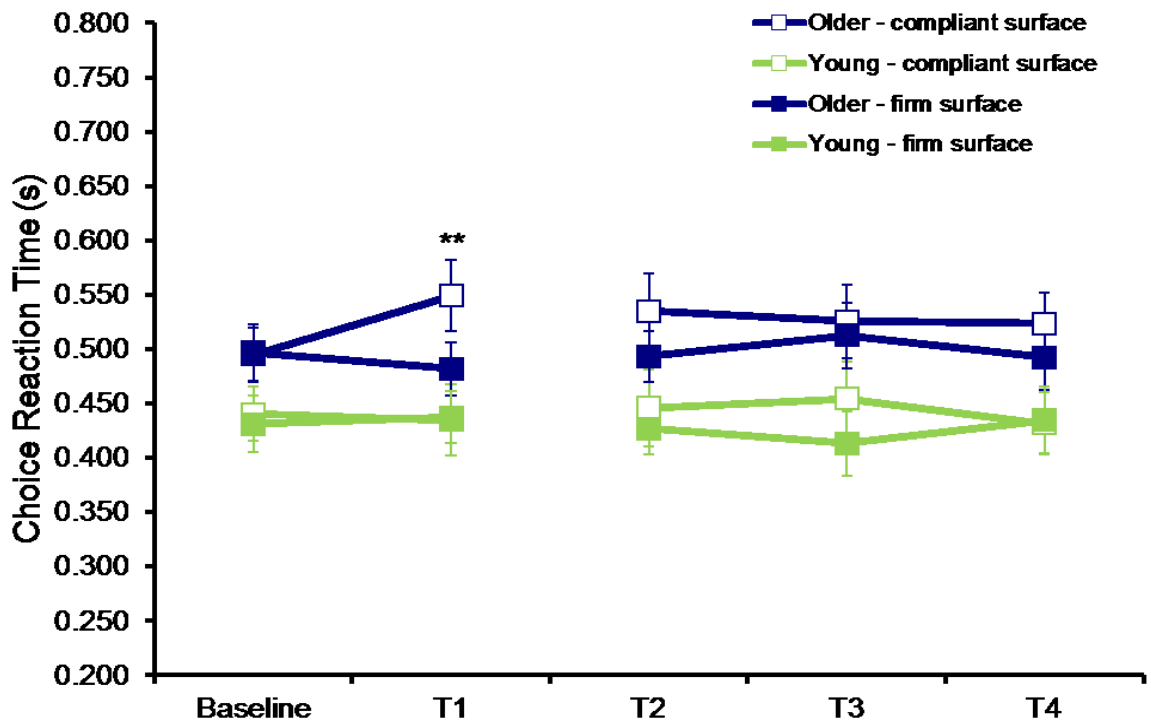


Figure 4



## CHAPTER 8. GENERAL DISCUSSION

The two primary objectives of this thesis were to examine: a) how the effect of muscle fatigue on postural control differs between healthy active older adults (60 years of age and older) compared with younger adults (18 to 35 years of age); and b) how changes in central processing (attentional demands and sensory re-weighting) could increase the effect of muscle fatigue on postural control of these two groups. We found that despite the muscle groups fatigued (ankle or hip) and the difficulty of the postural task (unipedal stance or bipedal stance on a CS), the attentional demands of young adults did not increase with fatigue. However, when the CNS needed to increase the weight of vestibular inputs due to sensory information being less reliable at the ankle joints as a result of standing on a CS (peripheral somatosensory information), postural control in young adults was more altered with ankle muscle fatigue compared to standing on the FS. We also found that healthy older adults were able to compensate for muscle fatigue as well as the young adults when visual information was available during a unipedal stance or when visual information was not available during a bipedal stance on a FS. In contrast, older adults showed greater fatigue-related postural control alterations and increased attentional demands when visual information was not available during a bipedal stance on a CS. The following sections will discuss the importance of task-dependency, the impact of muscle fatigue on postural control with aging, as well as considerations and avenues for future research studies.

## **8.1. Task-dependency**

### *8.1.1. Fatigue task-dependency*

A muscle or a group of muscles can be fatigued in multiple ways. The neurophysiological changes that occur during muscle fatigue are highly dependent on the type of task performed (Enoka & Duchateau, 2008). For example, sustained submaximal isometric contractions result in greater accumulation of substrate by-products (Boyas & Guevel, 2011), which may affect the proprioceptive system to a greater extent (Hiemstra *et al.*, 2001) than intermittent maximal concentric contractions, where blood flow is constantly washing out by-products. Furthermore, high intensity contractions are suggested to generate more peripheral fatigue, and low intensity contractions (but of long duration) greater central fatigue (Boyas & Guevel, 2011).

