

# Impact of neuromuscular fatigue on the postural response to externally initiated, predictable postural perturbations

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*To Matthew Silu Kennedy.  
Thank you for sharing a desk with me for the past 4 years.*

## **Authorization**

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### ***Habituation occurs over several anticipated postural perturbation trials***

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Bugnariu N: Writing of manuscript

Guével A: Writing of manuscript

Sveistrup H: Conceptualization of experiment, data analysis and writing of manuscript

### ***Neuromuscular fatigue induced by alternating isometric contractions of the ankle plantar and dorsiflexors.***

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### ***Impact of ankle muscle fatigue on anticipatory postural activity in perturbed postural control***

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## **Abstract**

Neuromuscular fatigue, even that caused by light submaximal exercise, impairs motor performance and alters motor planning. This impairment is evident in muscle reaction time, force production capacity and joint position sense as well as in more complex tasks such as postural stability. When an individual is fatigued their postural sway increases and they are less able to recover from unexpected postural perturbations. Although a large number of work-related falls are caused by fatigue every year, the mechanisms behind the instability are not well understood. Since postural control does not require a large amount of muscular strength it is unclear whether the post-fatigue changes in posture are due to impairment within the muscle fibers or are a central modification of the motor plan used to execute the movement task.

In order to better understand neuromuscular fatigue researchers have labeled fatigue occurring within the muscles ‘peripheral fatigue’ and that occurring within the central nervous system ‘central fatigue’. At the onset of a muscular contraction peripheral and central fatigue develop simultaneously, making it difficult to clearly articulate the role that they each play in the decreased motor performance found post-fatigue. Techniques such as transcranial magnetic and electrical nerve stimulation quantify the contribution of central fatigue to the decreased maximal force production but the impact on motor planning is still not well understood. Therefore, the primary aim of this doctoral dissertation was to isolate central fatigue from peripheral muscle fatigue and to compare the influence that it may have on dynamic postural control to the changes caused by general fatigue of the local postural muscles.

This overarching research goal was accomplished through five separate studies. The first study in this dissertation determined that at least seven postural trials needed to be performed to ensure that the participants had fully adapted to the postural task before the fatigue protocol was implemented. Experiment 2 characterized the fatigue produced by bilateral, isometric ankle muscle contractions and examined the recovery of the central and peripheral changes throughout a ten-minute post-fatigue recovery period. The results demonstrated that the alternating maximal ankle plantar and dorsiflexor contractions created central and peripheral fatigue. Central fatigue recovered within the first two minutes post-fatigue while peripheral fatigue lasted throughout the ten-minute post-fatigue period. Experiment 3 analyzed the impact of this ankle muscle fatigue protocol on the postural response to a continual, externally driven, sinusoidal oscillation of the

support platform. In this study the fatigued participants were able to stabilize their center of mass displacement using two different anticipatory postural responses to the backwards perturbation whereas all of the participants used the same anticipatory response to the forwards perturbation. All three postural responses became progressively more conservative throughout the ten-minute post-fatigue period, despite the rapid recovery of the ankle force production capacity.

The final two studies characterized the fatigue produced during a continuous, isometric forearm contraction and assessed the impact on ankle motor performance (Experiment 4) and on postural control (Experiment 5). Peripheral fatigue created in the forearm muscles during this contraction remained throughout the post-fatigue testing session. Central fatigue and a decreased maximal force production capacity were quantified in both the forearm and ankle plantarflexor muscles immediately after the forearm contraction, indicating that central fatigue created during the forearm exercise crossed over to the distal and unrelated ankle plantarflexor muscles. The influence of the central fatigue created during the forearm contraction affected the anticipatory postural response in a similar way to the fatigue created by the ankle fatigue protocol. The post-fatigue modification of the postural response dissipated as the central fatigue recovered. Taken together, these five studies extend the current understanding of how exercise induced neuromuscular fatigue modifies the central nervous system's control of complex motor tasks.

## Résumé

La fatigue neuromusculaire, y compris celle causée par l'exercice sous-maximal modéré, nuit à la performance et à l'organisation motrice. Ce problème s'observe clairement au niveau du temps de réaction moteur, de la capacité de production de la force, de la sensibilité à la position articulaire ainsi que lors de l'exécution d'autres tâches plus complexes comme le contrôle postural. Lorsqu'une personne éprouve de la fatigue, son balancement postural augmente et elle éprouve plus de difficultés à se remettre des perturbations posturales inopinées. Bien qu'un grand nombre de chutes liées au travail soient causées tous les ans par la fatigue, on comprend mal les mécanismes à l'origine de l'instabilité posturale. Étant donné que le contrôle postural nécessite peu de force musculaire, on ne sait pas vraiment si les changements de posture consécutifs à la fatigue sont attribuables à une déficience des fibres musculaires ou à une modification centrale de la zone de planification motrice utilisée pour exécuter les mouvements.

Afin de mieux comprendre la fatigue neuromusculaire, des chercheurs ont distingué deux types de fatigue, la fatigue musculaire, appelée « fatigue périphérique » et la fatigue du système nerveux central, nommée « fatigue centrale ». Au début d'une contraction musculaire, les fatigues d'origine périphérique et centrale se développent simultanément, d'où la difficulté de comprendre clairement le rôle joué par chacune dans la diminution de la performance motrice consécutive à la fatigue. Des techniques comme la stimulation magnétique transcrânienne et la stimulation électrique des nerfs permettent de quantifier dans quelle mesure la fatigue centrale contribue à la baisse de production de la force maximale, mais les répercussions sur le contrôle moteur sont encore mal comprises. C'est pourquoi l'objectif principal de cette thèse de doctorat visait à distinguer la fatigue centrale de la fatigue musculaire périphérique et à comparer l'impact de la fatigue sur le contrôle postural dynamique par rapport aux changements causés par la fatigue générale des muscles posturaux locaux.

Cet objectif de recherche déterminant a été mené par le truchement de cinq études distinctes. La première étude de cette thèse a permis d'établir qu'il fallait mener au moins sept essais posturaux préalables à la mise en œuvre du protocole de fatigue pour que les participants soient pleinement à l'aise avec la tâche posturale. La seconde expérience avait pour objectif de définir la fatigue engendrée par des contractions musculaires de la cheville, isométriques et bilatérales et d'examiner le rétablissement des changements centraux et périphériques lors d'une période de

récupération post-fatigue de 10 minutes. Les résultats indiquent que des contractions maximales et alternatives en flexion plantaire de la cheville et en flexion dorsale engendrent une fatigue centrale et périphérique. La fatigue centrale disparaît au bout de deux minutes de repos alors que la fatigue périphérique persiste durant les 10 minutes de récupération. La troisième expérience avait pour objectif d'analyser l'impact du protocole de fatigue musculaire de la cheville sur la réponse posturale face à une oscillation sinusoïdale de la plateforme de soutien imposée de façon externe continue. Dans cette étude, les participants éprouvant de la fatigue pouvaient, au moyen de deux réponses préventives distinctes à la perturbation vers l'arrière, stabiliser le déplacement de leur centre de gravité alors que tous les participants utilisaient la même réponse préventive à la perturbation vers l'avant. Les trois réponses posturales ont progressivement perdu de leur efficacité à mesure que la période de récupération de 10 minutes progressait, en dépit du rétablissement rapide de la capacité de production de la force de la cheville.

Les deux études finales avaient pour objectifs de définir la fatigue produite lors d'une contraction isométrique continue de l'avant-bras et d'évaluer l'impact sur la performance motrice de la cheville (expérience 4) et sur le contrôle postural (expérience 5). La fatigue périphérique ressentie dans les muscles de l'avant-bras lors de la contraction ne s'est pas atténuée durant la séance d'essais post-fatigue. La fatigue centrale et une baisse de la capacité de production de la force maximale ont été quantifiées immédiatement après la contraction de l'avant-bras, à la fois pour les muscles de l'avant-bras et les muscles fléchisseurs plantaires de la cheville, ce qui indique que la fatigue centrale ressentie lors de l'exercice avec l'avant-bras a affecté les muscles fléchisseurs plantaires de la cheville. L'impact de la fatigue centrale ressentie lors de la contraction de l'avant-bras a affecté la réponse posturale préventive, de la même manière que la fatigue créée par le protocole de fatigue musculaire de la cheville. La modification de la réponse posturale post-fatigue s'est dissipée durant le processus de récupération de la fatigue centrale. Considérées dans leur ensemble, ces cinq études approfondissent notre compréhension actuelle quant à la façon dont la fatigue neuromusculaire provoquée par l'exercice modifie le contrôle des tâches motrices complexes du système nerveux central.

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## List of Abbreviations

<b>ANOVA:</b> analysis of variance	<b>F0:</b> Trial occurring immediately post-fatigue
<b>APA:</b> anticipatory postural adjustment	<b>F1:</b> trial occurring 1 minute post-fatigue
<b>ATP:</b> adenosine triphosphate	<b>F2:</b> trial occurring 2 minutes post-fatigue
<b>BB:</b> <i>biceps brachii</i>	<b>F5:</b> trial occurring 5 minutes post-fatigue
<b>BF:</b> <i>biceps femoris</i>	<b>F7:</b> trial occurring 7 minutes post-fatigue
<b>BL-1:</b> Last pre-fatigue occurring immediately pre-fatigue	<b>F10:</b> trial occurring 10 minutes post-fatigue
<b>BOS:</b> Base of support	<b>FDS:</b> <i>flexor digitorum superficialis</i>
<b>Ca<sup>2+</sup>:</b> Calcium	<b>LG:</b> <i>lateral gastrocnemius</i>
<b>CMEP:</b> cervicomedullary motor-evoked potentials	<b>MG:</b> <i>medial gastrocnemius</i>
<b>CNS:</b> central nervous system	<b>MEP:</b> motor-evoked potential
<b>COP:</b> center of pressure	<b>MU:</b> motor unit
<b>COM:</b> center of mass	<b>MVC:</b> maximal voluntary contraction
<b>CV:</b> conduction velocity	<b>PF:</b> plantarflexor
<b>DF:</b> dorsiflexor	<b>RF:</b> <i>rectus femoris</i>
<b>EMG:</b> electromyography	<b>SOL:</b> <i>soleus</i>
<b>ECC:</b> Excitation-contraction coupling	<b>SD:</b> standard deviation
	<b>SR:</b> Sarcoplasmic reticulum
	<b>TA:</b> <i>tibialis anterior</i>
	<b>TMS:</b> Transcranial magnetic stimulation
	<b>TT:</b> twitch torque
	<b>VA:</b> voluntary activation

# **Chapter 1: General Introduction and Review of Literature**

In postural control afferent information from the visual, vestibular and proprioceptive systems is combined with cognitive factors such as previous experience (Horak, Diener et al. 1989) and expectation (Jacobs, Horak et al. 2008) to create a postural strategy that allows the individual to control the displacement of their center of mass (COM) within the base of support. The COM is controlled through muscle activity, described in more detail later in this section, which results in angular accelerations of the implicated body segments and movement of the center of pressure (Winter 1995).

If quiet stance is interrupted by an unexpected postural perturbation the vertical projection of the COM may be shifted outside the base of support resulting in a loss of balance. However, when the perturbation is voluntarily initiated, i.e. during a rapid arm lift, postural adjustments are made in anticipation of the perturbation to decrease the impact of the impending destabilizing force (Bouisset and Zattara 1987, Aruin, Forrest et al. 1998, Toussaint, Michies et al. 1998, Morris and Allison 2006). With only a little experience young healthy participants are also able to use anticipatory postural adjustments (APAs), including muscle activity and joint kinematics, to compensate for predictable but *externally* initiated postural perturbations (Shiratori and Latash 2001, Bugnariu and Sveistrup 2006).

The ability to compensate for a postural perturbation is reduced when afferent feedback is altered and/or impaired. Exercise induced neuromuscular fatigue not only impairs afferent feedback from the environment (Garland and Kaufman 1995, Darques, Decherchi et al. 1998, Martin, Smith et al. 2006, Martin, Weerakkody et al. 2008), it also changes the muscle reaction time (Wojtys, Wylie et al. 1996), force production capacity

(Bigland-Ritchie 1981, Miller, Giannini et al. 1987, Smith, Martin et al. 2007) and joint position sense (Skinner, Wyatt et al. 1986, Carpenter, Blasier et al. 1998) of the affected muscle group. An amalgamation of these fatigue induced changes causes a decrease in postural control during quiet stance (Johnston, Howard et al. 1998) and a reduced ability to recover from unexpected postural perturbations (Davidson, Madigan et al. 2009).

Presently, the mechanisms behind the instability are not well understood despite the large number of work-related falls caused by fatigue every year (Saks and Rahaman 2011). Part of the uncertainty regarding the impact of fatigue on motor control comes from the complex nature of exercise induced neuromuscular fatigue. Physiologically, the effects of fatigue are manifested at several levels throughout the body. These changes can generally be grouped into either central fatigue, affecting the central nervous system (CNS: brain and spinal cord) and motor neurons, or peripheral fatigue, occurring at the neuromuscular junction and within the muscle fibres. While the impact of peripheral fatigue is well understood, there is a paucity of experimental evidence regarding the influence of central fatigue on dynamic motor tasks (Rasmussen, Secher et al. 2007). This gap in knowledge is partially caused by the difficulty in disassociating the contribution of central and peripheral factors of neuromuscular fatigue. Techniques such as transcranial magnetic and electrical nerve stimulation are able to isolate the impact of central fatigue on well controlled maximal voluntary contraction tasks (Gandevia 2001); however, the impact of central fatigue on more complex tasks and motor planning is still not well understood.

The following review of literature will provide a summary of the important variables in postural control and will explore the physiological and cognitive changes caused by

exercise-induced fatigue. Finally, this review of literature will summarize what is known about the impact of neuromuscular fatigue on postural control.

## **1.1 Postural Control**

### **Theoretical Approach**

Throughout this dissertation postural control was assessed using Anne Shumway-Cook and Marjorie Woollacott's adaptation of systems theory (Shumway-Cook and Woollacott 2007). This theory was chosen because of the attention paid to the dynamic interaction between perception, cognition and action involved in motor control. The modified approach is based on Bernstein's early systems theory work that aimed to understand the human body as a mechanical system in which movement could be assessed by quantifying the internal and external forces acting on the body (Petrynski 2010). Shumway-Cook and Woollacott (2007) have further explored the complex interaction between the individual, the requirements of the motor task, and the characteristics of the surrounding environment. In fact, in their study of postural control Shumway-Cook and Woollacott break these main categories into several systems that work together to maintain orientation, defined as the ability to preserve an appropriate relationship between body segments and the environment, and stability, which refers to the ability to control the center of mass (COM) with respect to the base of support (BOS). These systems include, but are not limited to the individual sensory systems and the strategies used for sensory integration, the musculoskeletal system and motor system used to execute movement, the central nervous system, as well as movement strategies used to simplify complex motor tasks (Figure 1.1).

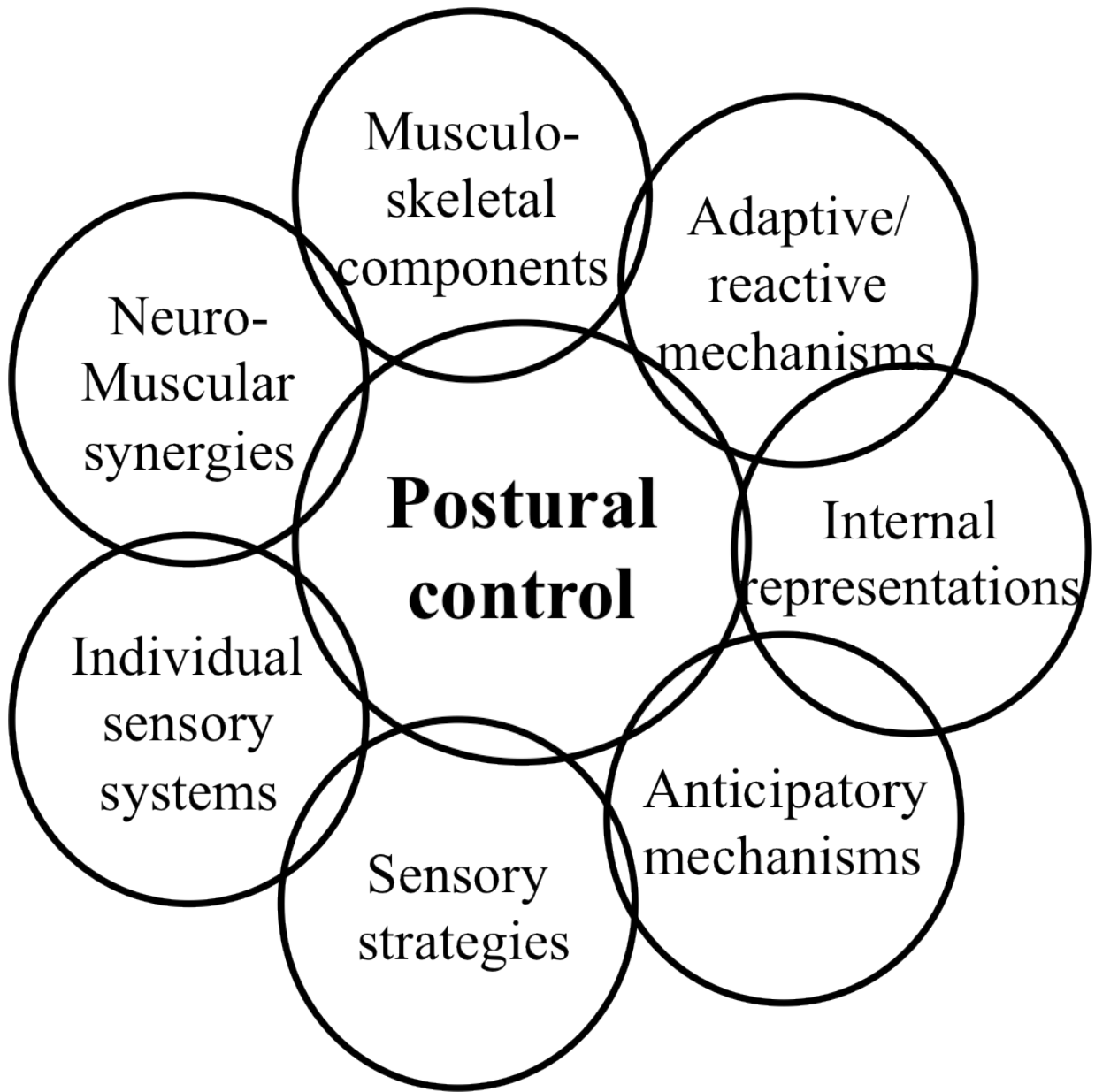


Figure 1.1: Systems approach to postural control (Reprinted with permission from: Shumway-Cook A, Woollacott MH, (2001) Motor control theory and practical applications, 2<sup>nd</sup> edition, Lipincott, Williams & Wilkins, p 165).

## **Sensory Systems**

Our senses, including the vestibular, visual and somatosensory systems, are responsible for acquiring information from the environment in order to create an internal representation of the world (Gurfinkel, Levik et al. 1988). In the context of postural control, the sensory system is responsible for relaying afferent information from the external environment to the CNS so that the individual can apply the appropriate restorative forces to control the body's movement in space. The specific role that these sensory systems play in postural control has been established through several experiments examining the impact of conflicting or reduced visual (Nashner and Berthoz 1978, Buchanan and Horak 1999, Oie, Kiemel et al. 2002, Bovea, Fenoglio et al. 2009), vestibular (Diener and Dichgans 1988, Orlov, Stolbkov et al. 2008, Mergner, Schweigart et al. 2009) and somatosensory (Nashner 1982, Buchanan and Horak 1999, Horak and Hlavacka 2001) feedback on stability. Although each sensory system provides a specific type of information, it is important to note that there is considerable overlap in the environmental characteristics that they describe, particularly when one of the systems is impaired (Peterka 2002).

The vestibular organs are located in the vestibule of the inner ear. This system provides position information about the orientation of the head relative to gravity and acceleration of the head (Latash 1998, Day and Fitzpatrick 2005). The vestibular system has static and dynamic functions that are mediated by the cells in the utricle and saccule, and the semicircular ducts respectively. The afferent information from the vestibular system is transported to the spinal cord, brainstem and the medulla and controls the vestibulo-ocular reflex to keep the gaze fixed while the head moves, the vestibulo-colic reflex to

keep the head stable during gait, and the vestibulo-spinal reflex to coordinate head and neck movement to maintain the head in an upright position and to adjust posture rapidly (Diener and Dichgans 1988, Peng, Hain et al. 1995, Goldberg 2004). In a young healthy adult the vestibular contribution to postural control is relatively low compared to the contribution of the visual and proprioceptive systems; however, vestibular impairment does decrease postural stability (Horak, Buchanan et al. 2002). In addition, if a sensory conflict occurs in either the visual or somatosensory systems, the contribution of the vestibular system can provide clarity for the CNS and increase postural stability (Horak and Hlavacka 2001, Peterka 2002, Dora, Angelaki et al. 2008).

The visual system uses information from the external environment to create an internal spatial representation of the world (Bovea, Fenoggioa et al. 2009) as well as to provide a reference of verticality and head position in space (Buchanan and Horak 1999). When vision is altered, even slightly by bifocal lens, the head postural position changes (Wilford, Kisner et al. 1996). When vision is completely occluded, healthy adults initially experience a substantial decrease in postural stability, particularly in more challenging postural tasks such as single leg stance (Hazime, Allard et al. 2012). Vision also plays an important role in feed-forward, or anticipatory, postural mechanisms when an adjustment in posture or gait must be made to maintain the COM displacement (Buchanan and Horak 1999) and/or avoid obstacles (McFadyen, Bouyer et al. 2007). However, if the visual information is incongruent with other sensory feedback the CNS may suppress the visual information in favour of the information from other sources such as somatosensory information (Buchanan and Horak 1999).

The somatosensory system provides information on proprioception, which codes body position and motion, nociception which describes pain sensation, and cutaneous sensation which includes temperature, pressure and touch (Flanagan and Lederman 2001). Of the sensory systems, the somatosensory system may be the most important in maintaining postural control (Kuo, Speers et al. 1998, Horak and Hlavacka 2001). Using a multilink, inverted pendulum model, Kuo et al (1998) quantified the extent and the type of sway that occurred when different types of sensory information were interrupted. They found that while visual and vestibular information were both very important in balance, reduced somatosensory information caused the most significant instability (Kuo, Speers et al. 1998). When somatosensory information is reduced, as it is during vibration of the Achilles tendon (Thompson, Bélanger et al. 2007) or in patients with neuropathies, the central nervous system compensates by becoming more sensitive to vestibular (Horak and Hlavacka 2001) and visual information (Redfern, Yardley et al. 2001). In conclusion, the aforementioned sensory systems work together to provide a complete picture of the internal, e.g. muscular strength, and external environments, e.g. characteristics of the support surface, that allow the human body to move effectively and efficiently through many different novel and unpredictable situations.