Thus, fatigue-related changes in postural control during quiet standing could depend on the type of fatigue present. Studies on postural control have used a variety of fatigue protocols (e.g., different mode of contraction, different intensities). For example, studies fatiguing only ankle muscles have shown increased COP sway displacement and/or velocity after heel raises (Corbeil *et al.*, 2003; Ledin *et al.*, 2004; Adlerton & Moritz, 1996), standing on toes (Vuillerme *et al.*, 2002b; Bisson *et al.*, 2010; Mello *et al.*, 2007; Vuillerme *et al.*, 2006a), and concentric contractions using a dynamometer (Gribble & Hertel, 2004a; Gribble & Hertel, 2004b; Harkins *et al.*, 2005; Boyas *et al.*, 2011). Since these studies used different intensities and/or did not report the amount of torque reduction due to fatigue, little is known about the differential impacts of the type of fatigue performed on postural control. As discussed in Chapter 2, the use of isometric versus isokinetic contractions to fatigue a muscle or muscle group could possibly have different impacts on postural control. Interestingly,

when controlling for the reduction in force and the delay time between the fatigue task and the postural task, our results do not show different effects of fatigue on COP sway displacement or velocity between the two modes of contraction when standing on a firm or compliant surface with the eyes closed. Our findings suggest that intensity may be a more important factor than contraction mode on the extent of postural control compensations needed to counter muscle fatigue. Harkins and colleagues have demonstrated greater COP sway velocity when fatiguing the ankles (concentric contractions) until the torque was reduced by 70% of MVC compared to 50% of MVC. As Paillard (2012) illustrated in a recent review, it seems that postural control compensation is required when the torque reduction is at least 30% of MVC. However, these findings were obtained with high intensity contractions (maximal contractions sustained until torque diminishes for a certain percentage of MVC). The effects on quiet standing seem to correlate with the amount of torque reduction, but the duration of the increase COP sway is very short (less than 2 min for most studies). Longer fatigue tasks at a lower contraction level can also affect postural control through central mechanisms (Paillard, 2012). Thus, the impact of the intensity of a fatigue task on postural control and the duration of the COP sway increase should be examined with different submaximal contractions protocols.

Although it is clear that postural control compensation is required to counter muscle fatigue during quiet standing independently of the fatigue task performed, studies have also demonstrated postural control alterations when fatiguing a variety of muscle groups. Postural control alterations, represented by an increase in COP sway displacement and/or velocity, were shown when fatiguing muscles of the neck (Gosselin et al., 2004), back (Davidson et al., 2004), hip (Gribble & Hertel, 2004a; Salavati *et al.*, 2007), knee (Gribble & Hertel,

2004b), and ankle (Vuillerme *et al.*, 2001; Vuillerme *et al.*, 2002b; Lundin *et al.*, 1993; Corbeil *et al.*, 2003) joints. Evidence suggests that proximal muscles can induce a greater increase in COP sway compared with distal muscles (Gribble & Hertel, 2004a; Salavati *et al.*, 2007). The results of the first manuscript in this thesis confirmed this. The main explanation proposed is that when distal muscles are fatigued, compensation using more proximal muscles (hip strategy) is possible, whereas when proximal muscles are fatigued, increasing the demand on distal muscles (ankle strategy) cannot be fully compensated. This is confirmed by studies that compared ankle and hip muscle fatigue during unipedal stance. Unipedal stance is mainly controlled by a hip strategy; thus, it is not surprising that fatiguing the main muscles implicated in this strategy would have greater effect on postural control. Since ankle muscles are mainly used during the bipedal quiet stance, it can be assumed that fatiguing these muscles would create greater postural control alterations, but there is no evidence to confirm this.

### *8.1.2. Postural task-dependency*

Postural control is also highly dependent on the type of task performed. During quiet standing, it is more challenging to maintain the center of mass within a small base of support (e.g., unipedal stance) compared to a wide base of support (e.g., shoulder width). It is also well established that reducing the amount of sensory information available creates greater impairments in postural control (Horak & MacPherson, 1996). Closing your eyes or standing on a CS increases COP sway considerably. COP sway will increase even more when different conditions are combined. For example, closing your eyes will have a greater effect during unipedal stance or during a bipedal stance on a CS, compared to a bipedal stance on a FS. In sum, COP sway displacement and/or velocity increases when the difficulty of the task

increases. Considering that muscle fatigue can reduce the reliability of proprioceptive information and motor command effectiveness (Paillard, 2012), it could be hypothesized that the effect of muscle fatigue on postural control could vary with the difficulty of the task.

Most studies examining the effect of muscle fatigue on postural control have used a unipedal task or a bipedal task with feet together, with the eyes open or closed. It has been clearly demonstrated that postural control alterations due to muscle fatigue can be attenuated by vision when the focused target is close (1m) to the subject but not far (4m) (Vuillerme *et al.*, 2006b). In a study parallel to this thesis (Bisson *et al.*, 2010), we demonstrated, using a similar fatigue task to Vuillerme and colleagues (2006b), that the effect of ankle muscle fatigue on COP sway displacement and velocity of young adults was similar when standing with feet together and eyes closed, with feet together with eyes open and during unipedal stance with eyes open (target at 2.5m). However, COP sway increase was greater during the unipedal stance with eyes closed compared to the other tasks. This suggests that: a) the visual target needed to be closer than 2.5m to attenuate the effects of muscle fatigue; or b) a combination of a difficult postural task (narrow base of support) and no visual information are required to see greater postural control alterations with fatigue.