Once it has been acquired, the CNS must organize this wealth of information so that it can provide a timely and appropriate efferent response to the afferent input. Several theories have been developed to explain the integration of the sensory systems and how this process impacts motor control. The intermodal theory describes motor tasks as being controlled by the CNS's interpretation of interactions between information from the various sensory systems (Stoffregen and Riccio 1988). This theory is founded on the

assumption that each of the sensory systems contributes a fixed amount of information to postural control. This approach does not account for the compensatory and adaptive nature of the sensorimotor system. Fitzpatrick et al. (1996) applied the intermodal-based approach to assess the contributions of the sensory systems to the torque produced in response to a postural perturbation. Since the theory does not take the dynamic nature of the sensorimotor system into account, Fitzpatrick concluded that sensory feedback was insufficient to explain postural control (Fitzpatrick, Burke et al. 1996).

Another theory that describes sensory integration is called the sensory reweighting hypothesis. This approach is based on the idea that the CNS dynamically and selectively adjusts the relative contributions of sensory inputs (Vuillerme and Pinsault 2007). It predicts that the CNS optimizes sensory input based on the accuracy and reliability of the sensory systems (Oie, Kiemel et al. 2002, Peterka 2002, Mahboobin, Loughlin et al. 2005). The contribution of each sensory system is referred to as the 'gain' and is continually fine-tuned depending on how well each system performs. Several studies have investigated the validity of this theory by changing the environmental conditions and assessing the postural response. These studies found that young, healthy participants (Nashner and Berthoz 1978, Nashner 1982, Shumway-Cook and Horak 1989, Mergner, Schweigart et al. 2009) and older adults (Tremblay, Mireault et al. 2004) are both able to reweight the sensory inputs to maintain postural stability when one of the sensory systems is temporarily removed or impaired. The plasticity of sensory input gain makes the sensory reweighting hypothesis a dominant theory in explaining the integration of sensory information during motor tasks and so it will be an underlying framework for sensory integration throughout this dissertation.

## **Musculoskeletal System**

Once the sensory information has been organized and processed, efferent motor responses are sent to the postural muscles to create the coordinated joint torques required to maintain postural control. In quiet stance the musculoskeletal system of the healthy human body is able to maintain balance with relatively little effort. It is designed in such a way that its natural muscle<sup>1</sup> and postural tone<sup>2</sup> combined with the underlying skeletal alignment provide a great deal of vertical stability. The skeletal alignment and muscle tone require little sensorimotor involvement; in part because the ligaments, muscles and tendons provide biomechanical limits which naturally constrain the degrees of freedom that the central nervous system must overcome in order to remain balanced (Horak and Macpherson 1996). Postural tone, on the other hand involves a great deal of sensory input to ensure that normal postural sway is regulated appropriately (Shumway-Cook and Woollacott 2007).

When quiet stance is disrupted, the motor system, including motoneurons and the associated musculature, responds to the efferent information sent by the nervous system to produce three different types of motor response (Lephart, Reimann et al. 2000). These motor responses can be distinguished from one another based on their reaction latencies. For example, the first vestibulospinal reflex that occurs in response to a postural perturbation is the short latency reflex (SL) which likely results from the activation of a mono or oligo-synaptic spinal circuit. This reflex occurs within 35 ms of the perturbation; however, the torque produced is not large enough to regain postural stability. Nashner et

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<sup>1</sup> Muscle Tone: The muscles' resistance to passive stretch during a rested state

<sup>2</sup> Postural Tone: The activity increase found in antigravity muscles when an individual is standing upright

al. (2001) hypothesize that this motor response may be more important in force regulation than in force production.

The next motor systems to respond are the functionally stabilizing medium (ML ~95 ms) and long latency (LL ~ 120 ms) postural responses. Depending on the task, it may be difficult to distinguish between these muscle onsets and so they are often combined into a single response called the automatic or the long-latency postural response (Horak and Nashner 1986, Horak and Macpherson 1996). The automatic postural response is mediated by the brainstem and sub-cortical structures, allowing these responses to be tailored to the environment through afferent input (Nashner 2001). Although the initial automatic response is generated by the brainstem (Honeycutt and Nichols 2006), there is evidence that as the response latency increases the cerebral cortex becomes more involved in the postural response (Slobounova, Halletta et al. 2005). In other words, the brainstem initiates the automatic response and the cortical circuit modifies it based on 'online' afferent information (Jacobs and Horak 2007).

### **Central Nervous System**

The CNS allows us to perceive our environment, process and organize this information and initiate the movement required to maintain postural stability. This section of the review of literature will provide an overview of the functional physiology of the spine, brainstem, cerebellum and basal ganglia and explain how each relates to posture and human movement.

The spinal cord receives afferent information from the limbs and is responsible for basic sensory integration as well as limited postural muscle activity. The spinal ligaments

(Sjolander, Johansson et al. 2002) and musculature (Ivanenko, Grasso et al. 2000, Lin and Crago 2002, Scheipati, Nardone et al. 2003) as well as the facet joints and capsules (Wyke 1973, Treleaven, Jull et al. 2003) acquire afferent information about the position of the head and trunk in space and are important in the maintenance of postural stability. When the cervical spine is perturbed, the vestibulocollic reflex works to stabilize the head in space (Wilson, Boyle et al. 1995). It is postulated that information from this reflex is sent to the reticular formation, allowing the CNS to incorporate the movement into larger scale postural changes (Wilson 1999).

The brainstem also mediates postural control by exciting or inhibiting postural muscle tone in response to external perturbations (Honeycutt and Nichols 2010). It is hypothesized that the brainstem is important in initiating early postural responses to external perturbation (Jacobs, Horak et al. 2008). The role of the cerebellum in postural control is more complex and multifaceted. It receives and integrates somatosensory information from the body and compares the resultant afferent feedback to the intended movement or the efferent copy of the motor plan that was sent to the muscles (Ghez and Thatch 2000). Corrective efferent signals can then be sent to the motor cortex to update the motor command. The cerebellum is involved in the control of visually guided and/or triggered movement as well as the timing and adjustments of motor tasks (Biedert 2000).

The basal ganglia influences postural control through several sensorimotor mechanisms, or loops, that are involved in coordinating sensory information and maintaining postural control (Horak and Macpherson 1996). The basal ganglia-cortical loop is involved in the regulation of anticipatory postural mechanisms while the basal ganglia-brainstem loop

influences the central set<sup>3</sup> involved in automatic postural responses (Horak and Macpherson 1996, Takakusaki, Saitoh et al. 2004). Most of the information about the basal ganglia has been determined based on work with patients with Parkinson's disease (Takakusaki, Saitoh et al. 2004).

Once the sensory information is organized and the information is conceptualized, the movements are planned and the efferent commands are sent to the motoneurons and muscle fibres. The cerebral cortex, particularly the parietal cortex and pre-motor areas, plays an important role in computing these complicated processes (Jacobs and Horak 2007). This computation combines the motor goals with input from the basal ganglia and cerebellum to elicit a postural plan or strategy, a term that will be explored in more detail in the following section, to maintain stability (Passingham 1993). Information is then sent to the motor cortex where the efferent signals are generated and sent to the spinal cord through descending axons to excite the motoneurons, causing the muscle fibres to contract. The involvement of the motor cortex in postural control has been confirmed directly by studies using transcranial magnetic stimulation during postural perturbations (Beloozerova, Sirota et al. 2003, Solopova, Kazennikov et al. 2003).

Signal transmission latency restricts how quickly the cerebral cortex can influence postural control after a perturbation; however, the cortex can be involved in this process earlier by modulating the 'central set' before the perturbation occurs (Horak, Diener et al. 1989). This 'central set' combines the initial task conditions with previous experience to prime the brainstem so that the appropriate automatic postural synergies are released, making them more effective in restoring stability (Schmidt 1982). Early work from

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<sup>3</sup> Refer to following paragraph for definition of central set.

Horak, Diener and Nashner (1989), which was later supported by Sveistrup and Woollacott (Sveistrup and Woollacott 1997), found that the central set tailors the postural response to the peripheral stimuli of a support surface translation, particularly if the participants are able to incorporate prior experience. Transcranial magnetic stimulation has recently confirmed an increased cortical activity that occurs prior to a predictable perturbation and has associated it with a modification of the central set which is followed by an improved postural response (Jacobs, Horak et al. 2008).

### **Movement Strategies**

As initially suggested by Bernstein in 1947, the countless degrees of freedom involved in maintaining postural control, particularly in more complex and dynamic situations, are streamlined by the CNS's use of postural synergies. In a synergistic activation, muscle groups, and thus joint movements, are functionally coupled to allow healthy participants to produce task level goals with less demand on the central nervous system than if each muscle were activated in isolation (Ting 2007). The timing of muscle activation and relaxation is carefully regulated in a muscle synergy to allow for optimal motor performance (Horak and Macpherson 1996). In humans, synergistic muscle activations of some muscles are tightly coupled while others have more autonomous flexibility based on the task requirements. These postural synergies are thought to be selected and tailored based on the central set to create the required restorative endpoint force between the foot and the floor (Henry, Fung et al. 1998), which in turn works to control the displacement of the center of mass (Scholz, Schoner et al. 2007). Henry et al. (1998) studied the postural muscle synergies that were activated in response to support surface translations that occurred in 12 different directions. They found that unique postural synergies were

not created for each perturbation but that there were three muscle groupings that produced postural responses in response to lateral or diagonal perturbations (Henry, Fung et al. 1998). It is now accepted that a muscle can belong to more than one synergy but that a limited number of synergies are used to regulate posture (Ting and Macpherson 2005).

Postural synergies and afferent information are grouped together through a complex sensorimotor integration process to create postural strategies designed to regain and/or maintain stability (Horak and Macpherson 1996). Nashner et al. (1977) confirmed that these motor responses are controlled as postural strategies, and not as individual muscle activations, by rotating a support surface in a 'toes up' fashion. The resultant gastrocnemius muscle stretch was adequate to trigger muscle activity throughout the body despite the fact that only the ankle musculature was affected (Nashner 1977). This synergistic muscle activity allows the individual to regulate posture in an effective way while ensuring that the cognitive load required to maintain stability remains low.

It is hypothesized that postural strategies are planned by the motor cortex and are stored and initiated by the brainstem (Jacobs and Horak 2007). When posture is perturbed in the anterior/posterior direction, the resultant postural strategies can be categorized into the 'fixed base of support' postural response, which may be divided into the ankle and hip strategies, the 'changing base of support' postural response, also called the stepping strategy (Horak 1987) and a reaching response (McIlroy and Maki 1995). If posture is perturbed in the medial/lateral direction, the participant will rely on a different hip strategy or a step to maintain stability (Winter, Prince et al. 1996).

Postural strategies have been previously described as rigid patterns of muscle activity designed to maintain postural stability (Nashner 1977); however, we now know that they are more flexible responses that meet the requirements of the task and the environment (Scholz, Schoner et al. 2007). A postural strategy maintains control of the center of mass through activation of the muscles around the ankle, knee, hip and back which in turn control the angular moments around the lower limb joints as well as the displacement of the center of pressure. Although participants usually use a combination of the ankle and hip strategies, each is described here independently for clarity.

In the ankle strategy the majority of the compensatory force is created at the ankle (Horak and Nashner 1986). In the ankle strategy the COP and COM are highly correlated in the anterior-posterior direction and any error between the two represents a horizontal acceleration of the COM (Winter 1995). This strategy is characterized by activation of the gastrocnemius or tibialis anterior muscles approximately 90 ms after a posterior or anterior perturbation. The muscle activation continues proximally with activation of the hamstrings or quadriceps and then the paraspinal or abdominal muscles (Figure 1.2). This postural strategy is used in response to a small anterior or posterior perturbation where the support surface is large enough to allow the individual to create the required compensatory force (Nashner 1977). Most healthy participants also use this strategy to regulate quiet stance performed under normal conditions (Riemann and Guskiewicz 2000).

When the support surface is small (Nashner 1982), the participant is nervous (Adkin, Frank et al. 2000), or the COM must be moved quickly in the anterior or posterior

direction, the hip strategy is employed to regain balance. In the hip strategy the muscle activity, and thus force production, begins at the hip and proceeds distally to the ankle and proximally to the head (Horak and Nashner 1986) (Figure 1.2). A different type of hip strategy is used to regulate postural control in the medial/lateral direction. Since the musculoskeletal structure naturally reduces the movement that can interrupt postural stability in the medial/lateral (ML) direction, there is limited muscle activity that is involved in regaining and maintaining stability in this direction. Instead, the principal movement that occurs is a lateral movement of the pelvis created by the adduction of one leg and the abduction of the other (Day, Steiger et al. 1993). Winter et al. (1996) found that the compensatory hip movement used to maintain balance in the ML direction, controlled by the gluteus medius and tensor fascia latae, precedes compensatory ankle and head movement (Winter, Prince et al. 1996). In addition to the aforementioned strategies participants may also use a step (Horak 1991) or a reaching arm motion (Maki and McIlroy 2006) to realign or maintain the centre of mass over the base of support.

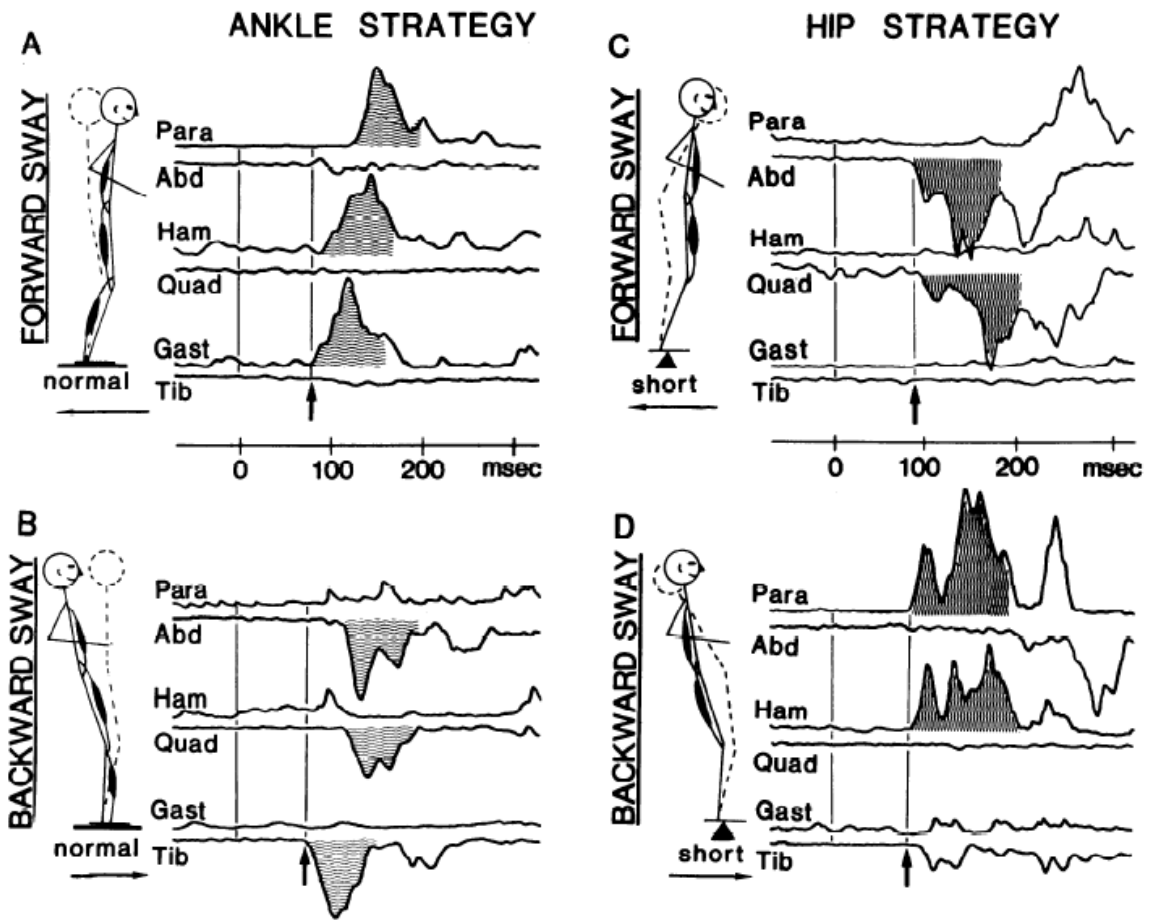


Figure 1.2: Ankle (left) and hip (right) strategies used to maintain postural control during backwards and forwards postural perturbations during forward (top) and backwards postural sway (bottom). Reprinted with permission from: *Horak F, Nashner L (1986) Central programming of postural movements: adaptation to altered support surface configuration. J Neurophysiol, 55: 1372).*

Experience, initial task conditions, attention and fatigue may all influence how postural strategies are used. When healthy individuals are not expecting a postural perturbation they use postural strategies in an automatic and reactive way. The automatic postural response occurs rapidly to counteract the destabilizing force. In humans, this response begins ~ 70-100 ms after the perturbation (Horak, Diener et al. 1989). However, it is important to note that relying solely on reactive postural responses may provide insufficient muscle activity that occurs too late to prevent a fall (Frank and Earl 1990).

When an individual has prior experience with a perturbation (Nashner 1976, Bugnariu and Sveistrup 2006) or when the perturbation is caused by a voluntary movement (Cordo and Nashner 1982) the nervous system activates the postural response in anticipation of the destabilizing force to decrease the mechanical effects of the disruption (Horak and Macpherson 1996). For example, in a reaching task the postural muscles are activated between 50 and 100 ms in advance of the arm movement (Massion 1992). After the first postural perturbation anticipatory postural control can be fine-tuned by afferent feedback, providing improved postural stability (Latash 1998).

Anticipatory postural adjustments are also found in externally initiated postural perturbations when the timing and characteristics of the destabilizing forces can be accurately predicted. Santos et al. found that when participants had their eyes open to receive a sagittal postural perturbation, the displacement of the COP and COM was significantly less than when they could not predict the timing of the perturbation (Santos, Kanekar et al. 2010). Predictable perturbations also resulted in earlier anticipatory muscle

activity (McChesney, Sveistrup et al. 1996) and smaller compensatory or reactive muscle activity relative to the unpredictable destabilizing forces (Santos, Kanekar et al. 2010).

### **Postural Adaptation**

Postural control is further improved with repetition of the motor task. When assessing the changes caused by repetition it is important to consider the type of perturbation. For example, when perturbations are delivered discretely participants modify their response within five to fifteen oscillations (Horak and Nashner 1986). When the perturbations are delivered continuously the adaptation occurs more rapidly. Deitz et al. (1993) found that the postural response to continual, 12cm, anterior/posterior sinusoidal oscillations of the platform was modified to meet the changing oscillation frequency within four cycles, or approximately 15 seconds (Dietz, Trippel et al. 1993) while Bugnariu and Sveistrup (2006) found that participants began to reliably activate their postural muscle in advance of the perturbation after only three to five oscillations (Bugnariu and Sveistrup 2006). Presently it is unclear whether the adaptation that occurs within one continuous trial is translated to subsequent trials or whether the participant must readapt the next time they are presented with the postural task. Finally, VanOoteghen et al. (2008) demonstrated that when the characteristics of the perturbation are less predictable, participants adapt their postural response based on the general characteristics of the movement. These changes may be less efficient than when the perturbations are predictable but they are translated to subsequent trials.

## **Postural Anxiety**

The data from this series of studies suggests that neuromuscular fatigue may increase postural anxiety, particularly in participants who do not have experience with fatigue. There is a paucity of literature relating fatigue and anxiety and so a brief review of postural anxiety in rested participants is provided here.

Carpenter et al. (1999) examined the impact of anxiety on postural control by placing young healthy adults on various platform heights and assessing their postural responses. They found that when an individual was placed on a high platform the amplitude of their postural sway decreased while the frequency of sway increased. They hypothesize that the CNS limits the risk of the COM moving outside the base of support by ‘tightening’ the postural control mechanisms (Carpenter, Frank et al. 1999). This desire for increased control over posture is further supported by research investigating the neurophysiological changes that occur when an individual is anxious. Sibley et al. (2007) demonstrated postural anxiety causes a reduced excitability of the spinal reflex (Sibley, Carpenter et al. 2007) which is proposed to improve supra-spinal control over posture. Although these anxiety-induced postural changes may be less energy efficient, they seem to provide increased stability when the participant is uncomfortable with a motor task.

## ***Conclusion***

The sensorimotor systems encompass several different processes involved in the acquisition of sensory stimuli, organization and conversion of that stimuli into efferent signals and execution of the desired motor response (Lephart, Reimann et al. 2000). The goal of this section of the review of literature was to describe these systems and to

provide a discussion on how they interact and compensate for one another. The interaction of the sensory systems ensures that the CNS receives the most reliable information from the environment. Communication of afferent information to the CNS allows appropriate postural responses to occur rapidly when balance is challenged. Finally, the afferent information from the motor response is weighed against the desired or expected motor response and any necessary corrections are made to the central set. This information is then stored as experience in preparation for future perturbations. This process is complex and task specific and relies on a high level of interaction between the sensorimotor systems.

## **1.2 Neuromuscular Fatigue**

Exercise induced neuromuscular fatigue causes a decreased physical performance that is associated with an increase in real or in perceived difficulty in task execution (Enoka and Stuart 1985, Gandevia 2001, MacIntosh, Gardiner et al. 2005, Ament and Verkerke 2009). Although fatigue is generally quantified through a decline in the force production capacity of a muscle, many neurophysiological mechanisms are altered before force production capacity is reduced (Bigland-Ritchie and Woods 1984). In an attempt to organize and clarify the origins of these fatigue induced changes, researchers have divided neuromuscular fatigue into peripheral factors, occurring at the neuromuscular junction (NMJ) and within the muscle fibres, and central factors, occurring within the central nervous system (Merton 1954, Bigland-Ritchie, Jones et al. 1978, Place, Maffiuletti et al. 2007).

The following section of this review of literature will describe the general physiological changes that lead to central and peripheral fatigue. Although reviewed separately, fatigue is a complex process in which central and peripheral systems interact with one another continuously. Since different contraction types produce a different ratio of central and peripheral fatigue, the second section of this review will outline the physiological changes occurring in different contraction types, i.e. maximal versus submaximal contractions. Finally, the impact of fatigue will be assessed on more complex motor tasks in the third and final section of this review.

## **Central Fatigue**

Central fatigue occurs proximal to the NMJ and progressively decreases the central nervous system's (CNS) ability to maximally drive  $\alpha$ -motoneurons (Enoka and Stuart 1992, Taylor and Gandevia 2008). Central fatigue affects the nervous system at several levels including the motor cortex (Taylor, Todd et al. 2006), the spinal cord (Gandevia 2001) and the motoneurons leading to the muscles (Garland and Kaufman 1995, Butler, Taylor et al. 2003, Racinais, Girard et al. 2007) (Figure 1.3). In addition to local central changes, afferent feedback from the peripheral system may be involved in central modulation of motor control post-fatigue.

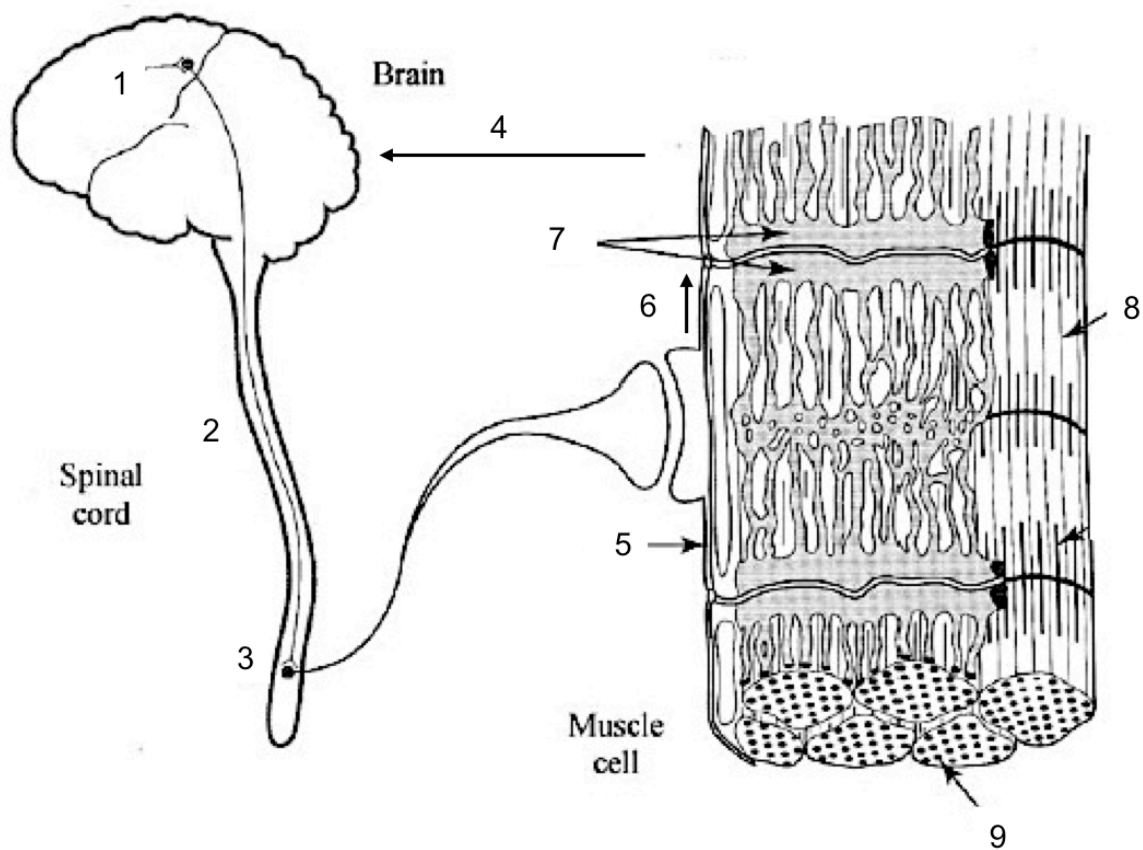


Figure 1.3. Locations of neuromuscular fatigue. Central fatigue may be caused by changes in the 1) activation of the motor cortex, 2) spinal column and/or 3) motoneurons as well as 4) in response to afferent feedback from the peripheral system. Peripheral fatigue may be caused by impairment of the 5) signal transmission across neuromuscular junction, 6) sarcolemma excitability 7) excitation-contraction coupling 8) muscle fiber contractile mechanisms, and 9) metabolic energy supply. (Modified from: *Bigland-Ritchie B. (1981) EMG/force relations and fatigue of human voluntary contractions. Exerc Sports Sci Rev, 9:75-117*)

This section of the review will first describe the experimental quantification of central fatigue. Next, it will address the possible locations of central fatigue in more detail and investigate metabolic changes that may be implicated in this process. Finally, the role of afferent feedback on cortical output and the CNS's ability to compensate for the negative effects of fatigue will be reviewed.

### ***Quantification of central fatigue***

The presence of central fatigue is determined experimentally by stimulating a nerve or muscle that is already voluntarily maximally contracted. If the stimulus causes an increase in force production over and above the maximal voluntary contraction (MVC), the individual's central drive can be said to be suboptimal (Merton 1954). If the force production created by the stimulus above the MVC force is larger after compared to before a fatiguing exercise, it can be assumed that the central drive has been diminished by central fatigue (Gandevia, Allen et al. 1996). This type of stimulation can be performed at the motor nerve, the motor point of the muscle, the cervicomedullary junction and the motor cortex in order to explore different mechanisms responsible for the suboptimal central drive. Increased force production above MVC by an electrical stimulation at the motor point and motor nerve reveals central fatigue occurring anywhere proximal to that stimulation point (Merton 1954, Belanger and McComas 1981, Kent-Braun 1999, Allman and Rice 2002). External stimulation of the CNS proximal to the vertebral column is almost exclusively performed using transcranial magnetic stimulation (TMS) (Todd, Taylor et al. 2003). When TMS is executed at the cervicomedullary junction it excites the corticospinal tract and induces cervicomedullary motor-evoked potentials (CMEP) (Gandevia, Petersen et al. 1999, Taylor and Gandevia 2004).

Comparing the CMEPs, measured distally at the muscle, to pre-fatigue levels provides information on motoneuron excitability (Martin, Smith et al. 2006). Additionally, any increase in force production above voluntary MVC from this stimulation is indicative of central fatigue occurring proximal to the cervicomedullary junction or supraspinally. Finally, the excitability of the motor cortex can be determined by measuring the amplitude of motor-evoked potential (MEP) induced by TMS over the motor cortex (Gandevia, Allen et al. 1996, Andersen, Westlund et al. 2003). An increase in force production above voluntary MVC by TMS at the motor cortex denotes inadequate neural drive 'upstream' of the cortex, namely the planning centers of the brain (Gandevia, Allen et al. 1996). When these techniques are used in conjunction with peripheral nerve stimulation, it is possible to approximate the amount of central fatigue present at different levels of the CNS (Butler, Taylor et al. 2003, Smith, Martin et al. 2007, Hoffman, Oya et al. 2009).

### ***Locations of central fatigue***

There are several local changes that occur within the brain that contribute to the decreased motor output including the level of brain serotonin, changes in brain glucose metabolism and an increased uptake of ammonium ions.

The level of brain serotonin (5-HT; 5-hydroxytryptophan) has been identified as an important factor in supraspinal fatigue (Nybo and Secher 2004). The 5-HT-central fatigue hypothesis explains that the precursor to 5-HT, free tryptophan (f-TRP), competes with several branch-chain amino acids (BCAAs) to cross the blood-brain barrier. In prolonged exercise the concentration of f-TPR in the blood increases while the level of BCAAs decreases as it is metabolized by skeletal muscle. The change in concentration allows the

f-TRP to cross into the brain, causing an increase in the 5-HT level in the hypothalamus, brain stem and cerebrospinal fluid (Curzon, Friedel et al. 1973, Chaouloff, Laude et al. 1986). 5-HT impacts arousal and lethargy in healthy individuals and has been hypothesized to affect the perceived effort of a task (Davis and Bailey 1997) as well as a decreased central command and thus, motoneuron recruitment (Newsholme and Blomstrand 2006).

Changes in brain glucose metabolism are also associated with central fatigue. After intense exercise, the brain's carbohydrate uptake increases to replace the cerebral glycogen levels that were used during the contraction (Dalsgaard, Ide et al. 2002). This increased uptake of blood carbohydrates indicates depleting glycogen stores within the brain, likely leading to impaired function. The increased brain metabolism that occurs during a fatiguing exercise may be caused by the increased mental exertion (Dalsgaard, Ide et al. 2002) or the overload of sensory feedback from the skeletal muscles (Nybo and Secher 2004).

Exercise induced fatigue has been shown to increase the level of cerebral uptake of ammonium ions (Nybo et al. 2005). This increase is measured through changes in the concentration of ammonia in the cerebral fluid and has been associated with central fatigue as it increases the perceived level of effort (Guezennec et al. 1998), possibly by decreasing the metabolism of neurotransmitters such as acetylcholine, dopamine and glutamate (Nybo and Secher 2004). Interestingly, training (Baldwin et al. 2000) and glucose supplementation (Snow et al. 2000) both reduce the uptake of ammonia.

### *Afferent feedback*

Muscle afferents, describing the biochemical status and force generating capacity of the muscles, may also be involved in the supraspinal inhibition caused by exercise (Gandevia 2001). Muscle ischemia examines the impact of afferent feedback more closely by preventing the recovery of the afferent discharge rates. Research has demonstrated that while the muscle is ischemic, supraspinal fatigue remains (Gandevia, Allen et al. 1996) but corticospinal and motoneuron function return to the pre-fatigue values (Butler, Taylor et al. 2003), suggesting that afferent feedback from the fatigued muscles alters the higher level motor planning centers of the brain (Taylor, Todd et al. 2006). This type of communication between the muscular and nervous system can be clearly displayed through the decreased  $\alpha$ -motoneuron excitability, increased pain sensation and decreased proprioception found during neuromuscular fatigue.

As the peripheral system becomes fatigued, muscle afferents decrease the  $\alpha$ -motoneuron pool excitability in the spine (Garland and McComas 1990, Kent-Braun 1999, Girard and Millet 2008). This decrease in excitability is caused by central regulation at the spinal and supraspinal level (Bigland-Ritchie and Woods 1984, Racinais, Girard et al. 2007). At the spinal level the group III, IV afferents decrease  $\alpha$ -motoneuron excitability through reflex inhibition (Garland and Kaufman 1995, Rozzi, Yuktanandana et al. 2000). At the supraspinal level the CNS decreases the  $\alpha$ -motoneuron excitability by down-regulating the descending supraspinal drive (Taylor, Todd et al. 2006). The decreased spinal motoneuron excitability is quantified experimentally by comparing the H-reflex<sup>4</sup> found in

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<sup>4</sup> The H-reflex (or Hoffmann reflex) is induced by short duration, small amplitude square wave current to assess the modulation of the monosynaptic reflex activity in the spinal cord. The H-reflex is an estimation of the alpha motoneuron excitability (Palmieri et al. 2004).

the electromyographical signal before and after the fatigue protocol (Zehr 2002). Isometric contractions have been shown to decrease the H-reflex in both high and low intensity contraction (Kuchinad, Ivanova et al. 2004); however, this change is likely specific to the fatiguing task and the motor task in which the H-reflex is measured.

Muscle afferents also allow us to sense the muscular pain and damage associated with fatigue. Group III (chemoreceptive) and IV (nociceptive) small-diameter muscle afferents carry information regarding these noxious signals occurring within the muscles fibers to the central nervous system (Rotto and Kaufman 1988, Martin, Butler et al. 2008). This type of nociceptive information has been associated with protective changes occurring in the central motor drive and result in increased activity of antagonistic muscle, a decreased activation of the agonist muscles and an overall decrease in the force produced by the painful contraction (Lund, Donga et al. 1991, Graven-Nielsen, Svenssonb et al. 1997, Ervilha, Farina et al. 2005).

Joint proprioception describes the afferent information regarding the sensation of joint position and movement (Lephart, Reimann et al. 2000). Mechanoreceptors within the skin, muscles and joints transmit mechanical and functional changes of the limb to the CNS (Lephart, Reimann et al. 2000). Of the mechanoreceptors, muscle spindles have been highlighted as the most important in proprioception (Myers, Guskiewicz et al. 1999). It is hypothesized that as a muscle fatigues the metabolic changes cause an increase in the muscle spindle discharge threshold (Skinner, Wyatt et al. 1986, Balestra, Duchateau et al. 1992). The increased discharge threshold reduces the amount of afferent information sent from the muscle spindles to the CNS and thus, impairs proprioception

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(Myers, Guskiewicz et al. 1999). This decrease in proprioceptive ability has been demonstrated in fatigue of the shoulder (Carpenter, Blasier et al. 1998, Myers, Guskiewicz et al. 1999), knee (Lattanzio, Petrella et al. 1997, Miura, Ishibashi et al. 2004) and elbow (Sharp and Miles 1993). The mechanoreceptors located within the musculotendinous junction are called golgi tendon organs and are hypothesized to inhibit neuronal activity (Gandevia et al. 1998); however, their exact role in neuromuscular fatigue is still not clear.

### ***Compensation for fatigue***

It is important to note that several mechanisms compensate for the presence of exercise-induced fatigue at the spinal level as well as upstream in the planning centers of the brain. Spinal compensations include changes in the reflex activities and motor-unit firing rate. The changes in the spinal reflexes occur in response to the afferent feedback from the mechanoreceptors of the fatigued muscles (including the neuromuscular spindles and golgi tendon organs) (Boyas and Guével 2011). When a rested muscle is stretched afferent feedback causes an increase in alpha motor neuron activity and a reflexive contraction of the muscle (Silverthorn 2004). When an individual is fatigued this stretch reflex increases to compensate for the joint laxity caused by neuromuscular fatigue (Zhang and Rymer 2001). It is important to disassociate the stretch reflex from the H-reflex which is often decreased post-fatigue (Zehr 2002).

The second spinal process compensates for exercise-induced fatigue by modifying the discharge rate of motor units (MU) to match the post-fatigue lengthening rate of the muscle fibers (Bigland-Ritchie, Johansson et al. 1983, Garland and Gossen 2002). In low

intensity contractions the MU discharge rate increases while it decreases during higher intensity contractions (Kuchinad, Ivanova et al. 2004). This modification of the MU firing rate is called the muscle wisdom hypothesis and it works to optimize the muscle force production of the fatigued muscle (Marsden, Meadows et al. 1983, Enoka and Stuart 1992, Gandevia 2001). Windhorse (2007) proposed several mechanisms to explain this phenomenon including a diminished descending motor command and facilitation of muscle spindle afferents as well as a modification of the reflex effects caused by fatigue induced changes in the group III and IV muscle afferents (Windhorst 2007).

Modifications originating upstream of the spine also compensate for neuromuscular fatigue. This type of 'central regulation' may include changes that affect the local motor unit recruitment patterns as well as those that modify the overall motor strategy used to complete the task. Locally, the CNS compensates for neuromuscular fatigue by rotating the motor units that are recruited so that the fatigued fibers recover while the rested fibers perform the motor task (Fallentin, Jørgensen et al. 1993). On a larger scale the CNS may also modify the activity level (Turpin, Guével et al. 2011) or timing (Kanekar, Santos et al. 2008) of muscle contractions to compensate for the decreased force production capacity caused by fatigue. More details regarding this type of large-scale change in muscle activity will be assessed later on in this review of literature.

The central governor model (CGM) proposes that the fatigue-induced modification of motor strategies occurs in response to afferent feedback from the peripheral system and that these changes are designed to protect the body from injury (Noakes, St Clair Gibson et al. 2005). The CGM goes on to explain that the central nervous system assesses the

physical state of the body, predicts the length of the exercise and then determines the appropriate pace at which the body can safely function for the duration of the effort (Noakes, St Clair Gibson et al. 2005). An example of central regulation is found in Amann & Dempsey's (2008) investigation into the effect of locomotor muscle fatigue on central motor drive. In this study the quadriceps were fatigued to different levels before the participants biked for 5 km. They were asked to select their own pace but were encouraged to complete the distance as quickly as possible. The researchers found that the pre-existing fatigue had a dose dependent relationship with the central motor output in the biking trial and that this variable was controlled by the pedalling speed. In other words, despite encouragement to finish the 5 km biking task as rapidly as possible, the individuals automatically selected a pace that ensured the level of peripheral fatigue did not rise to dangerous levels. There was an inhibitory effect of the pre-existing fatigue on the central motor drive indicating that peripheral fatigue is carefully regulated by the CNS (Amann and Dempsey 2008).

Ross *et al.* (2007) also investigated central regulation by examining the impact of a marathon on ankle muscle function. While it is clear that peripheral fatigue would impact performance post-fatigue, this research group also demonstrated that there was a significant amount of central fatigue produced during the marathon and that this fatigue continued to impair the participants' ability to fully voluntarily activate their tibialis anterior for four hours post-fatigue (Ross, Middleton et al. 2007). The researchers acknowledged that there are likely several mechanisms responsible for the central fatigue produced during the marathon but noted that the CNS's regulation of peripheral function may be an important part of the body's protective mechanism.

## **Peripheral Fatigue**

In this review of literature the mechanisms of peripheral fatigue are organized by the functional impairment that they cause including changes in the neuromuscular junction signal transmission, sarcolemma excitability, excitation-contraction coupling, muscle fibre contractile mechanisms and metabolic energy supply (Bigland-Ritchie, Furbush et al. 1986, Fitts 1996, Enoka and Duchateau 2008) (Figure 1.3). Only fatigue caused by voluntary contractions will be examined in this review of literature.

### ***Signal Transmission***

Peripheral fatigue begins at the neuromuscular junction. Impairment at this site may be caused by a decreased release of acetylcholine from the pre-synaptic terminal of the nerve (Smith 1984) and/or desensitization of the end plate cholinergic receptors (Sieck and Prakash 1995); however, these types of changes are not always quantifiable in fatigue caused by voluntary contractions (Bigland-Ritchie, Kukulka et al. 1982). Exercise also causes an attenuation of the action potential propagation velocity along the sarcolemma (Bigland-Ritchie and Lippold 1979, Fowles, Green et al. 2002). This attenuation is at least partly caused by fatigue-induced changes in the efflux of potassium and influx of sodium, which renders the sodium channels less efficient (Juel 1986, Clausen, Overgaard et al. 2004).

Impaired signal transmission can be quantified by a decrease in the electromyographical (EMG) frequency spectrum (De Luca 1984), particularly during sustained maximal contractions (Ament, Bonga et al. 1993). In submaximal or intermittent contractions the frequency spectrum has been shown to increase initially due to an increased motor

neuron discharge rate (Bigland-Ritchie, Rice et al. 1995) and an increased number of motor neurons involved in the contraction (Garland, Enoka et al. 1994). Although controversial, the neuromuscular transmission and sarcolemma action potential can also be quantified through change in the amplitude and/or area of the compound muscle activation potential, also called the M-wave, which occurs in response to neuromuscular stimulation. Some research has found an association between the reduced level of force production and the reduced M-wave response during fatigue (Fuglevand, M. et al. 1993, Avela, Finni et al. 2006, Racinais, Girard et al. 2007) while other research found no change in the M-wave caused by fatiguing voluntary contractions (Kent-Braun 1999, Taylor, Allen et al. 2000). The reasons for the discrepancies between these studies are unclear; however, they are likely associated with the type of fatigue protocol and muscles used in the assessment.

### ***Excitation-Contraction Coupling***

Excitation-contraction coupling (ECC) is the process by which sarcolemma excitation is translated into force production within the muscle fibres (Enoka 1994). In a fatigued state the number of active actin-myosin cross-bridges and the force produced by these cross-bridges are reduced (Place, Bruton et al. 2008). The cross-bridge impairment is partly caused by a decrease in the amount of calcium ( $\text{Ca}^{2+}$ ) released from sarcoplasmic reticulum (SR). Several hypotheses have been proposed to explain this inhibition of  $\text{Ca}^{2+}$  release including the theory that during fatigue inorganic phosphate enters the SR and precipitates with  $\text{Ca}^{2+}$  (Allen, Clugston et al. 2011). The impairment of the cross-bridge formation may also be caused by a diminished myofibril sensitivity to  $\text{Ca}^{2+}$  (Edwards, Hill et al. 1977, Place, Bruton et al. 2008). Finally, decreased ECC force may be caused

by a fatigue induced increase in efflux of potassium ions from the muscle fibers, causing an accumulation in the lumen of the t-tubule which may block the tubular action potential and impede the ECC process (Ament and Verkerke 2009).

The effect of fatigue on ECC efficiency is quantified by comparing the force produced pre and post-fatigue in response to a neuromuscular electrical stimulation using a predetermined voltage delivered to the nerve or muscle while the muscle is at rest (Merton 1954). The resultant force is called the twitch tension or twitch torque (TT). Once the ECC efficiency has been impaired by fatigue, its impact on force production capacity remains for at least 10 minutes post-fatigue (Baker, Kostov et al. 1993, Sogaard, Gandevia et al. 2006).

### ***Metabolic Changes***

Metabolic changes, including an increased concentration of inorganic phosphate ( $P_i$ ), the depletion of muscle glycogen stores and an accumulation of lactate, are important in the neurophysiologic mechanisms behind fatigue (Brooks, Fahey et al. 2005, Ament and Verkerke 2009). In a muscle contraction adenosine triphosphate (ATP) provides energy for actin-myosin bridging and the generation of the power stroke causing sarcomere shortening (Brooks, Fahey et al. 2005, Allen, Lamb et al. 2008). In the early stages of exercise, phosphocreatine (PCr) disassociates to replenish the depleting ATP stores (Rozzi, Yuktanandana et al. 2000). Although the rising concentration of creatine (Cr) does not significantly affect muscle contractibility, the accumulation of  $P_i$  has been hypothesized to decrease contractile function (Debold, Dave et al. 2004). In exercise bouts of longer duration muscle glycogen becomes a more important source of muscular

energy (Brooks, Fahey et al. 2005). The anaerobic breakdown of glycogen causes an accumulation of lactic acid. At physiological pH, lactic acid disassociates into lactate and hydrogen ion ( $H^+$ ). The increased concentration of  $H^+$  ions is hypothesized to interfere with the contractile machinery of the muscle fibres (Rozzi, Yuktanandana et al. 2000); although, the importance in muscle fatigue has been debated (Westerblad and Allen 2002). As high intensity exercise continues, muscle glycogen stores become depleted causing further muscular fatigue. In addition to their role in peripheral fatigue, these aforementioned biochemical changes provide afferent feedback to the central nervous system, likely causing a change in the central plan for movement.