Both of our studies examining the effect of ankle muscle fatigue on postural control while standing on a CS showed similar results (manuscripts 3 and 4). Standing on a CS with eyes closed resulted in greater postural control alterations after fatigue compared to standing on a FS with eyes closed. Paillard (2012) suggested using unipedal stance with eyes closed to study the effect of muscle fatigue on postural control. However, a bipedal stance performed on a CS with eyes closed has the advantage of: a) reducing the amount of data lost due to

steps; and b) allowing for inclusion of a greater portion of the population (e.g., balanced-impaired), since this task requires less physical strength.

### 8.1.3. Dual-task dependency

It is well known that COP sway regulation requires some attentional resources (Fraizer & Mitra, 2008). These attentional demands have been shown to increase with the difficulty of the task (Lajoie *et al.*, 1993; Redfern *et al.*, 2001a; Woollacott & Shumway-Cook, 2002). During muscle fatigue, factors such as the force reduction (and slower rate of force production) and the reduction of muscle spindle efficiency lead the CNS to compensate by increasing joint stiffness, changing muscles synergies, and re-weighting sensory information. As a result, central processing is possibly increased to efficiently regulate COP sway. Indeed, two studies (Vuillerme *et al.*, 2002b; Simoneau *et al.*, 2006) have shown a significant attentional cost of muscle fatigue using a probe (button-press) reaction time task. Vuillerme and colleagues (Vuillerme *et al.*, 2002b) showed an increase in reaction time of 20 ms due to isometric ankle muscle fatigue. However, our findings demonstrated that the attention allocated to the postural task did not increase significantly due to muscle fatigue when the secondary task was a simple (12 ms increase) or a choice vocal reaction time task (6 ms increase). Even when standing on a CS, young adults did not increase their choice reaction time after muscle fatigue (6 ms decrease). One explanation could be that the young adults in our studies were comfortable with the dual-task (due to practice). Therefore, subjects either: a) had enough attentional resources to perform both tasks; or b) switched their attention to the CRT task (even if instructions were to prioritize the postural task) and relied on more automated processes to maintain posture. Nonetheless, future research should

compare different reaction time tasks with muscle fatigue under similar conditions, in order to better understand the potential attentional costs of muscle fatigue on COP sway regulation.

## **8.2. Impact of muscle fatigue on postural control with aging**

There is ample evidence in the literature to support the assertion that postural control is temporarily altered due to muscle fatigue in young adults. The main mechanisms suggested are alterations of proprioceptive inputs from the fatigued muscle and degradation of motor output efficiency (Paillard, 2012). The level and duration of postural control alterations seem to depend mainly on the intensity of the fatigue task and the difficulty of the postural task to perform. Nonetheless, young adults are able to limit the impact of muscle fatigue on their postural control through several compensatory strategies such as increasing joint stiffness, changing muscle synergy patterns (increasing activation of intact muscles), reducing reliance on proprioceptive information from the fatigued muscle, and increasing reliance on proprioceptive information from other non-fatigued muscles (Paillard, 2012).

The impact of muscle fatigue on postural control in older adults could be more pronounced than in young adults due to the deterioration of the musculoskeletal, neuromuscular and sensory systems seen with normal aging. Since the ability to integrate (and re-integrate) sensory information is also affected with aging (Sturnieks *et al.*, 2008), it is possible that older adults may be less efficient at using the required compensation strategies to limit the effect of muscle fatigue on postural control compared to young adults. Not surprisingly, as it will be discussed in detail shortly, our work suggests that the difference between age groups concerning the effects of muscle fatigue on COP sway is also task-dependent.

### 8.2.1. *Standing on a firm surface*

Although older adults generally had greater COP sway compared to young adults, our work showed that they were able to compensate similarly to young adults for ankle muscle fatigue during a unipedal task with eyes open (manuscript 2) and during a bipedal task with eyes closed (manuscript 4). The level of difficulty of these two tasks was likely different, and so are the possible explanations as to why older adults were not affected to a greater extent by the fatigue task. Older adults definitely have more difficulty standing on one leg compared to standing with feet together, but the fact that visual information was available may have helped them to limit their COP sway after fatigue. It has been shown that older adults rely more on visual information compared to young adults (Borger et al., 1999). When subjects were asked to stand still with feet together and eyes open, Egerton and colleagues (2009) also reported no differences in any COP parameters measured after fatigue between older and young adults.

Indeed, because older adults rely more on vision, the difference between young and older adults in COP sway during a bipedal stance increases when the eyes are closed (Teasdale *et al.*, 1991a; Abrahamova & Hlavacka, 2008; Teasdale *et al.*, 1991b). However, the high functioning level of our group of older adults in manuscript 4 may explain why they performed as well as young adults before and after fatigue. Furthermore, older adults may tend to prefer a hip strategy (Bellew & Fenter, 2006). This may have helped them to better compensate when ankle muscles were fatigued. Finally, although older adults have less efficient peripheral proprioception (e.g., skin receptors, pressure receptors under the feet),

this information was still available during both task tested on the FS, likely providing enough sensory information at the ankle to limit postural control compensation requirements.