### **Contraction type on manifestation of fatigue**

Exercise induced fatigue is highly task dependent; varying with the duration, type and intensity of the muscular contraction as well with the muscle groups involved in the task (Enoka 1994). The following section will explore the manifestation and recovery of fatigue produced by different types of contractions and will briefly discuss the fatigability of different types of muscles.

#### ***Static vs. dynamic contractions***

Simple muscle contractions provide a clear description of the manifestation of neuromuscular fatigue. The type of contraction that is easiest to control experimentally is an isometric contraction in which the muscle remains at a constant length throughout the contraction. When all other variables are held consistent, the rate of fatigue is slower for this type of a contraction compared to an isokinetic contraction in which the muscle contracts at a constant external velocity. Compared to isometric contractions, dynamic

contractions cause more tissue damage (Faulkner, Opiteck et al. 1992) which likely contributes to the accelerated decrease (Christensen, Sogaard et al. 1995) and slow recovery of force production found in these contractions (Beelen, Sargeant et al. 1995).

The impact of fatigue is more difficult to evaluate during dynamic contractions since factors such as the geometry and lever arm of the muscle relative to the joint do not remain constant. Furthermore, as the muscle changes shape the electrodes move across the muscle fibers, making classic spectral analysis difficult to interpret (Merletti and Parker 2004). Finally, in a dynamic contraction the force production cannot be regulated, making it difficult to be sure that the muscle is in fact becoming fatigued. In less regulated dynamic movements fatigue analysis becomes even more difficult to assess.

### ***Contraction Intensity***

An important difference between maximal and submaximal contractions is their depletion of ATP. Although ATP fuels muscle contractions, intramuscular stores are relatively small. Therefore, ATP is resynthesized from its components during prolonged muscular activations. In a maximal muscle contraction this process cannot be maintained very long before ATP demand surpasses ATP production capacity. This rapid demand for ATP forces the muscle to rely on the less efficient anaerobic metabolic pathways resulting in metabolite accumulation causing reduced muscle contractibility (Gaitanos, Williams et al. 1993, Fitts 1996). In submaximal exercise the rate of ATP depletion is slower and the ATP can be restored during the contraction, prolonging duration of the contraction before exhaustion (Maughan 2009).

In addition to the differences in energy use, maximal and submaximal contractions tend to affect the peripheral and central systems slightly differently. For example, contractile failure has been highlighted as an important factor during maximal contractions (Bigland-Ritchie and Woods 1984) while conduction velocity seems to be an important contributing factor to the decreased motor performance during submaximal contractions (Arendt-Nielsen, Mills et al. 1989). Central fatigue develops during both submaximal contractions (Sjøgaard G 1986, Loscher, Cresswell et al. 1996, Smith, Martin et al. 2007) and maximal efforts (Gandevia, Allen et al. 1996, Todd, Butler et al. 2005); however, supraspinal fatigue is hypothesized to contribute more to the overall decreased force production capacity caused by submaximal contractions (Taylor and Gandevia 2008). In fact, research has demonstrated that 40% of the decreased force production capacity that occurs during a sustained submaximal elbow flexion is caused by supraspinal factors (Sjøgaard, Gandevia et al. 2006) while only 20% of the force reduction is caused by central fatigue in maximal contractions (Kent-Braun 1999). It is possible that maximal fatigue protocols produce just as much central fatigue as submaximal protocols but that the central fatigue contributes less to the overall decrease in motor performance because of the rapid depletion of ATP and large amount of peripheral fatigue created during the maximal effort.

Fatigue created during a submaximal contraction recovers slowly, showing effects lasting for up to 60 minutes after the exercise (Sjøgaard, Gandevia et al. 2006, Martin, Weerakkody et al. 2008). Contrarily, fatigue created during maximal contractions recovers within minutes or even seconds of the contraction (Jones, Bigland-Ritchie et al. 1978, Bigland-Ritchie and Lippold 1979).

### ***Intermittent vs. sustained contractions***

Taylor et al. (2000) compared the level of fatigue that developed during intermittent and sustained, maximal elbow flexion performed with different duty cycles (Taylor, Allen et al. 2000). They used TMS to determine that the central changes were similar between intermittent and sustained maximal contractions. Contrarily, when sustained and intermittent triceps brachii MVCs were compared, Bilodeau (2006) found important differences in the fatigue produced. In the sustained maximal contraction the central fatigue developed earlier and was greater than the fatigue created in an intermittent task. Bilodeau explained that since the motor cortex recovers quickly, the rest periods in the intermittent task were long enough to allow some recovery of the central factors. Interestingly, the peripheral measure and overall force production were similar after the intermittent and continuous contractions (Bilodeau 2006).

### ***Muscle Type***

The manifestation of neuromuscular fatigue is also dependent on the fiber type of the implicated muscles. Muscles with predominately type II, fast-twitch fibers fatigue more quickly than those with type I, slow-twitch fibers (Linssen, Stegman et al. 1991). The difference between the fatigue resistance in these two muscle fiber types is partly associated with the biochemical properties of the myofilament ATPase activity (Pette and Staron 2001). Practically, these differences cause the cross-bridge cycle rate to be slower in type I fibers relative to type II (Millar and Homsher 1992). Type I fibers are also better suited to participate in oxidative metabolism than those that are less fatigue resistant (Ament et al. 2009). Muscles that are activated for long periods of time, e.g. the soleus muscle, have a higher percentage of fatigue resistant fibers than those involved with

short, dynamic movements, e.g. the tibialis anterior muscle. In addition to muscle fiber type the structure of the muscle, e.g. fusiform vs. bipennate, and its relationship with the surrounding skeletal structure, e.g. mono or biarticular, are important factors in their fatigability.

### ***Impact of fatigue on a homologous, contralateral muscle group***

The impact of a fatigue protocol is typically examined on the fatigued muscle group. Interestingly, fatigue of one limb also affects the contralateral, homologous muscle (Todd, Taylor et al. 2003, Rattey, Martin et al. 2006). This cross-over effect has been demonstrated in the arms and legs and is hypothesized to be caused by an impairment in central drive caused by either an increased central load (Zijdewind, Zwarts et al. 1998) or a centrally mediated mechanism designed to maintain coordination post-fatigue (Rattey, Martin et al. 2006). In the upper limbs the cross-over effect of fatigue causes minimal changes in the level of voluntary muscle activation (Zijdewind, Zwarts et al. 1998, Todd, Taylor et al. 2003). In the lower limbs the cross-over of central fatigue measured in the non-fatigued homologous muscle may be more pronounced; however, the force production capacity does not seem to be affected (Rattey, Martin et al. 2006). Presently, there is a paucity of literature examining the ability of fatigue to cross from one muscle group (e.g. the arm) to a distal and unrelated muscle (i.e. the leg).

### **Impact of neuromuscular fatigue on movement strategies**

Examining the impact of fatigue on complex, multi-joint movements allows researchers to determine if and how the movement strategy is modified to compensate for neuromuscular fatigue. The modification of the motor strategy seems to depend on the

fatiguing exercise as well as on the motor task being evaluated (Enoka and Duchateau 2008). In some situations the CNS scales pre-existing muscle synergies in an attempt to meet the new requirements of the task; however, this type of scaling is often inadequate to maintain the pre-fatigue performance levels. For example, Rodacki et al. (2002) found that when the thigh extensor muscles were fatigued the participants scaled the pre-existing motor strategy in an attempt to continue to perform a vertical jump to the pre-fatigue standards. Despite the effort to maintain the pre-fatigue level of performance the fatigue protocol decreased the joint force and angular velocity of the knee joint as well as the height of the jump (Rodacki, Felix et al. 2002).

The impact of fatigue on the coordination of muscle synergies was examined in more detail in the evolution of the muscles activity that occurs during a seven minute rowing task. Similar to Rodachi et al. (2002), Turpin et al. (2011) found that the temporal activation of the muscles involved in the motor task was not modified by fatigue. Instead, the activity level of these muscles increased as the individual began to fatigue. These two studies support the theory that a limited number of robust muscle synergies are used during a motor task and that these synergies are maintained in a range of situations (Torres-Oviedo and Ting 2010, Hug 2011).

Contrarily, Billaut et al. (2005) found that a series of maximal cycle sprints caused an earlier activation of the antagonist muscles (Billaut, Basset et al. 2005). This temporal change in muscle onset did not correspond with a change in the amplitude of the integrated EMG, indicating that the ability to generate maximal neural drive was not affected by the exercise. Instead, the authors hypothesized that the modification of the

muscle coordination was caused by a centrally initiated change in the motor plan; however, it is unclear whether this modification is caused by an impairment of the CNS or by a regulated response designed to prevent peripheral muscle damage.

### **1.3 Neuromuscular fatigue on postural control**

The impact of fatigue on the motor strategy has also been explored in postural control. This section of the review of literature will examine the fatigue-induced changes in quiet and in dynamic postural control in order to provide a brief overview of how the CNS maintains postural stability post-fatigue.

Exercise induced neuromuscular fatigue affects quiet stance (Scheippati, Nardone et al. 2003) and perturbed postural control (Wilson, Madigan et al. 2006, Kanekar, Santos et al. 2008). The central nervous system compensates for this impairment through basic physiologic alterations as well as more complex sensory and strategy based changes. This section will examine the impact of peripheral and central fatigue on postural control as well as the CNS's ability to overcome these changes to maintain stability.

Many of the exercise-induced changes described in the fatigue section of this paper affect postural control. For example, peripheral fatigue impairs muscle contractibility (Allen, Clugston et al. 2011) and affects the quality of sensory feedback (Myers, Guskiewicz et al. 1999) and the effectiveness of motor output (Racinais, Girard et al. 2007). The quality of motor output is further affected by impairment of the propagation velocity of the motor output signal (Fuglevand, M. et al. 1993) and discharge rate of the alpha motoneurons (Bigland-Ritchie, Johansson et al. 1983, Davis and Bailey 1997), which may in turn affect the body's response to efferent signals from the central nervous system. Central

fatigue affects posture by decreasing the central drive and thus the motor output to the muscles (Gandevia 2001), requiring an increased muscle fiber recruitment and sense of effort (Enoka and Stuart 1992, Abbiss and Laursen 2005). Central fatigue may also alter the motor plan used to accomplish the postural task to ensure the participant's safety (Noakes, St Clair Gibson et al. 2005).

In quiet stance the presence of exercise induced neuromuscular fatigue causes a clear decrease in postural stability (Vuillerme, Forestier et al. 2002, Davidson, Madigan et al. 2004), particularly in one-legged or tandem stance (Bisson, Chopra et al. 2010). Fatigue of the muscles crossing the ankle (Lundin, Feuerbach et al. 1993, Yaggie and McGregor 2002, Corbeil, Blouin et al. 2003, Gribble and Hertel 2004), knee and hip joints (Gribble and Hertel 2004) all increase postural sway; however fatigue of proximal muscles seem to affect stability more than distal groups (Gribble and Hertel 2004). In these experiments postural instability is characterized by an increase in the center of pressure sway area and velocity (Pline, Madigan et al. 2006), joint variability (Madigan, Davidson et al. 2006) and/or latency between the muscle activity and COP movements (Mello, Oliveira et al. 2007).

The central nervous system compensates for some of these fatigue-induced impairments through physiological changes that augment the stability of the affected joints. Important changes include an increased muscle co-activation (Weir, Keefe et al. 1998, Wright, Ball et al. 2009) and an improved dynamic stretch reflex (Zhang and Rymer 2001). Under normal circumstances postural control does not require maximal muscle activation and so

the CNS is able to increase the muscle fiber motor unit recruitment to maintain the required force production post-fatigue (Leonard, Kane et al. 1994).

Sensory augmentation, described through the sensory re-weighting hypothesis, may also improve postural performance post-fatigue (Vuillerme, Nougier et al. 2001, Vuillerme and Pinsault 2007). The sensory re-weighting hypothesis explains that when afferent feedback from one system is unreliable, e.g. proprioception of a fatigued muscle, the CNS relies more heavily on the other systems, e.g. the visual and vestibular system, to provide afferent feedback (Garland and Gossen 2002, Peterka 2002, Vuillerme, Pinsault et al. 2005).

When quiet stance is disrupted by a perturbation the CNS uses compensatory postural strategies to maintain balance. When a postural perturbation is *externally* initiated, rested participants rely on afferent information from both the ankle and hip to maintain postural control. When fatigued, the involvement of the hip increases significantly (Wilson, Madigan et al. 2006). It is suggested that the post-fatigue shift to a predominately ‘hip strategy’ is correlated with increased *rectus abdominus* muscle activity, which likely increases the amount of afferent information available to the CNS. Despite the increased involvement of the hip joint, the COM displacement is not always controlled post-fatigue when the postural perturbation is externally initiated in an unpredictable manner (Davidson, Madigan et al. 2009).

When quiet stance is disrupted by an self-initiated postural perturbation, such as a voluntary movement of the arms, participants activate their postural muscles in advance of perturbation to minimize the destabilizing effects (Cordo and Nashner 1982). Fatigued

participants activate their postural muscles even further in advance of the perturbation (Strang and Berg 2007) with smaller burst amplitudes and an increased rate of muscle co-activation (Kanekar, Santos et al. 2008) relative to when they are rested. These anticipatory postural adjustments (APAs) allow fatigued individuals to improve control of their COM displacement; however, further research is required to understand whether it is the self-initiated nature of the postural task that allows these participants to remain stable post-fatigue or if they would be able to perform a similar postural adaptation to externally initiated postural perturbations that are predictable in nature.

Participants demonstrate a similar or 'common' response to postural perturbations regardless of the postural muscles that are fatigued. This common response suggests that the post-fatigue postural modification is centrally, as opposed to peripherally, mediated (Morris and Allison 2006). For example, Kanekar et al. (2008) found that hamstring and deltoid muscle fatigue caused a similar increase in anticipatory muscle co-activation of the calf muscles during self-initiated postural perturbations (Kanekar, Santos et al. 2008). In an externally initiated postural perturbation Davidson et al. (2009) found that fatigue of either the ankle plantar-flexors or the lumbar muscles resulted in increased COM displacement, decreased COP displacement and increased COP displacement velocity in response to an external perturbation (Davidson, Madigan et al. 2009). While the results from these two experiments suggest that central mediation controls posture post-fatigue, the presence of peripheral fatigue convolutes the findings.

To clarify the influence of central changes on post-fatigue postural control, Strang et al. (2009) examined the impact of an isokinetic fatiguing contraction on the anticipatory

postural activity found in non-fatigued muscles (Strang, Berg et al. 2009). They found that after fatigue of the right thigh both the fatigued and non-fatigued postural muscles were activated earlier in anticipation of a self-initiated postural perturbation. These changes reflect a general shift to a more conservative postural strategy designed to overcome the destabilizing effects of neuromuscular fatigue. However, the post-fatigue central changes do not always improve postural stability. Paillard et al. (2010) found that thigh muscle fatigue of one leg impaired unilateral postural control of the contralateral thigh (Paillard, Chaubet et al. 2010). The authors suggested that the change in postural control was central in nature, resulting from an impairment of the descending central drive to the motor units of the balancing leg or from inhibitory effects of group III and IV muscle afferents. The latter study did not verify whether the fatigue protocol created fatigue in the muscles surrounding the hips or the contralateral leg. If peripheral fatigue were present in these muscle groups, it would have certainly contributed to the impaired postural stability. Further research is required to elucidate the role of central fatigue on postural control.

### ***Conclusion***

The manifestation of neuromuscular fatigue involves changes at every level of the neurophysiological system from the biochemical modifications occurring within the muscle fibres to the altered descending central drive. It is clear that these systems interact with one another in order to protect our bodies from irreversible damage (Noakes, St Clair Gibson et al. 2005), allowing us to maintain motor performance in sport or everyday life. However, the CNS is not always able to prevent fatigue-induced changes. This is especially evident in simple maximal isometric muscle contractions where the

CNS is not able to compensate for the fatigued muscle fibres. As the degrees of freedom of the task increase, the CNS uses compensatory strategies to increase stability or motor performance. As this compensation increases it becomes substantially more difficult for researchers to differentiate between fatigue induced impairments and CNS compensation.

## 1.4 Aim of Dissertation

As discussed in the review of literature, the impact of fatigue on postural control is not well understood. This is particularly true in dynamic postural tasks where young healthy participants use anticipatory postural responses to compensate for externally initiated, destabilizing perturbations. Therefore, **the overarching aim of this dissertation was to investigate the impact of central and peripheral fatigue on the motor planning strategies used by the central nervous system to compensate for externally initiated but predictable postural perturbations.** The complexity of the postural task and the manifestation and recovery of exercise induced fatigue made it clear that several research questions needed to be answered before it would be possible to understand the influence of fatigue on the response to this particular postural task. Therefore, this main objective was accomplished through a series of five experimental studies that built upon one another to increase our understanding of peripheral and central fatigue on postural control. The rationale behind the development of each of these studies is presented in figure 1.4. The objectives and hypotheses of each of these five studies are as follows:

Study 1: **Adaptation Study.** The overall aim of Study 1 was to identify the point at which participants reached a steady state in their postural adaptation in order to meet the requirement of the postural task. The specific objectives of this study were to determine whether the improvement that occurs during one, continuous postural trial translated to subsequent continuous postural trials. This study also quantified the amount of practice required to reach a steady postural response that did not improve with further practice. The results from this experiment ensured that the postural tests were designed to avoid the learning effects in the post-fatigue postural changes.

The main hypothesis was that the improvement in postural response that occurred over one postural trial would translate to subsequent trials as demonstrated by earlier muscle onset latencies and decreased COP displacement. In addition, it was postulated that the muscle onset latencies and COP displacement would become consistent *before* ten minutes of practice and that the COM displacement would remain consistent throughout the adaptation process.

**Study 2: Characterization of ankle muscle fatigue.** Exercise produces both central and peripheral fatigue. Without careful quantification it is difficult to determine the influence these factors have on subsequent motor tasks. Therefore, the main objectives of Study 2 were to quantify the central and peripheral fatigue created by intermittent, bi-directional ankle plantar and dorsiflexor contractions and to document the recovery of central and peripheral fatigue for ten minutes post-fatigue. It was hypothesized that central and peripheral fatigue would both contribute to the overall decrease in force production capacity of the ankle muscles and that the proportion of peripheral and central fatigue would differ between the ankle plantar and dorsiflexor muscle groups. It was also hypothesized that the quantifiable central changes would recovery substantially faster than the peripheral fatigue.

**Study 3: Ankle muscle fatigue on postural control.** The next step in this research process was to determine the impact of the ankle plantar and dorsiflexor muscle fatigue protocol on postural control. The results from the first study were used in the design of the posture protocol and determined the amount of practice required before the fatigue protocol was implemented. The fatiguing exercise used in the second study were repeated

in this study, allowing the results of the study to be interpreted with respect to the manifestation and recovery of the peripheral and central fatigue quantified in Study 2. The objectives of Study 3 were to examine the impact of the bidirectional ankle fatigue protocol on the postural response to predictable, continual postural perturbations in the anterior/posterior direction immediately post-fatigue and as the peripheral and central fatigue subsided during a ten-minute post-fatigue testing session. It was hypothesized that the participants would be able to maintain their balance, as quantified by the displacement of the COM relative to the BOS, post-fatigue by activating their postural muscles in advance of the postural perturbation, decreasing their COP displacement and increasing the incidence of ankle muscle co-activation. Furthermore, it was predicted that the postural response would return to a pre-fatigue pattern as the ankle muscle force production capacity returned to the pre-fatigue levels. This posture study provided a detailed depiction of the impact of postural muscle fatigue on the CNS's control of posture; however, the role of central fatigue was still ambiguous.

Experiments four and five were designed to isolate and characterize the central fatigue produced during exercise of a non-postural muscle group and to assess the impact on ankle motor function and on postural control. The forearm muscles were not involved in the postural task studied and so they were fatigued using a sustained, isometric bilateral handgrip contraction. Since the forearm muscles were not used in the postural task it was postulated that any postural changes found after the forearm contraction would be caused by central fatigue.

Study 4: **Characterization of forearm muscle fatigue.** The main aim of Study 4 was to characterize the central and peripheral fatigue created in the forearm muscles after a maximal and a submaximal isometric, fatiguing forearm contraction and to determine if and how central fatigue created in the forearm muscles affected ankle muscle activation and force production. Data were collected immediately post-fatigue and throughout a ten-minute recovery period. It was hypothesized that the submaximal forearm fatigue protocol would produce more central fatigue and affect handgrip force production longer than the maximal fatigue protocol. It was also predicted that the central fatigue created in both fatigue protocols would reduce the level of voluntary muscle activation but that the force production capacity would not be affected. Finally, it was hypothesized that any impact that central fatigue had on the ankle plantar-flexors would dissipate rapidly post-fatigue but that the peripheral fatigue created in the forearm muscles would linger until the end of the ten-minute post-fatigue testing session.

Study 5: **Forearm muscle fatigue on postural control.** The main objectives of Study 5 were to examine the impact of the forearm fatigue protocol from Study 4 on the postural response to predictable, continual postural perturbations in the anterior/posterior direction and to quantify any changes in the post-fatigue postural response that occurred as the forearm muscle fatigue subsided. It was hypothesized that the postural strategy used during the perturbed postural control task would be altered immediately after the forearm fatigue protocol, showing an earlier postural muscle onset latency, an increased muscle co-activation and a decreased COP displacement. It was also predicted that the recovery of the postural strategy would coincide with the dissipation of afferent feedback from the fatigued forearm muscles.

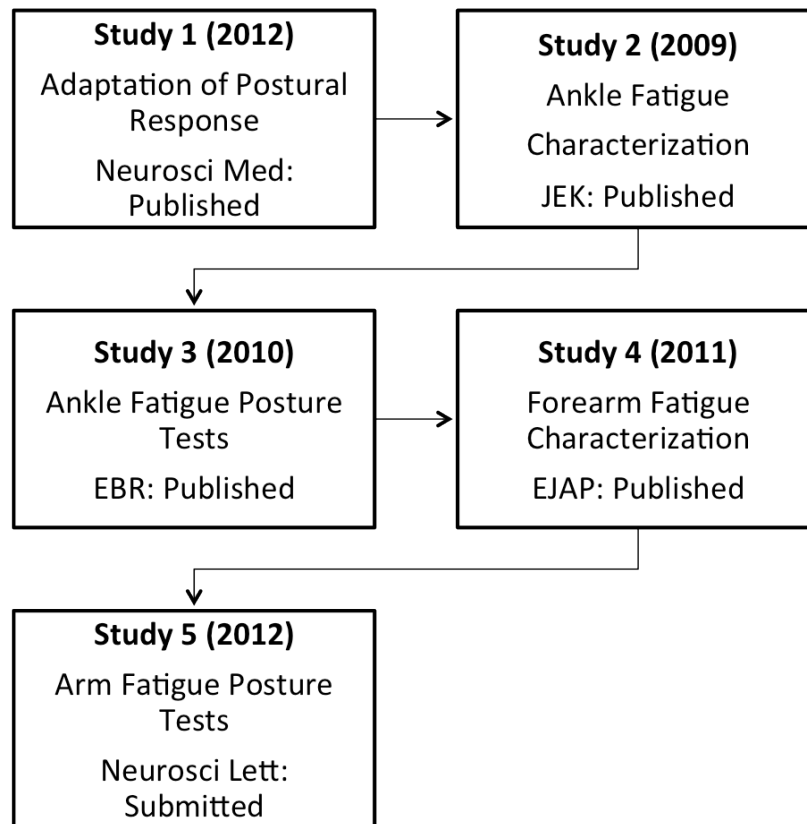


Figure 1.4 Rational for the experimental design of the dissertation. This diagram depicts the logic behind the five studies performed in this doctoral dissertation. Study 1 ensured that the post-fatigue posture tests were performed after the participants had already adapted to the postural task. This study confirmed that the changes found post-fatigue were caused by the fatigue protocol and not by an extended learning period. Study 2 quantified the manifestation and recovery of the ankle plantar and dorsiflexor muscles after a bilateral ankle contraction. Study 3 assessed the impact of the ankle fatigue on postural control. Study 4 quantified the central and peripheral fatigue created in the forearm and ankle plantarflexor muscles during and after a sustained forearm contraction. This study confirmed that the forearm fatigue protocol did not produce peripheral fatigue within the postural muscles but that central fatigue was present immediately after the contraction. Study 5 assessed the impact of the fatiguing forearm contraction on postural control in order to gain insight into the impact of central fatigue on postural control.

## **1.5 Limitations**

In the postural experimental protocols information about the participant's general level of activity was collected; however, specific questions regarding their athletic history outside whether or not they were elite athletes or dancers was not gathered. This information would have been helpful in explaining variability in how different participants compensated for neuromuscular fatigue, particularly that occurring in the ankle muscles, during the postural perturbations. It would have also been helpful to measure physiological and/or emotional effects of anxiety caused by the fatigue protocol as anxiety has been shown to change the postural strategy used by participants (Carpenter, Frank et al. 2004).

In the two fatigue characterization studies we quantified central fatigue as a decreased level of voluntary activation (VA) of the affected muscles. While the VA provides a sensitive measure of the decreased central output (Bilodeau 2006), it is unable to differentiate between the changes occurring within the peripheral nerves, the spine and the higher planning centers. Furthermore, the VA calculations are partly based on the control twitch torque (TT) and so a substantial decrease in the TT could have caused an artificially high measure of central fatigue.

In the forearm muscle fatigue characterization study measures were taken to isolate the medial nerve, located proximal to the cubital fossa; however, we were unable to confirm that the ulnar nerve was not also stimulated by the 2 X 2 cm electrode used in this experiment. This limitation prevented publication of data describing the manifestation and recovery of central and peripheral fatigue in the forearm muscles.

**Chapters 2, 3, 4, 5, and 6 have been submitted to peer-reviewed journals and are formatted accordingly. All studies were approved by the University of Ottawa, Health Science Research Grants and Ethics Services.**

**Chapter 2:** Adaptation of the feedforward postural response to repeated continuous postural perturbations

In press: Neuroscience & Medicine (2013)

# Adaptation of the feedforward postural response to repeated continuous postural perturbations

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## 2.1 Abstract

We examined the adaptation of the postural response to repeated predictable platform oscillations. Our main goals were to determine whether the short-term changes that occurred during a minute long continuous postural perturbation trial were maintained in subsequent trials and to determine how many trials were required before participants fully adapted to the postural task. Ten participants performed ten minute-long postural trials on a platform that oscillated at 0.25 Hz before increasing to 0.50 Hz half way through each trial. Postural muscle onset latencies, burst amplitudes, and anterior posterior displacements of the center of pressure (COP) and center of mass (COM) were calculated for the last five cycles performed in each trial at 0.50 Hz. The postural strategy evolved in two phases: 1) immediate decrease in COP displacement, 2) earlier activation of the postural muscles with smaller muscle burst amplitudes. After seven trials the postural response remained consistent.

**Keywords:** adaptation, postural control, continual perturbations

## 2.2 Introduction

Postural stability is maintained during externally initiated perturbations through modifications of the postural muscle activity and center of pressure (COP) displacement [1-4]. These changes allow effective control of postural stability in novel conditions; however, they may be initially inefficient, requiring a high level of tibialis anterior (TA) and soleus (Sol) muscle activity [5]. With further experience short-term adaptation occurs, allowing the participants to tailor their postural response to meet the requirements of the environmental and internal variables [6, 7].

In discrete postural perturbations experience provides participants with performance feedback resulting in activation of postural muscles earlier in advance of the perturbation and at smaller muscle burst amplitudes [8]. Postural adaptation also occurs during continuous, sinusoidal oscillations of the platform [5, 9-11]. In this type of recurrent, continual perturbation the postural response evolves rapidly to meet the environmental requirements. In fact, within only 3 to 5 sinusoidal platform oscillations young healthy adults transition from a reactive to an anticipatory postural response [10, 11].

It is clear that short-term changes occur during both discrete and continuous postural perturbations; however it has not been determined whether the rapid changes that occur during one postural trial are maintained in the steady state postural response of subsequent trials. To address this question we examined how postural muscle activity, center of mass and center of pressure displacement changed over the steady state of 10 distinct continuous postural trials. The secondary aim of this study was to determine how many trials were required for the participant to reach a stable and consistent postural response. We hypothesized that it would take several trials for the postural response to reach this point and that once the response was stabilized; the ankle muscles would be consistently activated earlier in anticipation of the postural perturbation with smaller muscle burst amplitudes [8]. Since the COM is a priority variable in dynamic postural control [12], we hypothesized that it would be maintained while the COP displacement adapted to meet the environmental and task requirements.

## 2.3 Methods

### Participants

Ten (five men, five women) young healthy subjects (aged 19-27; men height  $180.8 \pm 6.3$  cm, weight  $77.8 \pm 10.4$  kg; women height  $166.7 \pm 17.7$  cm, weight  $57.6 \pm 9.4$  kg) with no neurological impairment or history of serious injury that prevented them from participating in sport for more than 6 months gave informed consent to participate in this study. Elite athletes (collegiate level or higher) and dancers (participation more than four times/week) were excluded from the sample. The experimental procedures were approved by the ethics board at the University of Ottawa and were performed in accordance with the Tri-Council Policy Statement [13].

### Measurement Devices

Data from seven VICON cameras (Vicon Peak, Oxford, UK) and thirty-six retro-reflective markers, placed on anatomical landmarks and on four corners of the force plate, were used to estimate the position of the center of mass (COM) and the platform during the postural trials. A movable platform instrumented with a Kistler force plate (Type 9286, Kistler Instrument Corp, New York, USA) was used to record the ground reaction forces at 500 Hz during the postural trials (Nexus, Vicon Peak, Oxford, UK). Kinematic data were recorded at 200 Hz.

Surface electrodes (Myomonitor Wireless Delsys EMG system, Boston, USA) recorded electromyographical (EMG) activity from the gastrocnemius medialis (GM), biceps femoris (BF), tibialis anterior (TA) and rectus femoris (RF) in accordance with SENIAM recommendations [14]. A ground electrode was placed on the patella. The EMG signals were pre-amplified, sampled at 1000 Hz and full wave rectified.

### Procedure

Ten postural trials, each consisting of ~ 60 seconds of continuous, sinusoidal oscillations of the platform in the anterior/posterior direction, were performed. Fifteen seconds of rest was afforded between each postural trial. During the trials participants stood barefoot with their eyes open and feet shoulder width apart on the platform as it oscillated 20 cm in the anterior-posterior plane (for further details see Bugnariu and Sveistrup 2006). In each postural trial,  $8 \pm 2$  oscillations were performed at 0.25 Hz before the frequency of oscillation increased to 0.50 Hz for another  $10 \pm 2$  cycles.

## Data Analysis

The VICON Plug-in Gait biomechanical model, combined with anthropometric measurements and kinematic data, was used to estimate the forward and backward displacement of the center of mass (COM). The anterior/posterior movement of the platform was subtracted from the COM data in order to provide a true representation of COM displacement relative to the base of support. Ground reaction forces were used to estimate the maximum anterior/posterior COP displacement.

Muscle burst onsets were determined using a two standard deviation threshold derived from the quiet stance period that occurred before every trial. Once the thresholds were identified (BioProc version 3.06, D.G.E. Robertson), muscle onset latencies were visually coded relative to the start of the forward or backward platform translations. Muscle onsets occurring in anticipation of the platform movement were coded as negative. Dynamic responses had to be recorded in at least 25% of the directionally specific oscillations in order to be included in calculations of group muscle onset latencies.

The COM and COP displacement, muscle onset latency and amplitude of the TA, GM, RF and BF were analyzed for the first (T1), third (T3), fifth (T5), seventh (T7) and tenth (T10) trials. In each trial, the values for the last five cycles at 0.50 Hz were averaged [10]. Data were ensemble averaged across participants in each of the time periods and reported for forward and backward platform translations separately.

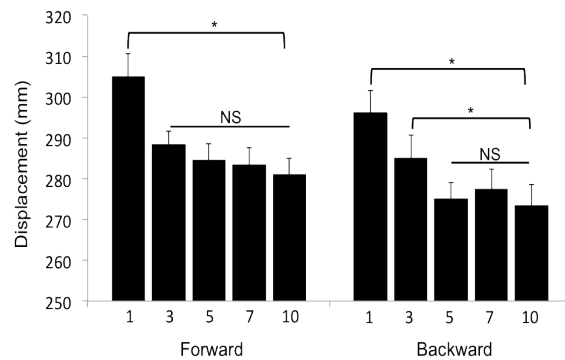
## Measurement Devices

Repeated measures analyses of variance (ANOVA) tests were used to determine whether COP and COM displacement and muscle burst amplitudes adapted with experience following forward and backward oscillations. Post-hoc analyses performed with Tukey corrections were used to determine the point at which no further adaptation occurred. Muscle onset latencies of the four postural muscles were not normally distributed so significant differences between trials were determined using non-parametric Wilcoxon sign-ranked tests.

## 2.4 Results

### COM and COP displacement

The COM displacement did not adapt over the 10 postural trials for the forwards ( $F(4, 36) = 0.654, p > 0.05$ ) or backwards ( $F(4, 36) = 0.345, p > 0.05$ ) oscillations (data not shown). There was, however, a main effect of trial for the COP displacement in response



**Figure 1. Center of pressure (COP) displacement during forward and backward translation of the platform.** Following forward platform translation, the amplitude of COP displacement decreased significantly after the first trial (T1) with no further decrease through to the 10<sup>th</sup> trial (T10). Following backwards translation, the COP decreased until the fifth trial (T5), with no additional decrease. Data displayed as mean ± SE. \* indicates  $p < 0.05$  and NS indicates no significant difference.

to the forwards ( $F(4, 36) = 5.34, p < 0.05$ ) and backwards ( $F(4, 36) = 4.02, p < 0.05$ ) oscillations (Figure 1). Post-hoc analysis revealed that in forward direction the COP displacement decreased from  $305.0 \pm 5.6$  mm at T1 to  $288.1 \pm 3.8$  mm at T3 ( $p = 0.002$ ). The COP displacement then stabilized, showing no significant adaptation between T3 and T5 ( $p = 0.387$ ), T5 and T7 ( $p = 0.775$ ) or T7 and T10 ( $p = 0.625$ ) (Figure 1). In the backwards direction the COP displacement decreased ( $F(4, 36) = 4.02, p < 0.05$ ) from  $296.0 \pm 5.5$  at T1 to  $285.0 \pm 5.6$  at T3 ( $p = 0.045$ ) and again to  $275.1 \pm 3.9$  at T5 ( $p = 0.043$ ). After this point the COP displacement did not change further (T5 to T7  $p = 0.318$  and T7 to T10  $p = 0.708$ ).

### Muscle Burst Amplitude

The TA muscle burst amplitude adapted to the postural task over the first five trials ( $F(4, 36) = 20.268, p < 0.05$ ) with a significant decrease between the amplitude found at T1 and T3 ( $p = 0.01$ ) and between T3 and T5 ( $p = 0.019$ ). There was no further decrease between T5 and T7 ( $p = 0.053$ ) or T7 and T10 ( $p = 0.686$ ). The muscle burst amplitude of the GM also adapted throughout the postural trials ( $F(4, 36) = 10.133, p < 0.05$ ), decreasing significantly between T1 and T3 ( $p = 0.001$ ). There was no further decrease between T3 and T5 ( $p = 0.299$ ), T5 and T7 ( $p = 0.21$ ) or T7 and T10 ( $p = 0.274$ ). The RF muscle burst amplitudes, which were only assessed for trials T1, T5, T7 and T10, showed a significant main effect of adaptation ( $F(3, 27) = 3.294, p < 0.05$ ); however, post-hoc analysis did not reveal any specific

locations of change throughout the 10 minute training period. The BF muscle amplitude, assessed for T1, T7 and T10, also showed a significant main effect of adaptation ( $F(2, 18), 3.805, p < 0.05$ ). Post-hoc analysis did not reveal any specific location of change between these time points.

### Muscle Onset Latency

The TA muscle onset latency adapted to the postural task over 10 trials ( $X^2(4, 10) = 12.12, p < 0.05$ ). There was no change between T1 and T3 ( $p = 0.385$ ) or T3 and T5 ( $p = 0.58$ ); however, the TA was activated significantly earlier at T7 than it was at T5 ( $p = 0.017$ ) with no further change in the onset latency between T7 and T10 ( $p = 0.35$ ). The GM muscle onset latency also adapted to the postural task ( $X^2(4, 10) = 7.2, p < 0.05$ ). There was no difference between the onset latency found at T1 and T3 ( $p = 0.110$ ) but the GM muscle was activated significantly earlier at T5 than it was at T3 ( $p = 0.041$ ). After this point there was no further change in the GM muscle onset latency (T5 and T7  $p = 0.929$ , T7 and T10  $p = 0.859$ ) (Figure 2). Due to the infrequent muscle bursts, statistical analysis was only performed on the RF muscle onset latency at T1, T5, T7 and T10 and on the BF muscle onset latency at T1, T7 and T10. Adaptation did not occur over these time points for either the RF ( $X^2(3, 3) = 7.4, p > 0.05$ ) or BF ( $X^2(4, 2) = 1.5, p > 0.05$ ).

### 2.5 Discussion

The aim of this study was to determine how the postural response adapted to meet the requirements of the motor task as well as to establish the point at which the motor task no longer changed with further experience. The hypothesis that the COM displacement would be maintained was based on previous research showing that

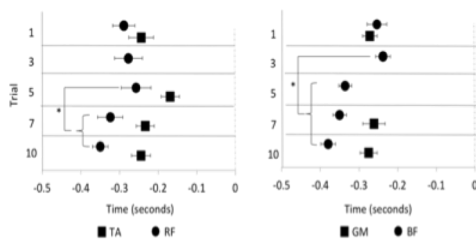
the COM displacement is a performance variable that is preferentially controlled using muscle activity and individual joint motion in postural tasks [5, 15]. The data from the present study confirmed our hypothesis, showing no change in the COM displacement over the 10 postural trials.

We also hypothesized that with experience the COP displacement and muscle activity would be progressively modified to maintain control of the COM in a more efficient way. Data from this study confirmed our hypothesis, showing a progressive adaption of the postural response throughout the first seven trials, after which point it no longer evolved. This adaptation process occurred in two phases beginning with a decrease in the COP displacement (Figure 1), followed by an earlier activation of the postural muscles at a smaller muscle burst amplitude (Figure 2). This process is well described by the modified systems theory in which the participant initially constrains the body's degrees of freedom to improve motor control. Practice then optimizes the movement, improving the efficiency and adaptability of the task, allowing the participant to take advantage of the increased degrees of freedom [7].

At the start of the first phase the COP displacement was quite large; however, the transition towards a more conservative postural response occurred rapidly, causing a significant decrease in the COP displacement between the first and third postural trials in both the forward and backwards directions. Similar to the temporal evolution of the postural kinetics found in previous research [16], the COP displacement measured in this study reached a stable level after 5 postural trials. After these initial changes the COP displacement no longer evolved with further experience, marking the end of the first phase of postural adaptation.

In the second phase of adaptation the postural response became more energy efficient. The postural muscles were recruited progressively earlier during this phase, reaching a stable level after 7 oscillations in the forward direction and 5 in backwards direction (Figure 2). Interestingly, these muscles were activated with smaller muscle burst amplitudes than were used in the first phase of adaptation (data not shown). Previous research has shown a similar decrease in the burst amplitude of the postural muscles as participants become more experienced with discrete [8] and continuous [5] postural perturbations, although no one has examined the evolution of the postural response from one continuous postural trial to the next. We postulate that these changes in muscle activity represent the optimization of the postural response to avoid fatigue and/or to reduce the expenditure of energy required for the task [7].

In conclusion, the data from this study demonstrated that young healthy participants transferred the experience gained in one postural trial to subsequent trials. With



**Figure 2. Muscle onset latencies of the tibialis anterior (TA) and rectus femoris (RF) coded relative to forward surface translations and the gastrocnemius medialis (GM) and biceps femoris (BF) coded relative to the backwards surface translation. The TA and GM muscles were activated progressively earlier with experience. At some time points the RF and BF muscles were activated too infrequently to run statistical analyses (depicted by missing data); however, the onset latency did not change between the trials in which there were enough muscle bursts to assess statistically. Data displayed**

experience the COP displacement decreased and the postural muscles were activated earlier in anticipation of the perturbation with smaller muscle burst amplitudes. After seven, minute long trials, the anticipatory postural response no longer evolved with further experience. Experimental manipulations of factors influencing postural control, such as augmented feedback and/or fatigue, should be performed after this point to ensure that the postural changes found in the performance of the motor task are due to the experimental manipulation and not to the adaptation process.

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**Chapter 3: Neuromuscular fatigue induced by alternating isometric contractions of the ankle plantar and dorsiflexors**

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# Neuromuscular fatigue induced by alternating isometric contractions of the ankle plantar and dorsiflexors

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### **3.1 Abstract**

Ankle muscle activity is important in regulating postural control as well as more complex movement tasks. Fatigue of these muscles clearly influences postural stability; however, the mechanisms responsible for this change have not been well characterized. In this study the fatigue produced in the plantar (PF) and dorsiflexors (DF) during intermittent, isometric contractions was examined and the recovery process was monitored for ten minutes post-fatigue. Fifteen healthy participants alternated between isometric PF and DF contractions until the torque was reduced to  $> 50\%$  of the pre-fatigue maximal voluntary contraction level in both directions. Peripheral fatigue was identified by measuring the change in the twitch torque and M-wave amplitude pre and post-fatigue. Central fatigue was determined by comparing the level of voluntary activation in the PF and DF between pre and post-fatigue. The fatigue protocol decreased the torque production in PF and DF to similar levels; however, the characteristics and recovery of the fatigue were different for the two muscle groups. This study demonstrates that although the torque produced by two antagonist muscles can be reduced to the same level, the mechanisms responsible for this change may not be similar and therefore may not impact motor tasks in the same way.

**Keywords:** central and peripheral factors, recovery, twitch, voluntary activation

### **3.2 Introduction**

Neuromuscular fatigue is defined as the decline in maximal torque or power output that a muscle can produce following sustained activity (Enoka and Duchateau, 2008). However, the process of fatigue is gradual and includes important physiological changes that occur before and during the mechanical failure. In fact, fatigue-related processes can take effect with the onset of any muscle contraction whether or not the functional goal is impacted (Hoffman et al., 2009). While the deleterious effects of neuromuscular fatigue have been demonstrated in simple torque production (Merton, 1954; Kawakami et al., 2000) and joint stability (Rozzi et al., 1999; McLean et al., 2007), fatigue also impacts complex motor tasks such as running (Christina et al., 2001), jumping (Chappell et al., 2005) and cutting (McLean et al., 2007). Interestingly, the central nervous system (CNS) is often able to compensate for the effect of neuromuscular fatigue on motor tasks. Postural control, for example, is maintained post-fatigue by alterations in the center of pressure (COP) displacement (Gribble and Hertel, 2004; Wilson et al., 2006; Davidson et al., 2009; Bisson et al., 2010). In order to understand the CNS's compensatory strategies it is important to first identify and quantify the fatigue being produced by specific activities.

Neuromuscular fatigue occurs at multiple locations from the motor cortex (Taylor et al., 2006) and spinal cord (Butler et al., 2003) to individual muscle fibres (Cresswell and Loscher, 2000; Enoka and Duchateau, 2008). The location of fatigue, divided into central and peripheral levels, dictates the influence it will have on motor tasks. Peripheral fatigue reduces the muscles' ability to produce torque by impairing the system at and distal to the neuromuscular junction (Enoka and Stuart, 1992). Specific mechanisms of peripheral fatigue include the reduction of the action potential propagation across the neuromuscular junction (NMJ) and along the muscle fibre (Sieck and Prakash, 1995), as well as changes in the excitation-contraction coupling mechanisms within the muscle fibres (Bigland-Ritchie and Woods, 1984; Nordlund et al., 2004). Central

fatigue, on the other hand, occurs proximal to the NMJ and progressively impairs the CNS's capacity to fully activate a muscle (Gandevia et al., 1996). This impairment may be due to physiologic and/or cognitive factors. The central governor model suggests that central fatigue prevents peripheral injury (Noakes et al., 2005); however, metabolically induced impairment in the central processor may also be involved in changes in central drive (Davis et al., 2003) and may impact the efficiency with which motor tasks are performed (Meeusen et al., 2006).