Thus, older adults were able to use the most reliable information to limit the impact of muscle fatigue on COP sway just as well as young adults when standing on a FS. However, contrary to young adults, the compensation strategy may have increased the attention required to perform the postural task in older adults. Since the attention allocated for postural control increases with normal aging, more so when proprioceptive information is less reliable due to environmental constraints (Shumway-Cook & Woollacott, 2000), we expected to observe a greater increase in attentional demands due to muscle fatigue in older adults compared to young adults.

To the best of our knowledge, studies in this manuscript (manuscript 2 and 4) are the first to examine the effects of aging on the attentional costs of muscle fatigue on postural control. In contrast to previous studies with young adults, we have compared older with young adults during a more difficult postural task (unipedal vs. bipedal), and used a complex reaction time task (choice vs. simple). Despite the higher level of difficulty for these two tasks, the attention allocated for postural control in older adults did not increase with fatigue, as was also observed among their younger counterparts. Older adults did not have a greater reaction time compared to young adults even before fatigue (in both studies), suggesting that they both had enough attentional resources available to execute both tasks without affecting their performance. This was not expected, but may be due to the high level of functioning of the older adults we tested. Our participants needed to be able to stand on one leg or stand on

a CS with the eyes closed for multiple bouts of 30-s, and withstand an exhausting fatigue exercise, in order to be included in the studies.

It is also possible that there was enough sensory information still available after fatigue to limit the impact on the central processing system. During both tasks, peripheral proprioceptive information was still available. As the mechanoreceptors under the feet have been shown to contribute to postural control (Roll *et al.*, 2002; Hong *et al.*, 2007; Kavounoudias *et al.*, 1998; Kavounoudias *et al.*, 1999b; Meyer *et al.*, 2004), healthy older adults may have been more likely to use that information to limit the impact of muscle fatigue.

Nonetheless, it is remarkable to find that healthy older adults could compensate for muscle fatigue to limit increased COP sway and increased attentional demands, similar to young adults. However, a frailer group of older adults, with reduced proprioception and/or reduced vision could possibly have more difficulty to elicit similar compensation strategies.

### *8.2.2. Standing on a compliant surface*

Our findings on the CS are what best differentiates the work of this thesis compared with previous studies. The fourth manuscript of this thesis is the first study to look at the effect of muscle fatigue on COP sway parameters and to examine age-related changes with reduced proprioceptive information at the ankle joint. When standing on the CS without visual information, older adults had significantly greater COP sway velocity compared to young adults. This supports other studies stating that age differences in postural control are accentuated when inputs from two of the three sensory systems are not available/reliable

(Teasdale *et al.*, 1991a; Woollacott *et al.*, 1986). However, the innovative finding is that older adults had a greater increase in COP sway displacement compared to young adults after fatigue. Previous studies (including manuscript 2 of this thesis) have not found any differences in any COP parameters between age groups due to fatigue when standing on a FS. By reducing the amount of sensory information available under the feet and around the ankle joint to regulate COP sway displacement, we made it more difficult to compensate for muscle fatigue. Indeed, when standing on a CS, reliance on vestibular information increases, and contribution of the hip muscles (hip strategy) increases (Horak & Hlavacka, 2001). Weaker lower limb muscles (Frontera *et al.*, 2000) and more difficulty using vestibular information (Teasdale *et al.*, 1991b; Hay L *et al.*, 1996), may be reasons why COP sway displacement was increased after muscle fatigue in older adults compared to young adults.

During this type of task (standing on a CS with eyes closed), older adults have been shown to have a greater increase in attentional demands compared to young adults (Teasdale & Simoneau, 2001; Shumway-Cook & Woollacott, 2000). However, no study has looked at the attentional demands during this condition after fatigue. When standing on the CS before fatigue, our results did not show an increase in CRT compared to CRT during sitting, and no differences were found between groups. This, again, suggests that the older adults recruited were highly functional. On the other hand, contrary to the young adults, older adults increased their CRT after muscle fatigue. Thus, the fact that both groups increased their COP sway displacement and velocity, but only older adults increased their CRT when standing on the CS after fatigue, suggests that the difference in postural control alterations due to fatigue between groups may be centrally driven. Previous work has shown that older adults have more difficulty re-weighting less-to-more reliable sensory information (Teasdale *et al.*,

1991b; Hay L *et al.*, 1996). Therefore, our findings suggest that older adults may need more attention to maintain stability when only one sensory system is intact after ankle muscle fatigue. These findings contradict our results with a (potentially) similar postural task difficulty (one leg standing) but with the eyes opened, where the attentional demands did not increase after ankle muscle fatigue. It is possible that the secondary task (simple reaction time) was too easy to detect an increase in attentional demands for one leg standing after fatigue. More studies looking at both unipedal stance on FS and bipedal stance on a CS are needed to support the possible attentional costs of fatigue during quiet standing, and whether the increase in attentional demands for postural control is only apparent when two sensory systems are reduced or not available.

From a clinical perspective, our findings could be more relevant if we had tested a more frail population compared with the present group of high-functioning healthy older adults. Balance-impaired older adults have already been shown to be unable to stand on a CS with eyes closed (Shumway-Cook & Woollacott, 2000; Teasdale & Simoneau, 2001). Thus, it would not be feasible to test the impact of muscle fatigue on this population with this type of postural task. On the other hand, the fact that frail individuals may already have reduced proprioceptive information at the foot and ankle (Shaffer & Harrison, 2007; Goble *et al.*, 2009) could lead to an effect of fatigue on a FS, similar to the effect of fatigue observed on the CS in high-functioning older adults. Our high-functioning older adults increased their COP sway area by 78%, their sway velocity by 38% and their CRT by 50 ms. It is possible that frail older adults with reduced peripheral proprioception could be more at risk of falling when fatigued.

### **8.3. Considerations and avenues for future research**

One initial idea behind studying the impact of muscle fatigue on postural control was to verify whether older adults may be at a greater risk of falling after a bout of physical activity (leisure or work related). Although the findings of this thesis suggest that this may be the case, additional considerations need to be taken into account and future research is needed to confirm whether muscle fatigue can be considered a risk factor for falls in older adults.

#### *8.3.1. Experimental considerations*

Compensation strategies to limit the effect of muscle fatigue on postural control include increased joint stiffness, changes in muscle activation/synergies and re-weighting of sensory information (Paillard, 2012). We have shown that these compensation strategies may be less effective with reduced proprioceptive information at the feet and ankles. Furthermore, older adults seem to have more difficulty compensating for fatigue and may need more attention to do so. However, similar to previous studies, we only looked at the effect of these compensation strategies on conventional COP sway parameters.

The potential role of the above-mentioned compensation strategies also needs to be confirmed experimentally. Our studies did not report on muscle activation, joint stiffness or proprioception measures. Studies have demonstrated an increase in muscle activation and joint stiffness in fatigued muscles (Caron, 2004; Corbeil *et al.*, 2003; Caron, 2003), but research on possible changes in muscle synergies and changes from an “ankle strategy” to a “hip strategy” with fatigue is needed, and should include both young and older participants. Furthermore, the direct link between a reduction in proprioception and a reduction in COP

sway displacement and/or velocity due to fatigue has yet to be confirmed. Healthy older adults may have similar COP sway characteristics compared with young adults after fatigue when standing on a FS, but the compensation strategies used between groups may be different.

Most previous studies, including the work presented in this thesis, have shown that the effect of localized muscle fatigue on postural control is relatively brief, even for older adults. This might be due to the nature of the fatigue task. Most studies have used relatively high intensity contractions to fatigue the targeted muscle, probably creating more peripheral rather than central fatigue. Previous work has shown that low force contractions held for a long period of time also lead to increased COP sway (Paillard *et al.*, 2010; Freitas *et al.*, 2005). Attention could be affected to a greater extent by a longer-lasting fatigue protocol (more centrally driven). This may explain the difference between the findings of Vuillerme and colleagues (2002b) and ours. These authors used a self-bearing task (stand on tip-toes) compared to a 50% MVC isometric continuous contractions used in the last study of this thesis. Lower intensity fatigue tasks with more central fatigue may also have a greater impact on the ability to re-weight sensory information. Thus, research comparing the impact of central vs. peripheral fatigue on postural control and attention is also needed for both age groups.

### 8.3.2. *Clinical considerations*

Standing quietly on one leg or on a compliant (foam) surface are two tasks commonly used in clinical settings to assess balance (Lord *et al.*, 2005). The amount of time one can remain on one leg has been shown to discriminate between fallers and non-fallers (Hurvitz *et*

*al.*, 2000). Stability on a CS has been shown to be more sensitive to balance problems observed with old age (Horak *et al.*, 1989; Woollacott *et al.*, 1986), pathologies such as vestibular disorders (Horak & MacPherson, 1996) and injuries (Lysholm *et al.*, 1998; Guskiewicz, 2001), compared with a FS. Since our results demonstrated no effect of fatigue on one leg stance and a short-term effect of fatigue on the CS with healthy older adults, it is now essential to investigate the effect of muscle fatigue in a population at greater risk of falling. For example, since individuals with diabetes may have reduced peripheral proprioceptive information and report general fatigue (Fritschi & Quinn, 2010), they might be at greater risk of falling when fatigued.

The ability to maintain a stable, upright stance is an essential component of daily activities. Our results suggest that young and older adults are able to compensate for muscle fatigue to limit postural control alterations during quiet standing. However, the compensation strategies used could have an impact on the performance of more complex tasks such as walking, avoiding obstacles, stepping abilities following a perturbation, etc. Research on the effect of muscle fatigue on these different functional tasks is needed to truly examine the impact of muscle fatigue on daily activities and quality of life of older adults.

#### **8.4. Conclusion**

As a consequence of the deterioration of the musculoskeletal, neuromuscular and sensory systems with normal aging, older adults generally have greater COP sway and need more attentional resources compared to their younger counterparts, which can contribute to the increased risk of falling in this population. Although it is well recognized that physical

activity can slow the deterioration process of normal aging, acute muscle fatigue following physical activity could be problematic as it has been shown to increase COP sway and attentional demands in young adults.