Central and peripheral factors impact the neuromuscular system differently. While some studies have quantified both the central and peripheral fatigue induced by a sustained exercise performed with the ankle plantar (PF) (Kawakami et al., 2000) or dorsiflexors (DF) (Kent-Braun, 1999), the contribution of central and peripheral fatigue has not been examined when the PF and DF are fatigued simultaneously. The recovery in both central and peripheral fatigue characteristics that occurs between the end of the fatigue protocol and the start of a subsequent motor task have not been quantified for the ankle muscles. Since components of fatigue, especially those associated with central fatigue, begin to recover rapidly after a fatiguing exercise, it is important to quantify these changes before examining the impact of neuromuscular fatigue on subsequent motor tasks.

The aim of this study was to characterize the fatigue and recovery of muscles involved in postural control (i.e. ankle plantar and dorsiflexor muscles) induced by an alternating flexor/ extensor isometric exercise and a 10-min post-fatigue recovery period. We hypothesized that the reduction in torque generating capacity would be caused by both central and peripheral fatigue and that the balance between these two types of fatigue would be different between PF and DF muscles.

### **3.3 Methods**

#### *Participants*

Fourteen healthy subjects (5 women and 9 men; ranged from 19 to 40 years; height  $177.1 \pm 7.9$  cm; weight  $68.4 \pm 10.6$  kg) without any neurological disorders or motor problems volunteered for this study. Participants were informed about the nature of the experimentation before giving written consent to the experimental procedure. This study was approved by a local ethics committee and conducted according to the Helsinki declaration (last modified 2004).

### *Experimental Setup*

Participants were seated with their legs fully extended and their trunk reclined  $30^\circ$  from vertical. Participants were strapped to the seat across the chest, waist, thighs and legs to prevent movement. They were asked to place their arms across their chest during the contractions. Each foot was strapped into a separate custom designed metal force pedal at  $10^\circ$  plantar flexion to ensure efficient muscle contraction of the PF and the DF (Fukunaga et al., 1996; Simoneau et al., 2007). Each pedal was instrumented with a force transducer (91 kg capacity; Intertechnology Inc. Don Mills, Ontario, Canada). Torque signals were amplified (Calex, Concord, CA, USA) and then digitized (low-pass filter of 200 Hz) at a sampling rate of 4kHz (Bagnoli 16, Delsys Inc, Boston, USA). Throughout the experiment, the PF and DF torque signals were displayed on a monitor placed in front of the subjects. The torque and EMG signals were sampled synchronously.

### *EMG Recording*

Bipolar surface electromyographic (EMG) signals were recorded with dry-surface electrodes (DE-2.1, Delsys<sup>®</sup> Inc., Boston, MA, USA; 1 cm inter-electrode distance) placed on the medial (MG) and lateral gastrocnemius (LG), the soleus (SOL), the tibialis anterior (TA), the rectus femoris (RF) and the long head of biceps femoris (BF) muscles of the dominant leg. The EMG

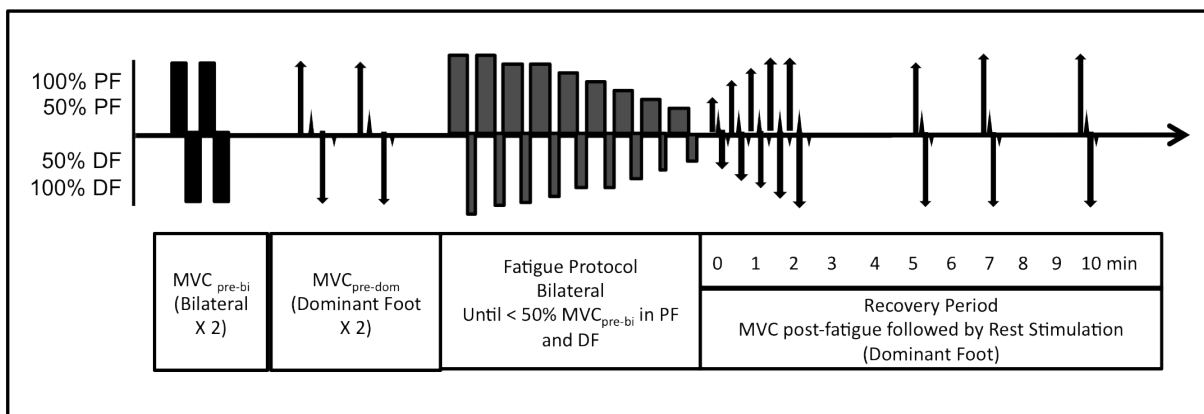
from the BF and the RF muscles were assessed to quantify any change in the contribution of the thigh muscles during the fatigue process. The electrodes were placed longitudinally with respect to the underlying muscle fibre arrangement, distal to the motor point in accordance with SENIAM recommendations (Hermens et al., 2000). A reference electrode was placed on the medial malleolus. Prior to electrode placement, the skin surface was cleaned with alcohol and shaved in order to minimize impedance. EMG signals were amplified (x1000) and digitized (bandwidth of 6 - 400 Hz) at a sampling rate of 4 kHz (Bagnoli 16, Delsys Inc, Boston, USA).

### *Electrical stimulation*

Twitch contractions of the PF and the DF muscles were elicited by alternating electrical stimulation of the tibial nerve, located in the popliteal fossa, and the deep fibular peroneal nerve, located 1-2 cm below the lateral condyle of the femur. One cathode was placed slightly distal to the patella and was used for both anodes. A conductive probe was used to find the specific nerve locations that provided the largest mechanical muscular response. When this location was found, 2 x 2 cm surface electrodes (Compex, Annecy-le-vieux, France) were fixed over the tibial (Scaglioni and Martin, 2009) and common peroneal nerves (Burrige and McLellan, 2000). A constant current stimulator (Digitimer DS7A, Digitimer Ltd, Letchworth Garden City, UK) delivered single electrical pulses (pulse duration = 200 $\mu$ s) through these electrodes. To find the appropriate intensity the stimulation began low and was incrementally increased (incremental step = 5mA, from 400 V) until there was no further increase in torque production by the stimulated muscle group (mean maximum current for PF= 102  $\pm$  31 mA, DF = 37  $\pm$  12 mA).

### *Procedures*

The ankle fatigue protocol consisted of four parts: warm-up, pre-fatigue, fatigue and recovery (Figure 1). In the warm-up session the participant became familiar with the alternating PF and DF contractions on the force pedals. The participants completed five sets of six repetitions of continuous alternating isometric contractions at 10, 25, 50, 75 and 100 % of their perceived maximal effort. The participant was afforded a 1-min rest between each set and a five minute recovery before the pre-fatigue testing period.



**Figure 3.1. Schematic representation of the experimental protocol.** *The protocol was divided into 4 sections. 1) Two **pre-fatigue MVCs** performed bilaterally ( $MVC_{pre-bi}$ ) in PF and DF (represented by the rectangles). 2) Two **pre-fatigue PF and DF MVCs** performed on the dominant foot ( $MVC_{pre-dom}$ ) with a supra-maximal percutaneous stimulation superimposed on each contraction (represented by an arrow) and delivered immediately after the contraction when the muscle was at rest (triangle following the arrow). 3) The bilateral **fatigue protocol** (represented by the grey rectangles) alternated 6 s in plantar-flexion and 2 s in dorsi-flexion and continued until the participant's torque production was reduced to < 50% of the  $MVC_{pre-bi}$  for at least three consecutive contractions in both plantar and dorsiflexion. 4) The **recovery period** consisted of dominant foot MVCs (with supra-maximal stimulations delivered during and immediately after each contraction) performed every 30 s for the first 2 mins and at 5, 7 and 10 min post-fatigue.*

Pre-fatigue: Two isometric maximal voluntary contractions (MVC) in PF and DF were executed with both legs and the largest MVC in each direction was used to determine the level of contraction for the fatigue protocol. The non-dominant leg was then removed from the pedal set-

up and two additional MVCs were performed in PF and DF using only the dominant leg ( $MVC_{pre-dom}$ ). A single pulse of electrical stimulation was delivered during and another immediately after each  $MVC_{pre-dom}$ .

**Fatigue:** The fatigue protocol was performed with both feet. Due to the physiological differences in the PF and DF muscles (Belanger et al., 1983), pilot work was done to determine the intensity and duration of contractions that provided simultaneous fatigue of both muscle groups to  $< 50\%$  of the pre-fatigue MVC level when the contractions were performed with both legs ( $MVC_{pre-bi}$ ). In accordance with the fatigue protocol developed, participants alternated between a maximal isometric contraction in PF for six seconds and sub-maximal isometric DF contraction ( $70\% MVC_{pre-bi}$ ) for two seconds. The fatigue protocol was stopped when both muscles were reduced to  $< 50\% MVC_{pre-bi}$  for 3 consecutive contractions. A mark was placed on the monitor at  $70\%$  DF  $MVC_{pre-bi}$  to provide a visual target for the participants to attain. A mark was also placed on the screen to indicated  $50\% MVC_{pre-bi}$  in PF and DF so that the investigator would know when to stop the fatigue protocol. The participants were not aware of the  $50\% MVC_{pre-bi}$  mark or the stopping criteria, and were encouraged to try and maintain maximal PF contractions and  $70\%$  DF  $MVC_{pre-bi}$  contractions throughout the fatigue protocol.

**Recovery:** Immediately after the fatigue protocol, the non-dominant foot was removed from the pedal and the participant performed a PF MVC followed by a DF MVC. Single stimulations were delivered during and immediately after ( $t=0$ ) the contractions similar to the pre-fatigue test. These measures were repeated for both muscle groups at 0.5, 1, 1.5, 2, 5, 7 and 10 minutes post-fatigue.

### *Data Analysis*

The PF and DF MVC peak torque, twitch torque (TT), voluntary activation (VA) and the GM, GL, SOL and TA muscles M-wave peak-to-peak amplitudes were measured before the fatigue protocol and throughout the recovery period (at 0, 0.5, 1, 1.5, 2, 5, 7 and 10 minutes) (Spike2 v5.06, Cambridge Electronic Design, UK). The VA level was estimated by equation 1 (Allen et al., 1995):

$$VA = [1 - (\text{extra torque} / \text{control twitch torque})] \quad \text{Equation 1}$$

### *Statistical Analysis*

Since PF and DF MVC torques were normally distributed, values are reported as mean  $\pm$  SD and one-way repeated measures analyses of variance (ANOVAs) were used to assess the effect of fatigue. Paired t-tests were used as post-hoc comparisons to determine how long the effect of fatigue remained. Due to the large number of comparisons made, the family wise alpha level for the Bonferroni correction was set at 0.01. A paired t-test was performed between each time point for both PF and DF MVC torque to test whether the recovery had a similar timeline in the two muscle groups. A paired t-test was also performed between the TT to MVC ratio present in PF and DF pre and immediately post-fatigue (time 0).

Non-parametric Friedman tests were used to assess the effect of fatigue on the VA, TT and M-wave, since they were not normally distributed. Wilcoxon rank sum tests were used in follow up analysis of significant main effect to determine how long the effects were present. The level of significance was set at 0.05 and where appropriate corrected for multiple comparisons.

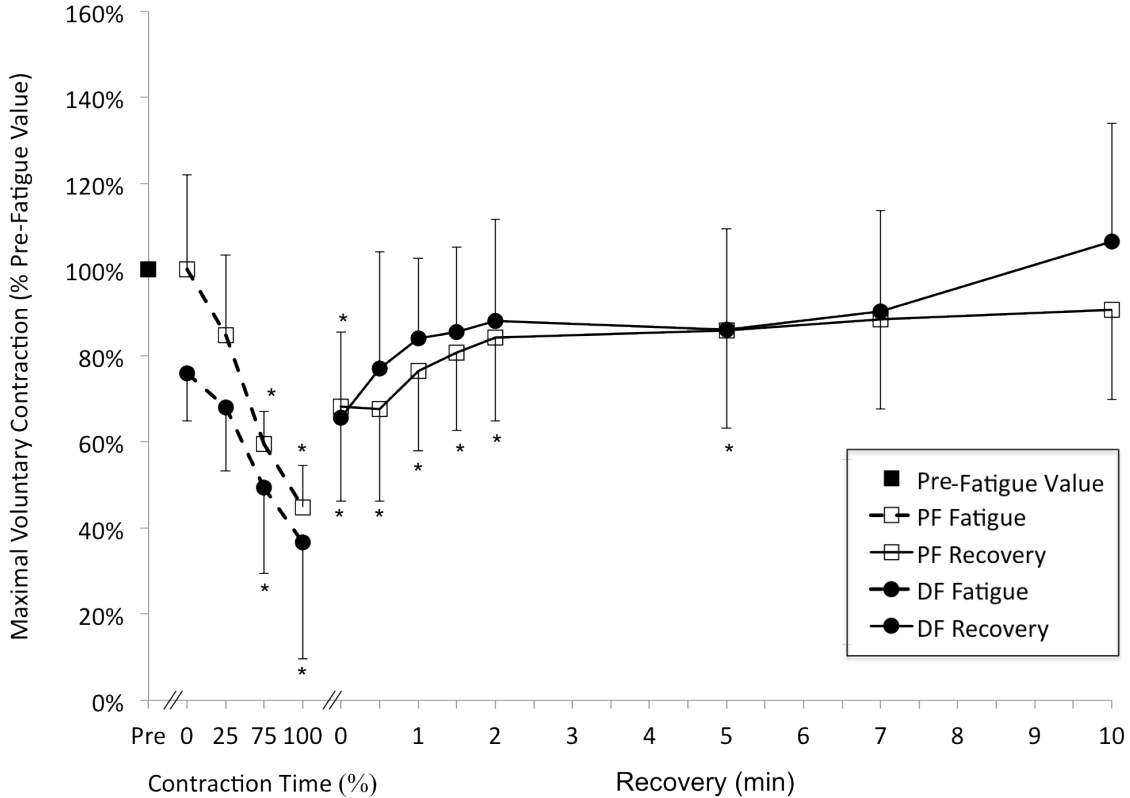
A Pearson correlation was performed between the MVC torque and the TT and VA in PF and in DF to determine whether there was a relationship between the reduction of the MVC and TT or VA.

### 3.4 Results

The average duration of the fatigue protocol for all participants was  $487 \text{ s} \pm 263 \text{ s}$  (ranged from 253 s to 860 s).

#### *Pre- and Post-Fatigue Maximal Voluntary Contraction*

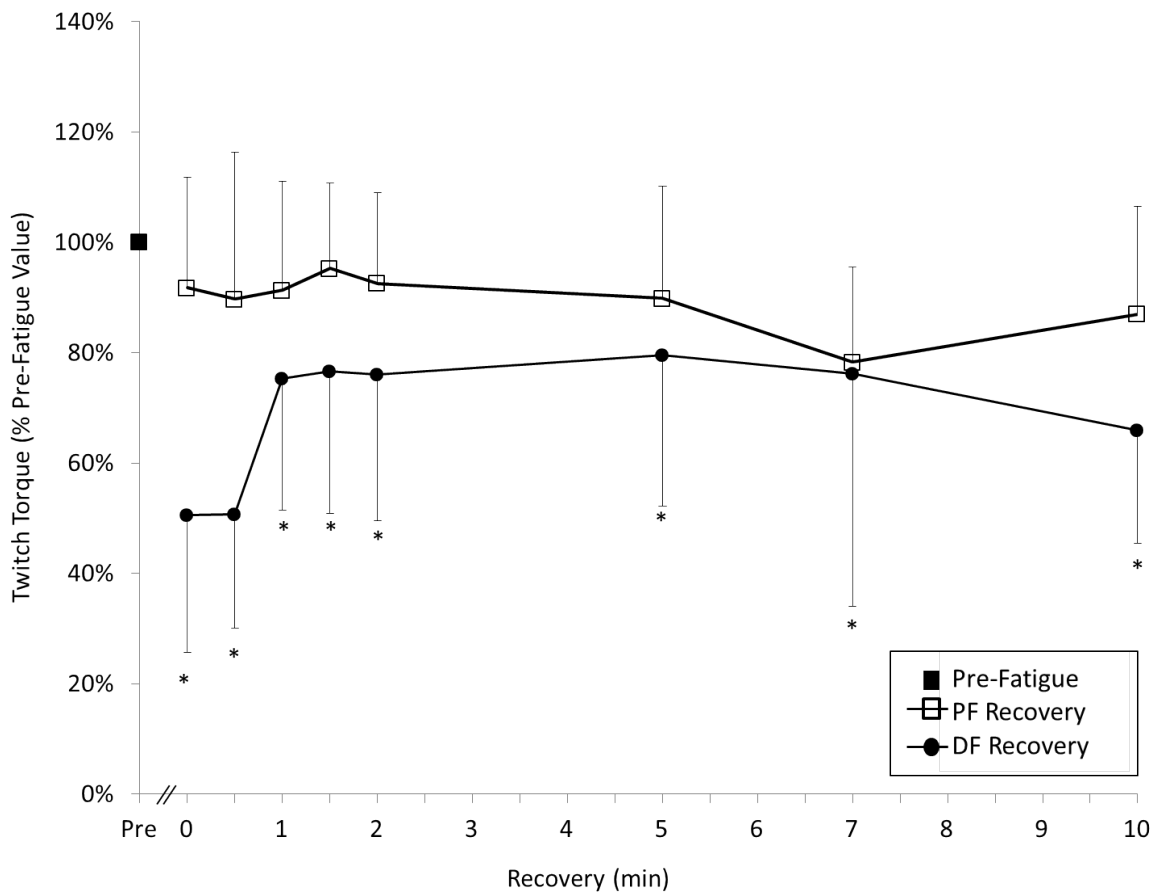
At the end of the fatigue protocol the PF and DF MVC torque produced with both legs was significantly decreased to  $44.8 \pm 9.6\%$  and  $36.7 \pm 14.2\%$  of the  $MVC_{\text{pre-bi}}$  respectively (Figure 2). No significant difference was found between the DF and PF voluntary torque measured at the end of the fatiguing exercise ( $t=100\%$ ). The MVC torque produced with the dominant leg was at  $68.0 \pm 5.9\%$  of the  $MVC_{\text{pre-dom}}$  in PF and  $68.2 \pm 5.3\%$  of the  $MVC_{\text{pre-dom}}$  in DF by the beginning of the recovery period (i.e., 0 min). Post-hoc analysis indicated that PF MVC torque returned to the pre-fatigue level at 7 min of recovery, while the DF MVC torque recovered by 0.5 min.



**Figure 3.2.** Maximal voluntary contraction (mean  $\pm$  SD; expressed as a percent of pre-fatigue values) performed for plantarflexor (PF) and dorsiflexor (DF) muscles before (Pre-), during (0, 25, 75 and 100%) and after the fatigue protocol (10 minute recovery period). (\* indicates significant difference from pre-fatigue values  $p < 0.01$ ).

#### Twitch Torque (TT)

The PF TT did not change significantly with fatigue ( $91.7 \pm 25\%$  of pre-fatigue at 0 min recovery); however the DF TT decreased significantly post-fatigue ( $50.5 \pm 20.0\%$  of pre-fatigue at 0 min recovery) and remained significantly lower than the pre-fatigue value throughout the 10-min recovery period ( $p=0.0001$ ) (Figure 3). The PF TT to MVC ratio was not affected by the fatigue protocol ( $p=0.118$ ). The DF TT to MVC ratio decreased from 14% pre-fatigue to 4% post-fatigue ( $p=0.003$ ).



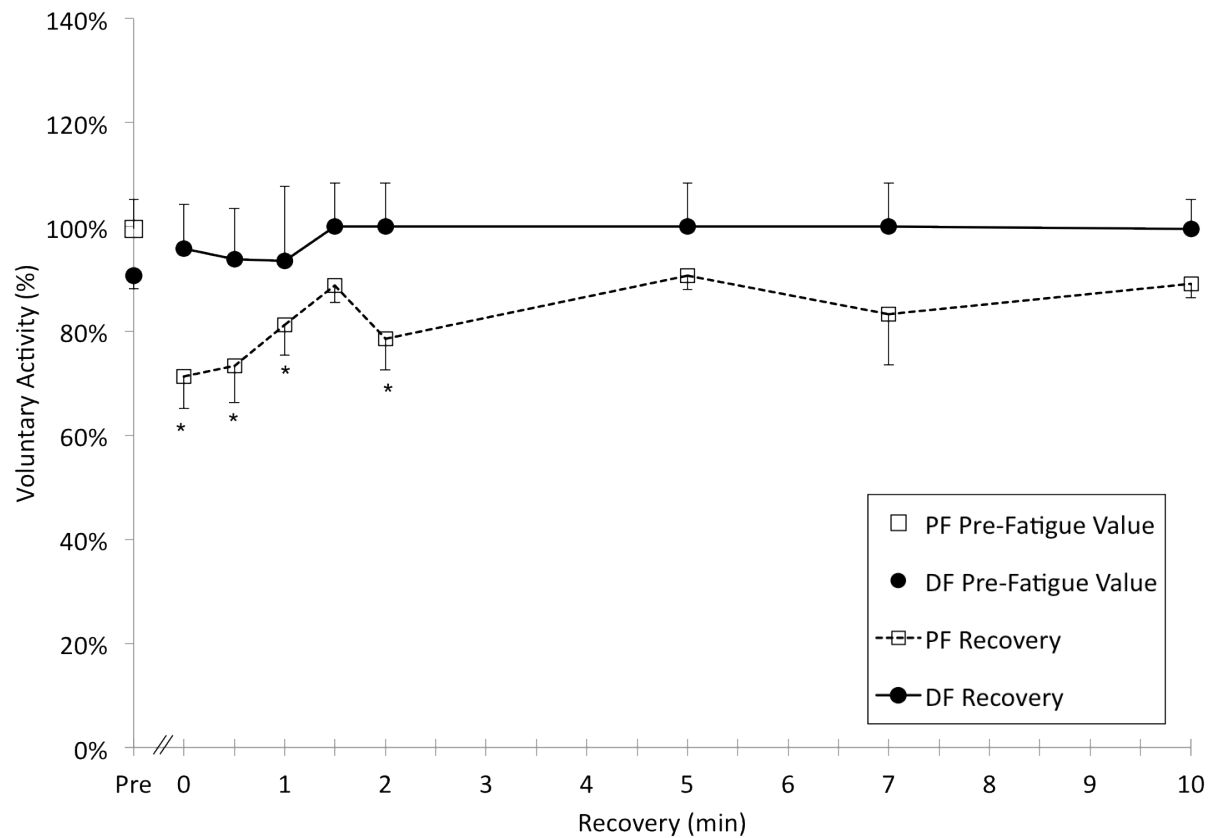
**Figure 3.3.** Twitch torque (mean  $\pm$  SD; expressed as a percent of pre-fatigue values) in response to neuromuscular stimulation delivered while the plantarflexor (PF) and dorsiflexor (DF) muscles were at rest before (Pre-) and after the fatigue protocol (10-min recovery period). (\* indicates a significant difference from pre-fatigue values  $p < 0.05$ ).