The differential effects of muscle fatigue on COP sway and related central processes (attentional demands and sensory re-weighting) in older adults compared with young adults were presented in this thesis. Our findings suggest that the differential effect of fatigue between older and young healthy adults is task-dependent. Even though the postural task was more difficult for older adults (greater COP sway), the increase in COP sway displacement and velocity induced by ankle muscle fatigue were not more pronounced than those observed for young adults when standing on a FS. Furthermore, older adults seemed to have sufficient attentional resources when standing on this type of surface to compensate for fatigue, as was observed in young adults. However, when proprioceptive information at the ankle was altered (CS) and visual information was not available, older adults seemed to have more difficulty in compensating for muscle fatigue compared to young adults. Although both groups had more difficulty standing quietly during this condition after fatigue, older adults had substantially greater COP sway displacements and may have needed more attention compared to young adults. This suggests that frail older adults with reduced peripheral proprioception and/or reduced vision could possibly have more difficulty in efficiently using the same compensation strategies, and may be at a greater risk of falling when fatigued, but this needs to be confirmed in future studies.

## CHAPTER 9. STATEMENT OF CONTRIBUTION

**Manuscript 1** - *Effects of Ankle and Hip Muscle Fatigue on Postural Sway and Attentional Demands During Unipedal Stance.* E.J. Bisson conceptualized the study, carried out the data collection, statistical analyses, and wrote and edited the manuscript. D. McEwen participated in the data collection, data analysis, and revised drafts of the manuscript. Y. Lajoie and M. Bilodeau participated in the conception and design of the study, provided advice and content expertise, and revised the manuscript. All authors read and approved the final manuscript.

**Manuscript 2** - *Changes in postural sway and attentional demands due to ankle neuromuscular fatigue with aging.* E.J. Bisson conceptualized the study, carried out the data collection, statistical analyses, and wrote and edited the manuscript. D. McEwen participated in the data collection, data analysis, and revised the manuscript. Y. Lajoie and M. Bilodeau participated in the conception and design of the study, provided advice and content expertise, and revised the manuscript. All authors read and approved the final manuscript.

**Manuscript 3** - *Effects of fatiguing isometric and isokinetic ankle exercises on postural control while standing on firm and compliant surfaces.* E.J. Bisson conceptualized the study, carried out the data collection, statistical analyses, and wrote and edited the manuscript. A. Remaud and S. Boyas participated in the design of the study, the data collection, data analyses and the writing of the manuscript. Y. Lajoie participated in the analysis and interpretation of the data, and revised the manuscript. M. Bilodeau participated in the conception and design of the study and revised the manuscript. All authors read and approved the final manuscript.

**Manuscript 4** - *The influence of age and surface compliance on changes in postural control and attention due to ankle neuromuscular fatigue.* E.J. Bisson conceptualized the study, carried out the data collection, statistical analyses, and wrote and edited the manuscript. Y. Lajoie and M. Bilodeau participated in the conception and design of the study, provided advice and content expertise, and revised the manuscript. All authors read and approved the final manuscript.

## CHAPTER 10. REFERENCE LIST AND APPENDICES

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## APPENDIX A - ETHICS APPROVALS



# Université d'Ottawa University of Ottawa

Service de subventions de recherche et déontologie Research Grants and Ethics Services

## HEALTH SCIENCES AND SCIENCE RESEARCH ETHICS BOARD

### CERTIFICATE OF ETHICAL APPROVAL

This is to certify that the University of Ottawa Health Sciences and Science Research Ethics Board has examined the application for ethical approval of the research project entitled **The Effects of Lower Limb Muscle Fatigue on One-leg Standing Balance and Reaction Time with Aging (file H 01-07-10)** submitted by Martin Bilodeau of the Élisabeth Bruyère Research Institute and School of Rehabilitation Sciences of the University of Ottawa, by Étienne Bisson of the Élisabeth Bruyère Research Institute and by Yves Lajoie of the School of Human Kinetics of the University of Ottawa. The Board found that this research project met appropriate ethical standards as outlined in the Tri-Council Policy Statement and in the Procedures of the University of Ottawa Research Ethics Boards, and accordingly gave it a Category 1a (approval). This certification is valid one year from the date indicated below.

May 16, 2007

Date

Protocol Officer for Ethics in Research  
For Dr. Daniel Lagarec, Chair of the  
Health Sciences and Science REB



*Bruyère pour des soins continus.  
Bruyère Is Continuing Care.*

November 11, 2008

Dr. Martin Bilodeau  
EBRI

**RE: Acute effects of exercise-induced neuromuscular fatigue on posture control with aging.**

Dear Dr. Bilodeau,

Your reply to our conditional letter of October 8, 2008 (received by us November 6, 2008) answered all the issues raised by the Research Ethics Board reviewers.

It is therefore with pleasure that the Bruyère Continuing Care Research Ethics Board (REB) gives ethical approval for one year to proceed with the above titled study.

Please note that any future changes to the protocol must be submitted to the REB for approval. You are also expected to provide notification of the termination of the study.

We wish you the best of luck with this study.

Affilié à / Affiliated with





*Bruyère pour des soins continus.  
Bruyère Is Continuing Care.*

September 28, 2011

Mr. Etienne Bisson  
PhD Candidate  
Faculty of Health Sciences  
School of Human Kinetics  
University of Ottawa

**RE: The influence of ankle muscle fatigue on different fall risk factors with aging.**

(Bruyere REB Protocol # M16-10-032)

### **Final Approval**

Dear Mr. Bisson,

Thank you for your response to our conditional approval (letter dated September 8, 2010) the last part of which we received September 26, 2011. With the revisions, the application has satisfied all ethical requirements.

As such, the Bruyère Continuing Care Research Ethics Board (REB) is pleased to give ethical approval for one year (September 28, 2011 to September 28, 2011) to proceed with the above titled study.

This approval includes the amendment received on September 26, 2011 and the revised consent form.

Please submit the Pledges of Confidentiality signed by each researcher on this project prior to initiation of recruitment activities.

Any complaints made by participants must be reported to the REB. You are also expected to provide a written request for annual renewal or written notification of the termination of the study by the end of the approved year, as stated above.

We wish you the best of luck with this study.

Sincerely,

*Affilié à / Affiliated with*



uOttawa

APPENDIX B - DATA SHEETS



Date:

ID:

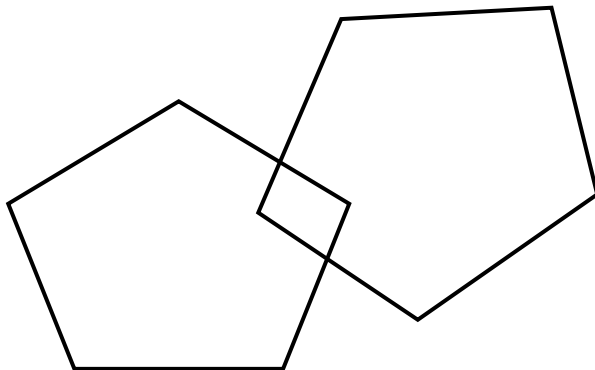
**Demographic**

Gender	Date of birth	Height (cm)	Weight (kg)	Leg dominance	Foot sensitivity

**Mini-Mental State Examination (MMSE)**

1. What is the date today?		/5	7. Repeat the phrase: "No ifs, ands, or buts."		/1
2. Where are we now?		/5	8. Take a paper in your right hand, fold it in half, and put it on the floor.		/1
3. Repeat all three <i>objects</i> after I have said them. (house, tree, car) # trials: _____		/3	9. Read and obey the following:		/1
4. Begin from 100 and count backwards by 7. (93, 86, 79, 72, 65) or Spell WORLD backwards		/5	10. Write a sentence about anything. Sentence must have a noun and a verb		/1
5. Name the three objects I asked you to name earlier.		/3	11. Please copy the picture below.		/1
6. Identify a pencil and a watch. Ask the patient to name them.		/2	<b>Total</b>		<b>/30</b>

**"Close your eyes."**





Date: \_\_\_\_\_

ID: \_\_\_\_\_

**PIMA Physical Activity Questionnaire**

1. In general, about how many **hours per week** did you regularly participate in sports and other vigorous physical activities (excluding walking and time spent in school physical education classes)?

... during the past year \_\_\_\_\_

... during the past week \_\_\_\_\_

2. Did you ever compete in an individual or team sport (not including any time spent in sports performed during school physical education classes)? If yes,

... how many *total years* did you participate in competitive sports \_\_\_\_\_

3. Have you ever had a job that required physically demanding work? If yes,

... how *many* physical active jobs have you ever held? \_\_\_\_\_

... what is the *total* number of *years* that you have worked in these physically demanding jobs? (Sum of years spent in jobs mentioned above) \_\_\_\_\_

4. Have you ever spent any time confined to a bed or a chair for more than 1 month as a result of an injury or an illness? If yes,

... how old were you when you first became confined to a bed or chair? \_\_\_\_\_

... how many *months* total did this confinement to a bed or chair last? \_\_\_\_\_

5. In general, about how many hours per day did you spend watching television?

... during the past year \_\_\_\_\_

... during the past week \_\_\_\_\_





Date:

ID:

6. Please circle below activities done more than 10 times in your lifetime, not including time spent in school physical education classes:

- |                         |   |                        |    |                          |    |
|-------------------------|---|------------------------|----|--------------------------|----|
| Running for exercise    | 2 | Football/soccer        | 10 | Calisthenics             | 18 |
| Swimming (laps)         | 3 | Racquetball/handball   | 11 | Walking for exercise     | 19 |
| Bicycling               | 4 | Horseback riding       | 12 | Hiking through mountains | 20 |
| Softball/baseball       | 5 | Hunting                | 13 | Rodeo                    | 21 |
| Volleyball              | 6 | Fishing                | 14 | Other                    | 22 |
| Bowling                 | 7 | Dancing/Indian dancing | 15 | Other                    | 23 |
| Basketball              | 8 | Gardening or yard work | 16 | Tennis                   | 24 |
| Skating (roller or ice) | 9 | Weight lifting         | 17 | Golf                     | 25 |
|                         |   |                        |    | Canoeing                 | 26 |

For each activity circled, list below each activity done during the past year (from \_\_\_\_\_ to this \_\_\_\_\_) and determine the AVERAGE amount of time spent in that activity over the past year.