#### *Voluntary Activation (VA) and M-wave*

Pre-fatigue VA values were  $98.6 \pm 2.5$  % in PF and  $90.6 \pm 5.6$  % in DF (Figure 4). At the beginning of the recovery period (i.e., 0 min), the PF VA was significantly decreased ( $p=0.001$ ) to  $71.0 \pm 6.2\%$  and remained significantly lower throughout the first minute of recovery and at 2 minutes post-fatigue. There was no significant effect of fatigue on the DF VA (Figure 4). There was also no effect of fatigue on the GM, GL, SOL or TA muscles M-wave amplitudes.

### Correlation between MVC and fatigue parameters

There was a significant correlation between the PF MVC and the PF VA pre and post-fatigue ( $r=0.827$ ,  $p=0.003$ ) but not the PF MVC and the PF TT. There was also no significant correlation between the DF MVC and the DF VA or the DF TT.



**Figure 3.4.** Voluntary activation (mean  $\pm$  SD; expressed as a percent of pre-fatigue values) for plantarflexor (PF) and dorsiflexor (DF) muscles before (Pre-) and after the fatigue protocol (10 minute recovery period). (\* indicates a significant difference from pre-fatigue values  $p < 0.05$ ).

### 3.5 Discussion

The aim of this study was to gain insight into the type and level of neuromuscular fatigue created by a bi-directional ankle fatigue protocol with the intention that the protocol may be used to reliably examine the effect of ankle fatigue on postural control and other motor tasks. Our findings indicate that while PF and DF torque production capacity may be reduced to approximately the same level, the mechanisms responsible for this decrease may be quite different between these two muscle groups. Our results suggest that central fatigue played an important role in the decreased PF torque production capacity, while peripheral fatigue appeared more important in DF. Voluntary torque production capacity returned to pre-fatigue levels by 7 min in PF and 1 min in DF (Figure 2).

#### *Methodological considerations*

The torque production capacity was reduced to  $\sim 50\%$   $MVC_{pre-bi}$  in PF and DF by using an alternating ankle dorsi and plantar-flexion protocol. Isometric contractions were used in this fatigue protocol to simplify issues regarding the velocity, angular position and the role of gravity in the contractions. Since the functional anatomy (Belanger and McComas, 1981) and histological composition (Johnson et al., 1973) of the plantar and dorsiflexors are dissimilar, different levels of contraction duration and intensity were needed to fatigue the muscle groups to the same level at approximately the same time. Pilot testing determined that a 6-s maximal PF contraction alternated with a 2-s,  $70\%$   $MVC_{pre-bi}$  DF contraction successfully reduced the torque production capacity to  $50\%$   $MVC_{pre-bi}$  for both muscle groups within a similar time frame. It is important to note that the DFs fatigued so quickly that participants had difficulty reaching  $70\%$  of their initial  $MVC_{pre-bi}$  very early in the fatigue protocol.

A single, supramaximal electrical stimulation pulse was delivered percutaneously over the nerve to characterize the central (VA) and peripheral changes (TT and M-wave) that occurred during and after the fatigue protocol. While the number of stimulations best suited for twitch interpolation has been disputed, single pulse stimulation is the least painful and has been shown to give a reliable measure of the participant's level of maximal voluntary activation (Behm et al., 1996; Scaglioni and Martin, 2009; Taylor, 2009). Similarly, the location of stimulation is debatable. Although Scaglioni and Martin (2009) found a similar level of voluntary activation with stimulations delivered over the nerve and the motor point of the muscle, they recommended neural stimulation since this technique allows reliable recruitment of the same motor pool between measures. Finally, the location of PF neural stimulation is well established in the literature (Belanger and McComas, 1981; Nordlund et al., 2004); however, the location of TA neural stimulation is less clear. The common peroneal nerve is not used to stimulate the DF since it elicits activity in the peroneus muscles which are involved in PF movements (Kent-Braun, 1999). In this study, researchers stimulated the most distal and ventral location of the fibular peroneal nerve in an attempt to stimulate the fibular peroneal nerve after the superficial nerve had branched off to the peroneus brevis and longus (Gosling et al., 1990). Careful attention was paid to ensure that the stimulating electrodes remained fixed to the same location on the skin throughout fatigue and recovery periods.

### *Central and peripheral fatigue*

Overall, the results are in agreement with previous work that examined the impact of fatigue on PF and DF performance despite the fact that their protocol fatigued the muscle groups independently (Belanger et al., 1983). Similar to Belanger et al. (1983), the present study found that central factors were highly involved in the decreased PF torque production while peripheral

factors played a more important role in DF. In this study, central fatigue was quantified by comparing the level of voluntary muscle activation that an individual was able to perform before and after exercise. In the present study the PF VA was reduced from  $98.6 \pm 2.5\%$  pre-fatigue to  $71 \pm 6.2\%$  post-fatigue. The impact of fatigue on the PF VA was similar to the impact of fatigue on the PF MVC torque. In fact, there was a strong statistical correlation between the changes that occurred throughout the fatigue protocol and recovery period in the PF MVC and the PF VA ( $r=0.827$ ,  $p=0.003$ ), further supporting the hypothesis that central fatigue was involved in the PF changes.

Central fatigue seemed to be less involved in the decreased DF torque since the DF VA measurement remained unchanged post-fatigue. However, it is possible that the high level of peripheral fatigue created in the dorsiflexors negatively impacted the VA calculation. The average ratio of the DF TT to the DF MVC significantly decreased from 14% pre-fatigue to only 4% post-fatigue ( $p=0.003$ ). This was not the case in PF where the ratio increased slightly from 17% pre-fatigue to 22% post-fatigue ( $p > 0.05$ ). Since the VA calculation is partly based on the control TT, a substantial decrease in this measure would cause an artificially high level of VA. In other words, the large amount of peripheral fatigue may have partially concealed the decrease in the participants' ability to maximally contract their dorsiflexors.

Nonetheless, it is clear that peripheral fatigue impacted the DF more than the PF torque. As briefly mentioned above, twitch tension was used to identify the presence of peripheral fatigue in both muscle groups post-fatigue. TT identifies impairment of the excitation-contraction coupling and muscle contractile mechanisms (Merton, 1954). Similar to Belanger et al. (1983) the fatigue protocol impacted the DF TT ( $50.5 \pm 20.0\%$ ) but not the PF TT. The resistance of the PFs to peripheral fatigue may be due to the histological composition of the predominantly slow twitch

soleus muscle (Johnson et al., 1973; Gollnick et al., 1974) and/or the PFs ability to share the torque production between the GM, GL and the SOL. DF torque, on the other hand, is primarily produced by the TA which is normally responsible for rapid ankle contractions (Mosher et al., 1972).

Peripheral fatigue can also occur at the neuromuscular junction and/or in the transmission of the action potential to the muscle fibres (Milner-Brown and Miller, 1986). This type of peripheral fatigue is measured by the compound muscle action potential produced in response to neuromuscular stimulation (M-wave). In this study the amplitude of the M-wave was unchanged in both PF and DF. This finding can be explained by the fact that fatigue-induced changes in M-wave amplitude are highly task specific and occur most often during long, sub-maximal fatigue protocols (Loscher et al., 1996) or in fatigue caused by electrical stimulation (Galea, 2001). Studies that use short, maximal fatigue protocols (Kawakami et al., 2000) similar to the present study typically do not find post-fatigue changes in the amplitude of the M-wave. In these studies it has been hypothesized that peripheral fatigue that cannot be explained by changes in the M-wave may be caused distal to the neuromuscular junction in the excitation-contraction coupling mechanism (Kent-Braun, 1999); however, other factors such as metabolic accumulation and/or depletion of ATP are also likely involved in this fatigue process (Kirkendall, 1990).

### *Recovery*

Peripheral and central fatigue may not recover at the same rate; therefore, in order to study the impact of neuromuscular fatigue on subsequent motor tasks, it is important to examine the recovery process for each muscle group. In the present study, the PF MVC torque did not return to the pre-fatigue levels until after 5 min of recovery. In contrast, as shown by others, the DF

MVC torque recovered more rapidly (Milner-Brown et al., 1986) despite the persistent reduction in DF TT. The cause of the peripheral impairment could be an alteration in the metabolically induced cross-bridge formation (Miller et al., 1987). However, the lack of recovery within the 10-min post-fatigue period suggests that it is more likely associated with changes in excitation-contraction coupling mechanisms which have been shown to take up to 60 min to recover (Edwards et al., 1977).

### *Conclusion*

Characterizing the neuromuscular changes that occur throughout a fatigue and recovery period allows researchers to understand the type of fatigue produced by exercise and to study the impact that this fatigue will have on motor tasks performed after the fatiguing exercise. In this study it was determined that although a bi-directional alternating ankle fatigue protocol was successful in simultaneously reducing the PF and DF voluntary torque production to 50%  $MVC_{pre-bi}$ , the central and peripheral contribution to this decrease were different for each muscle group. Furthermore, the DF torque production recovered by 1 min while the PF recovered 7 min post-fatigue.

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**Chapter 4: Impact of ankle muscle fatigue and recovery on the anticipatory postural adjustments to externally initiated perturbations in dynamic postural control**

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# **Impact of ankle muscle fatigue and recovery on the anticipatory postural adjustments to externally initiated perturbations in dynamic postural control**

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#### **4.1 Abstract**

The aim of this study was to determine if and how young participants modulate their postural response to compensate for postural muscle fatigue during predictable but externally initiated continuous and oscillatory perturbations. Twelve participants performed ten postural trials before and after an ankle muscle fatigue protocol. Each postural trial was one minute long and consisted of continuous backwards and forwards oscillations of the platform. Fatigue was induced by intermittent, bilateral isometric contractions of the ankle plantar- and dorsi-flexors until the force production was reduced to 50% of the pre-fatigue maximal voluntary contraction. Changes in the center of mass (COM) displacement, center of pressure (COP) displacement and anterior-posterior location of the COP within the base of support were quantified as well as the activity of the tibialis anterior (TA), medial gastrocnemius (MG), quadriceps and hamstring. All participants demonstrated postural stability post-fatigue by maintaining the displacement of their COM. Everyone also demonstrated a general forward shift in the anterior-posterior location of the COP within the base of support; however, two distinct postural modifications, corresponding to either an immediate fatigue-induced increase or decrease in the COP displacement during the backwards platform translation, were recorded immediately post-fatigue. The changes in muscle onset latencies lasted beyond the recovery of the force production of the fatigued postural muscles. By ten minutes post-fatigue, the participants showed a decrease in the COP displacement as well as an earlier activation of the postural muscles and an increased the TA/MG co-activation relative to pre-fatigue. Although different strategies were used, the participants were able to adjust to and overcome postural muscle fatigue and remain balanced during the postural perturbations regardless of the direction of the platform movement. These adjustments lasted beyond the recovery of the ankle muscle force production indicating that they may be part

of a centrally mediated protective response as opposed to a peripherally induced limitation to performance.

**Keywords:** anticipatory postural adjustment, neuromuscular fatigue, dynamic posture, recovery

## 4.2 Introduction

Postural control, including both stability and orientation, is an integral pre-requisite that facilitates the successful performance of complex motor tasks (Shumway-Cook and Woollacott 2007). Although it is largely regulated by the mechanical properties of the individual and surrounding environment, the motor goals of the individual also play an important role in postural control (Riccio and Stoffregen 1988). In fact, research has demonstrated that postural control is often modulated to improve the performance of tasks such as light touch (Riley et al. 1999), reaching (Thelen and Spencer 1998; van der Heide et al. 2003) and visual precision (Stoffregen et al. 2000) over stability.

When stability is disrupted, e.g. by a movement of the platform, individuals are able to modify their reactive and anticipatory postural adjustments to compensate for the destabilizing forces (Hughey and Fung 2005). Anticipatory postural adjustments (APA) are characterized through changes in muscle activity and/or in characteristics of the center of pressure (COP) and center of mass (COM) generated in anticipation of self- (Bouisset and Zattara 1987; Benvenuti et al. 1997) or externally- (Shiratori and Latash 2001; Santos et al. 2010) initiated predictable perturbations. Externally initiated predictable perturbations are commonplace in daily life and are studied using discrete and/or continuous perturbations. In continuous postural perturbations, such as those occurring while standing on a moving bus, train or ship, APAs evolve so that the response meets the requirements of the individual, environment and task (Dietz et al. 1993; Bugnariu and Sveistrup 2006; Schmid et al. 2011). In a previous study we found that participants reached this optimal, steady state postural response after seven one-minute long, continuously oscillating postural trials (Kennedy et al. 2011b). The postural responses found after seven minutes of practice were consistently more efficient than those used initially, showing an earlier

activation of the postural muscles with a smaller muscle burst amplitude relative to the first several trials.

An individual's ability to adapt their postural response, including the COP and COM characteristics and muscle onset latency, is influenced by the quality of the afferent information that the central nervous system is able to process regarding the perturbation characteristics. For example, sensory neuron disease, a disorder that impairs the vestibular system and central branch of the afferent fibers, prevents participants from adapting to postural perturbations while those with more local peripheral neuropathies are not as severely limited (Nardone et al. 2007). Older adults, who often demonstrate central nervous system (Seilder et al. 2010) and proprioceptive deficits (Goble et al. 2009), also show impaired postural control. In general their ability to activate their postural muscles in anticipation of a predictable, externally initiated perturbation is reduced while the COP displacement is increased, moving into unsafe regions of the base of support more often than young healthy individuals (Bugnariu and Sveistrup 2006; Bugnariu and Fung 2007). Older adults also have higher rates of muscle co-activation in postural control tasks relative to young adults (Laughton et al. 2003), a modification that has been associated with increased anxiety towards the postural task (Okada et al. 2001) which could be associated with the insufficient afferent feedback from the environment. Overall, these studies highlight the importance of accurate afferent information on an individual's ability to adapt to and overcome postural perturbations.

Similar to the postural changes caused by peripheral nerve damage (Nardone et al. 2007) and the normal aging process (Horak et al. 1989; Bugnariu and Fung 2007), exercise-induced neuromuscular fatigue also alters postural control (Johnston et al. 1998; Vuillerme et al. 2002; Mahyar et al. 2007). When an individual is fatigued their response to postural perturbations often

become more conservative compared to non-fatigued trials (Wilson et al. 2006) and, if the perturbation can not be predicted, the individual may show a decreased control of the COM relative to the base of support (Davidson et al. 2009). Presently, the mechanisms responsible for this impaired postural control are not well understood. This lack of clarity is in part due to the complex and task dependent nature of the manifestation and recovery of the peripheral and central components of neuromuscular fatigue (Enoka and Duchateau 2008). Although peripheral fatigue, occurring within the muscles and neuromuscular junction, and central fatigue, occurring within the CNS, develop concurrently, they likely do not affect motor performance in a similar way. Therefore, is it important to quantify the contribution of each type of fatigue to the overall decrease in motor performance before assessing the influence of the fatigue protocol on a more complex motor task such as postural control.

In a previous study we characterized the peripheral and central fatigue produced during alternating isometric ankle plantar and dorsiflexion contractions performed until force production was reduced to 50% of the initial maximal voluntary isometric contraction in each muscle group (Kennedy et al. 2011a). The primary measure of peripheral fatigue was the twitch torque produced by neuromuscular stimulation of the plantar and dorsi-flexor muscles while they were at rest pre and post-fatigue. To quantify central fatigue maximal contractions of the ankle plantar and dorsi-flexor muscles were super-imposed with neuromuscular stimulation. The additional force produced by the stimulation was normalized to the resting twitch torque to provide a measure of the level of voluntary activation for each of the muscle groups (for further details see Kennedy 2011a). These measures, combined with other secondary variables, suggested that peripheral fatigue persisted for ten-minutes after the exercise while central fatigue recovered

within 30 seconds. These results will be used in this study to interpret the impact of the bidirectional ankle fatigue protocol on postural control.

The primary aim of this study was to determine how the postural response was modified to maintain control of the COM during a predictable, continually oscillating, externally initiated postural perturbation immediately after an exhaustive ankle muscle fatigue protocol. The changes in postural response were examined in conjunction with the results from a previous fatigue characterization study (Kennedy et al. 2011a) to understand how the temporal recovery of the neuromuscular fatigue affected postural control throughout the ten minute post-fatigue period. We hypothesized that the participants would modify their postural strategy to compensate for fatigue and to control their COM displacement throughout the post-fatigue testing period by activating their postural muscles earlier than in the pre-fatigue state (Strang and Berg 2007) and by reducing the displacement of their COP (Davidson et al. 2009). We also predicted that there would be an increased co-activation between the fatigued muscle groups post-fatigue relative to the pre-fatigue postural trials. Finally, we hypothesized that the postural response would return to the pre-fatigue values as the force production recovered in the ankle muscles.

### **4.3 Methods**

#### **Participants**

Twelve (seven men and five women) healthy subjects (aged 19-27; men height  $1.76 \pm 0.14$  m, weight  $72.4 \pm 3.6$  kg; women height  $1.54 \pm 0.4$  m, weight  $58.6 \pm 9.2$  kg, mean  $\pm$  standard deviation) with no neurological impairment or history of serious injury that prevented them from participation in sport for more than six months gave informed consent to participate in this study. Elite athletes (collegiate level or higher) and dancers (participation more than four times/week) were excluded from the sample. The experimental procedures were approved by the ethics board

at the University of Ottawa and were performed in accordance with the Tri-Council Policy Statement (TCPS2 2010).

### Measurement Devices

Seven VICON cameras (Vicon Peak, Oxford, UK) and thirty-six retro-reflective markers, placed on anatomical landmarks and four corners of the force plate, were used to capture the center of mass (COM) displacement during the postural trials. A movable platform was instrumented with a Kistler force plate (Type 9286, Kistler Instrument Corp, New York, USA) to capture the ground reaction forces during the postural trials (Nexus, Vicon Peak, Oxford, UK). The kinematic data were sampled at 200 Hz while the ground reaction forces and platform position were sampled at 500 Hz.

Surface electrodes (Myomonitor Wireless Delsys EMG system, Boston, USA) were used to record electromyographical (EMG) activity from the medial gastrocnemius (MG), biceps femoris (BF), tibialis anterior (TA) and rectus femoris (RF) in accordance with SENIAM recommendations (Hermens et al. 2000). A ground electrode was placed on the patella. The EMG signals were pre-amplified, sampled at 1000 Hz and full wave rectified.

Instrumented ankle pedals were custom designed to measure ankle plantar and dorsiflexion force during the fatiguing ankle contractions (for details see Kennedy et al. 2011a). The data from each pedal were collected at 500 Hz.

### Procedure

The 1.5-hour testing period consisted of a brief ankle warm up, ten pre-fatigue postural trials, a bi-directional ankle fatigue protocol and ten post-fatigue postural trials. The warm-up consisted

of three sets of four repetitions of isometric ankle plantar and dorsiflexion contractions performed at 25%, 50%, and then at 75% of the individuals' perceived maximal effort for a total of 12 contractions. Each contraction was held for ten seconds with 15 seconds of recovery between repetitions and one minute recovery between sets.

### *Postural Trials*

Ten postural trials, one per minute for ten consecutive minutes, were performed pre-fatigue and post-fatigue. Each postural trial lasted ~50 seconds after which the platform remained still for ten seconds before the next trial began. During the postural trials the participants were asked to stand barefoot with their head forward, eyes open and feet shoulder width apart on the platform as it oscillated 20 cm in the anterior-posterior plane (for further details see Bugnariu and Sveistrup 2006). They were asked to not take a step unless necessary; however, none of the participants needed to step. In each postural trial the platform oscillations began at 0.25 Hz and were unpredictably increased to 0.50 Hz approximately halfway through the trial. Three to five platform cycles were required before the participants were able to use APAs at this new, higher frequency (Bugnariu and Sveistrup 2006). The series of pre-fatigue posture trials allowed the participants to habituate to the perturbations, ensuring that the changes found post-fatigue were due to postural muscle fatigue and not further habituation to the motor task. Previous research performed in our laboratory indicated that the postural response stabilized after seven minute-long practice trials in young healthy individuals (Kennedy et al. 2011b).

### *Fatigue exercise*

The fatigue exercise was designed to ensure that the ankle plantar and dorsiflexor muscles were simultaneously fatigued (for details see Kennedy et al. 2011a). During the pre-fatigue testing

period and the fatigue exercise participants sat on a dynamometer chair with their legs extended and supported in front of them and their feet strapped in separate instrumented foot pedals. They performed three pre-fatigue maximal voluntary isometric contractions ( $MVIC_{pre}$ ) in plantar (PF) and dorsiflexion (DF). The highest value was used to determine the stopping criteria for the fatigue protocol (50%  $MVIC_{pre}$ ). After a brief rest period the fatigue protocol began with alternating isometric contractions; 6 seconds at 100% PF  $MVIC_{pre}$  and two seconds at 70% DF  $MVIC_{pre}$ , performed until participants were no longer able to reach 50%  $MVIC_{pre}$  in either direction for at least three consecutive contractions. The participants were unaware of the stopping criteria and were verbally encouraged throughout the trial.

Our earlier characterization of this fatigue protocol demonstrated that the force production capacity of the muscles was reduced to less than 40% of the  $MVIC_{pre}$  for the ankle plantar and dorsiflexor muscles immediately post-fatigue and that this force recovered by seven minutes post-fatigue in PF and by 30 seconds in DF (Kennedy et al. 2011a). Although the DF force production recovered quickly post-fatigue, peripheral fatigue, identified by a decreased twitch torque, was present throughout the ten-minute recovery period. Finally, central fatigue, identified by a decreased level of voluntary activation, affected the ankle PF muscles for the first two minutes post-fatigue but did not alter the activation of the DF muscles.