PAST YEAR				PAST WEEK
Activity #	# of months over past year	Average # of times per month	Average # of hours* each time	Average # of hours* over the past 7 days

\* Number of hours should be rounded to the nearest 1/2 hour.



Date:

ID:

7. Have you had a job for more than 1 month over this past year, from last \_\_\_ to this \_\_\_ ?

List all JOBS that the individual held over the past year for more than 1 month. Account for all 12 months of the past year. (If unemployed/disabled/retired/housewife during all or part of the past year, list as such and probe for job activities of a normal 8 hour day, 5 day week)

Job name	Job code	Walk or bike to work (min/day)	AVERAGE JOB SCHEDULE			Was most of this time spent sitting? If yes, enter total # in hours sitting column. If no, determine how much time was usually spent sitting, then place a check in the category which best describes their job activities when they are not sitting.			
			Month / year	Day / week	Hours / Day	Hours spent sitting at work	Check the category that best describes job activities when not sitting		
							A	B	C

**Category A**  
(includes all sitting activities)

**Category B**  
(includes most indoor activities)

**Category C**  
(heavy industrial work, outdoor construction, farming)

Sitting; Standing sill w/o heavy lifting  
Light cleaning - ironing, cooking, washing, dusting;  
Driving a tractor, harvester;  
Slow, leisure walking

Carrying lights loads; Continuous walking  
Heavy cleaning - mopping, sweeping, scrubbing, scraping; Gardening - planting, weeding; Painting / plastering;  
Plumbing / welding; Electrical work

Carying moderate to heavy loads;  
Heavy construction; Farming—hoeing, digging, mowing;  
Digging ditches; Chopping (ax)  
Sawing; Shoveling

**JOB CODE**

Not employed outside of the home

Student; Home Maker; Retired; Disabled; Unemployed

Employed (or volunteer)

Armed services; Office worker; Non-office worker





**Demographic**

Gender	Date of birth	Height (cm)	Weight (kg)	Leg dominance

**Godin Leisure-Time Exercise Questionnaire**

1. During a typical 7-Day period (a week), how many times on the average do you do the following kinds of exercise for more than 15 minutes during your free time (write on each line the appropriate number)?	Time / Week
a) <b>STRENUOUS EXERCISE (HEART BEATS RAPIDLY)</b> (e.g., running, jogging, hockey, football, soccer, squash, basketball, cross country skiing, judo, roller skating, vigorous swimming, vigorous long distance bicycling)	
b) <b>MODERATE EXERCISE (NOT EXHAUSTING)</b> (e.g., fast walking, baseball, tennis, easy bicycling, volleyball, badminton, easy swimming, alpine skiing, popular and folk dancing)	
c) <b>MILD EXERCISE (MINIMAL EFFORT)</b> (e.g., yoga, archery, fishing from river bank, bowling, horseshoes, golf, snow-mobiling, easy walking)	
<b>2. During a typical 7-Day period (a week), in your leisure time, how often do you engage in any regular activity long enough to work up a sweat (heart beats rapidly)?</b>	
Often	Rarely / never
Sometimes	





**Demographic**

Gender	Date of birth	Height (cm)	Weight (kg)	Leg dominance	Foot sensitivity

**Godin Leisure-Time Exercise Questionnaire**

1. During a typical 7-Day period (a week), how many times on the average do you do the following kinds of exercise for more than 15 minutes during your free time (write on each line the appropriate number)?	Time / Week
a) <b>STRENUOUS EXERCISE (HEART BEATS RAPIDLY)</b> (e.g., running, jogging, hockey, football, soccer, squash, basketball, cross country skiing, judo, roller skating, vigorous swimming, vigorous long distance bicycling)	
b) <b>MODERATE EXERCISE (NOT EXHAUSTING)</b> (e.g., fast walking, baseball, tennis, easy bicycling, volleyball, badminton, easy swimming, alpine skiing, popular and folk dancing)	
c) <b>MILD EXERCISE (MINIMAL EFFORT)</b> (e.g., yoga, archery, fishing from river bank, bowling, horseshoes, golf, snow-mobiling, easy walking)	
<b>2. During a typical 7-Day period (a week), in your leisure time, how often do you engage in any regular activity long enough to work up a sweat (heart beats rapidly)?</b>	
Often	Sometimes
Rarely / never	





**Mini-Mental State Examination (MMSE)**

1. What is the date today?		/5	7. Repeat the phrase: “No ifs, ands, or buts.”		/1
2. Where are we now?		/5	8. Take a paper in your right hand, fold it in half, and put it on the floor.		/1
3. Repeat all three <i>objects</i> after I have said them. (house, tree, car) # trials: ____		/3	9. Read and obey the following:		/1
4. Begin from 100 and count backwards by 7. (93, 86, 79, 72, 65) or Spell WORLD backwards		/5	10. Write a sentence about anything. Sentence must have a noun and a verb		/1
5. Name the three objects I asked you to name earlier.		/3	11. Please copy the picture below.		/1
6. Identify a pencil and a watch. Ask the patient to name them.		/2	<b>Total</b>		<b>/30</b>

**“Close your eyes.”**