#### Data Analysis

The dependent variables analyzed in this study included the probability of TA/MG muscle co-activation and the anterior-posterior location of the COP within the base of support, which were both analyzed over full platform cycle, as well as the muscle onset latencies and the anterior-posterior displacement of the COM and COP, which were analyzed separately over backwards

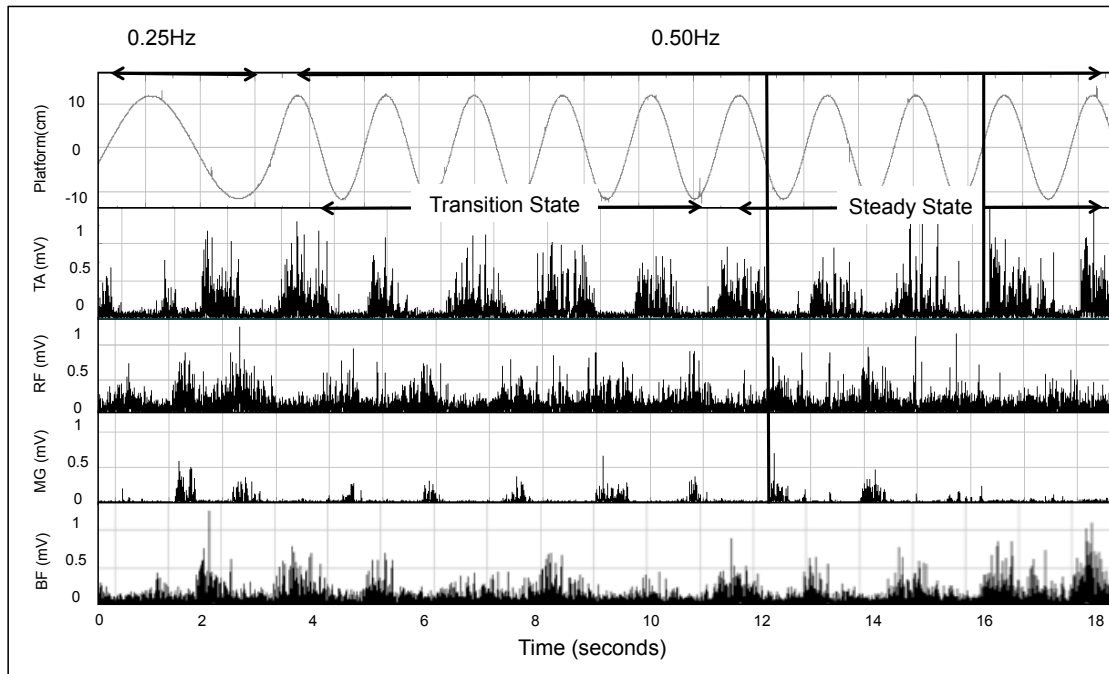
and forward translations of the platform. Values for the last five cycles performed at 0.50 Hz were averaged for each dependent variable in each trial.

The EMG data was full-wave rectified and the probability of ankle muscle co-activation was identified as simultaneous activation of the TA and MG muscles lasting longer than 50 ms (Bioproc 3 version 3.06, D.G.E. Robertson). Although muscle activity was only quantified for the last five oscillations performed at 0.50 Hz, a preliminary assessment of the muscle activity was performed to determine the muscle bursting frequency for all four muscles over the entire minute-long postural trial. If a muscle was activated in less than 15% of the oscillations it was not included in individual or group calculations of onset latencies to avoid the involvement of random muscle bursts in the data analysis.

The location of the COP within the anterior-posterior length of the base of support was calculated by averaging the length of the left and right feet and dividing this value into 5 sections for each participant: 0-20% = toe, 20-40% = fore arch, 40-60% = mid arch, 60-80% = rear arch and 80-100% = heel. The amount of time that the COP spent in each of these sections was calculated for each participant at each trial time.

The muscle burst onsets were determined using a two standard deviation threshold derived from the quiet stance period that occurred before every perturbation. The threshold was calculated using BioProc 3 (version 3.06, D.G.E. Robertson) and once identified, a cursor was placed on the screen to allow visual identification of the muscle onsets for each postural trial. Muscle onset latencies were coded relative to the start of the forward or backward platform translations and are presented as a percentage of one half cycle, which is defined as the translation of the platform from one extreme position to the other. Muscle activity occurring before platform translation was

coded as a negative onset indicating feed-forward or anticipatory muscle activity (Bugnariu and Sveistrup 2006) (Fig 1).



**Fig 1** (a) Posture Protocol. *Platform oscillation trace and EMG signals from the tibialis anterior (TA), rectus femoris (RF), medial gastrocnemius (MG) and biceps femoris (BF) muscles during the transition and steady state of the platform oscillations occurring at 0.50 Hz during the last pre-fatigue trial (PreF-10). Example of muscle onset provided by vertical lines extending from sinusoidal wave to MG and TA muscle bursts.*

The Plug-in Gait biomechanical model (VICON) was combined with anthropometric measurements and kinematic data to calculate the maximum anterior-posterior peak-to-peak displacement of the center of mass (COM). The anterior-posterior movement of the force plate was subtracted from the COM data in order to provide a true representation of the movement of the COM relative to the base of support. The maximum anterior-posterior peak-to-peak displacement was calculated for the COM and COP in each direction separately and the % of the pre-fatigue (PreF-10) values for these variables was used to perform the statistical analysis.

Preliminary analysis of these data suggested that participants responded using one of two distinct post-fatigue strategies during the backward translation of the platform. Therefore, participants were divided into two subgroups based on whether their COP displacement increased (subgroup 1: 5 men, 2 women) or decreased (subgroup 2: 2 men, 3 women) post-fatigue relative to the last postural trial occurring pre-fatigue (PreF-10). All participants responded in a similar way during the forward translation of the platform and so data from all of the participants were analyzed together in this direction. Data were ensemble averaged across the two subgroups pre-fatigue (PreF-10) as well as for the trials occurring one (F1), five (F5) and ten (F10) minutes after the fatiguing protocol.

#### Statistical Analysis

Repeated measure analysis of variance (ANOVAs) were used to assess whether fatigue affected the time the COP spent in each section of the foot as well as the probability of TA/MG co-activation pre- (PreF-10) and post-fatigue (F1, F5, and F10). Repeated measures ANOVAs were also used to compare the COM, COP and muscle onset latency pre-fatigue (PreF-10) to the changes occurring post-fatigue (F1, F5 and F10) for each subgroup in the backwards direction and for the full group in the forwards direction. Tukey corrected post-hoc paired t-tests were used to determine how long fatigue affected each of the dependent variables (Vincent 2005). The accepted significance level was 0.05 and data are presented as mean value  $\pm$  the standard error.

### **4.4 Results**

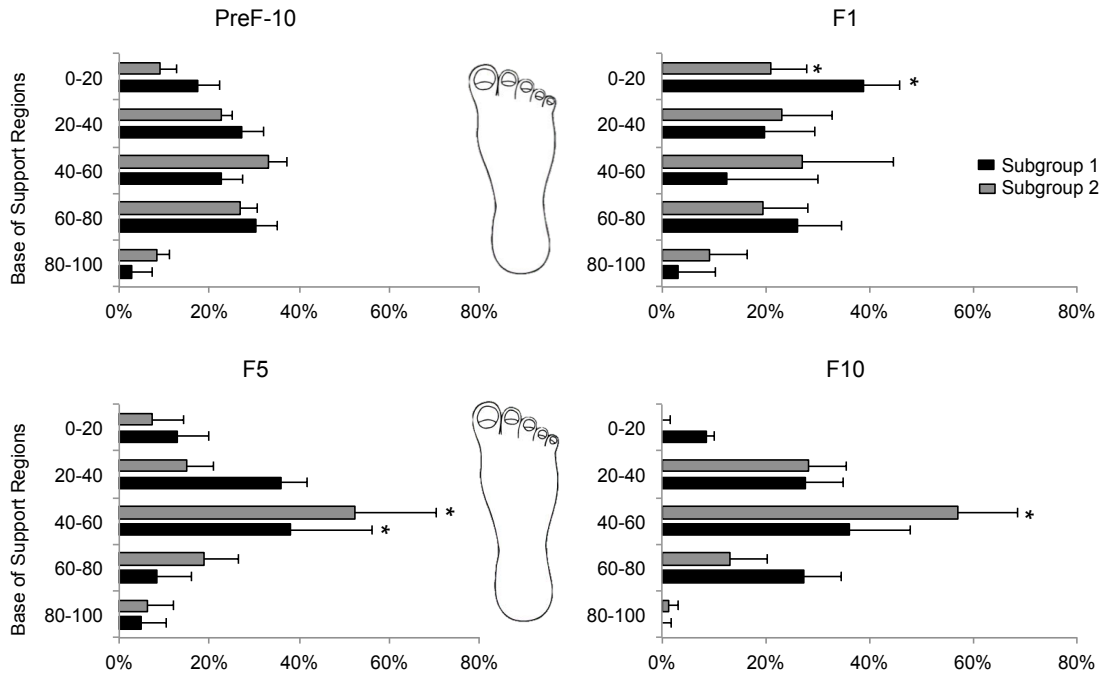
#### *Muscle co-activation*

The probability of co-activation between the TA and MG muscle was affected by the fatigue protocol in both subgroups (subgroup 1:  $F(3, 18) = 11.40, p = 0.001$ ) and (subgroup 2:  $F(3, 12)$ )

= 6.00,  $p = 0.010$ ). In subgroup 1 the value increased significantly from  $0.2 \pm 0.03$  at PreF-10 to  $0.45 \pm 0.11$  at F1 ( $p = 0.020$ ). The rate of muscle co-activation remained significantly higher than PreF-10, reaching  $0.48 \pm 0.09$  at F5 ( $p = 0.028$ ) before decreasing to  $0.28 \pm 0.05$  at F10 ( $p > 0.05$ ). Subgroup 2 increased the rate of co-activation between the TA and MG from  $0.18 \pm 0.03$  at PreF-10 to  $0.62 \pm 0.05$  at F1 ( $p=0.002$ ). They maintained this elevated rate at F5 ( $0.54 \pm 0.03$ ,  $p=0.025$ ) and F10 ( $0.47 \pm 0.08$ ,  $p=0.038$ ).

#### *Anterior-posterior location of the COP within the base of support*

Fatigue affected the time the participants spent in the toe region (0-20% of the foot length) for both the subgroup 1 ( $F(3,18) = 5.47$ ,  $p = 0.009$ ) and 2 ( $F(3, 12) = 7.69$ ,  $p = 0.004$ ) (Fig 2). Both subgroups showed a forward shift onto the toes at F1 (subgroup 1,  $p = 0.048$  and subgroup 2,  $p = 0.045$ ) after which the anterior-posterior location of the COP returned to the pre-fatigue values ( $p > 0.05$ ). Fatigue also affected the amount of time spent in the center of the foot (40-80% of the foot length) for subgroup 1 ( $F(3, 18) = 5.53$ ,  $p = 0.007$ ), increasing from PreF-10 at F5 ( $p = 0.046$ ) and F10 ( $p=0.001$ ), and for subgroup 2 ( $F(3, 12) = 9.28$ ,  $p = 0.003$ ), increasing only at F5 ( $p = 0.007$ ). The time the COP spent in the other sections of the foot did not change significantly throughout the post-fatigue period ( $p > 0.05$ ).



**Fig 2.** Percentage of time spent in each of the five regions of the base of support (0-20% = toe, 20-40% = fore arch, 40-60% = mid arch, 60-80% = rear arch and 80-100% = heel) for full cycles occurring in the past postural trial performed pre-fatigue (PreF-10) and the trials performed post-fatigue (F1, F5, F10) for subgroup 1 and 2. \* Significant differences from the last pre-fatigue trial (PreF-10) ( $p < 0.05$ ).

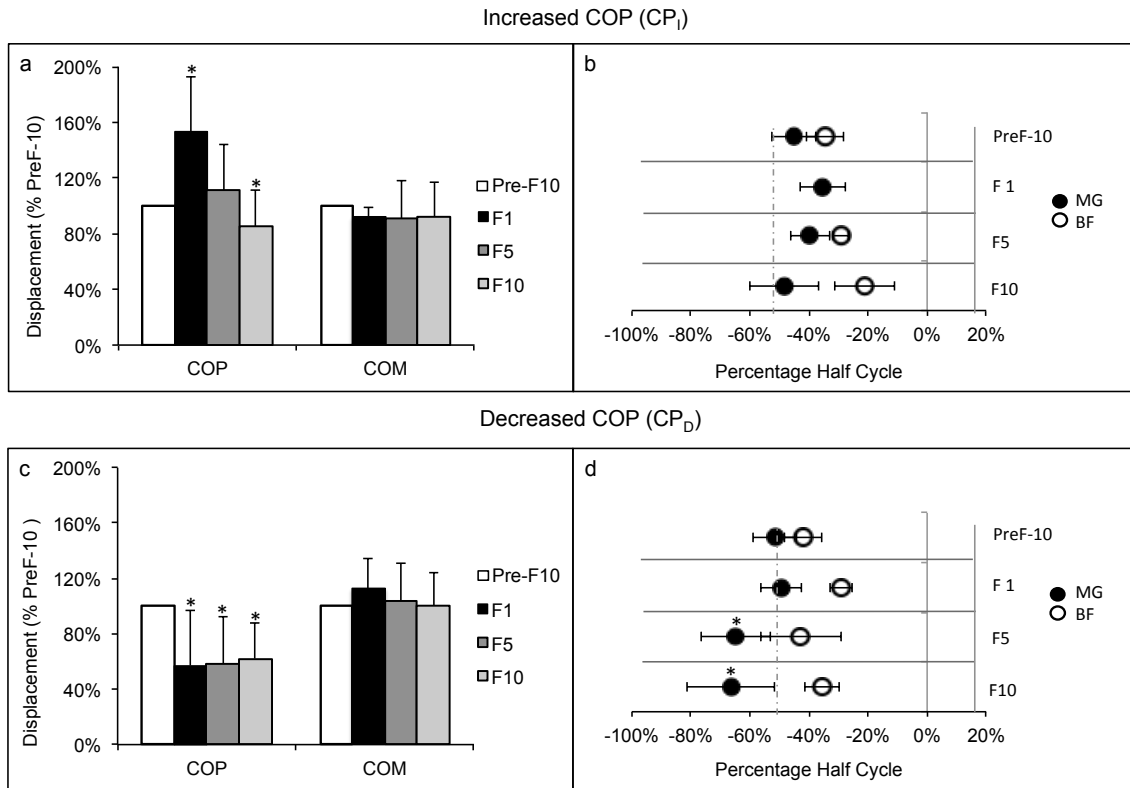
### Backward platform translation

The fatigue protocol affected the MG and BF muscle onset latencies in the two subgroups differently. In subgroup 1, the BF was activated in less than 15% of the trials in all subjects at F1 and so was not included in the analysis. The MG ( $F(3, 18) = 1.13, p = 0.36$ ) and BF ( $F(2, 16) = 0.995, p = 0.40$ ) onset latencies did not change with fatigue (Fig 3a). In subgroup 2, the MG muscle onset latency was affected by the fatigue protocol ( $F(3, 12) = 5.79, p = 0.011$ ), showing an earlier activation at F5 ( $p = 0.046$ ) and F10 ( $p = 0.034$ ) relative to PreF-10 (Fig 3c). The BF muscle latency was not affected by the fatigue protocol in this subgroup ( $F(3, 12) = 0.74, p = 0.55$ ).

The COM displacement of subgroup 1 was not affected by the fatigue protocol ( $F(3, 18) = 0.29$ ,  $p = 0.83$ ); however, the COP displacement increased ( $F(3, 18) = 4.4$ ,  $p = 0.017$ ) to  $153.3 \pm 26.4$  at F1 ( $p = 0.0018$ ) before decreasing to  $110.8 \pm 23.4\%$  at F5 ( $p = 0.23$ ) (Fig 3b). At F10 the COP displacement was significantly lower than pre-fatigue reaching  $85.3 \pm 34.5\%$  at F10 ( $p = 0.049$ ).

Similarly, the COM displacement of subgroup 2 was not affected by the fatigue protocol ( $F(3, 12) = 1.22$ ,  $p = 0.34$ ) although the COP displacement was ( $F(3, 12) = 11.83$ ,  $p = 0.001$ ), decreasing to  $56.8 \pm 9.8\%$  immediately post-fatigue (F1:  $p = 0.004$ ) and remaining low at  $58.4 \pm 18.3\%$  at F5 ( $p = 0.015$ ) and  $62.1 \pm 14.2\%$  at F10 ( $p = 0.012$ ) (Fig 3d).

### Backward Platform Translation



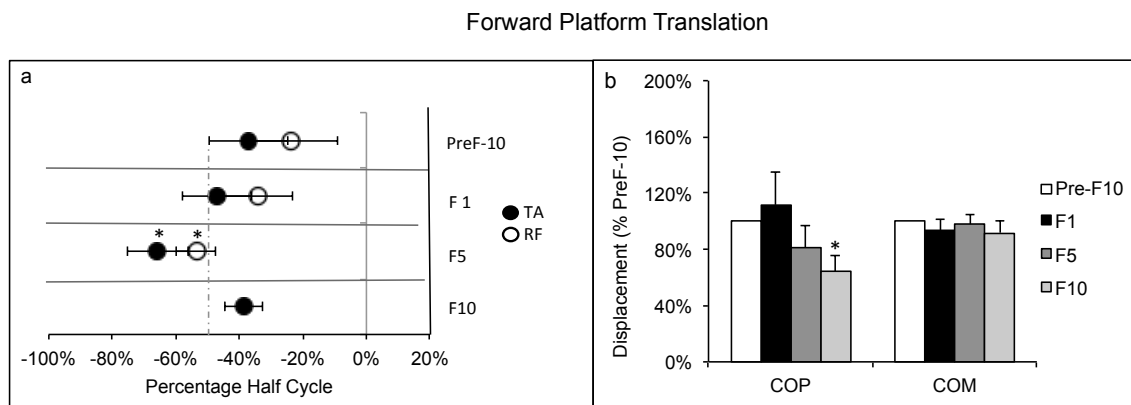
**Fig 3.** The muscle onset latencies (a, c) of the medial gastrocnemius (MG: closed circles) and biceps femoris (BF: open circles) muscles as well as the center of pressure (COP) and center of mass (COM) displacements (b, d) for the two subgroups during the backwards platform translation (mean  $\pm$  SE). Data from the last minute of oscillation in the last postural trial performed pre-fatigue (PreF-10) as well as for the first (F1), fifth (F5) and tenth (F10) minute post-fatigue are plotted. Participants were divided into two groups based on whether their COP displacement increased (top) or decreased (bottom) in the first minute post-fatigue. Post-fatigue COP and COM displacement values were normalized to values at PreF-10. Onset latencies are expressed as a percentage of half cycle time for the muscles normally associated with a backwards platform translation. Zero (solid vertical line) represents the time at which the platform changes direction while -50% (dashed vertical line) represents the time at which the platform begins to slow down. All participants activated the MG and BF muscles during the postural trials. \* Significant differences from the last pre-fatigue trial (PreF-10) ( $p < 0.05$ ).

#### Forward platform translation

The TA ( $F(3, 24) = 10.89, p = 0.001$ ) and RF ( $F(2, 16) = 4.02, p = 0.038$ ) muscles were activated earlier at F5 than when they were pre-fatigue (TA:  $p = 0.001$ , RF:  $p = 0.039$ ). At F10

the TA muscle onset latency returned to the pre-fatigue value ( $p = 0.078$ ) (Fig 4a). The RF was activated in less than 15% of the cycles in all participants at F10 and so was not included in the analysis.

The COM displacement was not affected by the fatigue protocol ( $F(3, 30) = 1.2, p = 0.325$ ) (Fig 4b). The COP displacement ( $F(3, 30) = 4.04, p = 0.016$ ) decreased progressively throughout the recovery period reaching  $80.9 \pm 12.3\%$  at F5 ( $p = 0.134$ ) and  $64.6 \pm 11.6\%$  at F10 ( $p = 0.001$ ).



**Fig 4.** The muscle onset latencies (a) of the tibialis anterior (TA, closed circles) and rectus femoris (RF, open circles) muscles and the center of pressure (COP) and center of mass (COM) displacements (b) (mean  $\pm$  SE) for the last minute of oscillation in the last postural trial performed pre-fatigue (PreF-10) as well as for the first (F1), fifth (F5) and tenth (F10) minutes post-fatigue. All participants recruited the quadriceps muscle in response to the platform oscillation while only 4 participants activated the TA muscle. \* Significant differences from the last pre-fatigue trial (PreF-10) ( $p < 0.05$ ).

#### 4.5 Discussion

We characterized the impact of exercise induced ankle muscle fatigue on the anticipatory postural adjustments to externally initiated, predictable postural perturbations and quantified the evolution of this postural response as fatigue subsided within the ankle muscles. It was initially hypothesized that the predictability of the postural perturbations would allow participants to tailor their postural response to overcome the destabilizing effects of fatigue and that the response would return to the pre-fatigue characteristics as the neuromuscular fatigue of the ankle

muscles subsided. The data show that the postural response was modified in two distinct ways to overcome the effects of fatigue during the backwards platform translation and that the changes in the response to the backwards and forwards translations lingered beyond the recovery of the ankle muscle fatigue.

When posture is disrupted by an externally initiated perturbation the nervous system controls the displacement of the COM through a range of motor equivalent changes suited to the meet requirements of the motor task, environment and individual (Scholz et al. 2007). Using the uncontrolled manifold hypothesis, Schultz demonstrated that the COM is a priority variable that remains constant as the motor response is modified to maintain postural control. In this study we found that fatiguing bi-lateral ankle contractions did not affect the displacement of the COM during either the forward or backwards platform translation but that the muscle onset latencies, rate of TA and MG muscle co-activation and location and displacement of the COP were modified to ensure that the individual remained balanced.

There are two possible explanations for why the participants in this study changed their postural response post-fatigue. The first is that the ankle contractions developed a high level of peripheral fatigue within the postural muscles, rendering them unable to execute the appropriate postural response. This option is unlikely given that the maximal muscle activity is rarely required for young healthy adults to maintain posture (Kuo and Zajac 1993) and that the force production capacity of the fatigued muscles had already returned to  $\sim 70\%$  of the  $MVIC_{pre}$  by the first post-fatigue postural trial (F1) (Kennedy et al. 2011a). Our interpretation of the post-fatigue results has lead to a second explanation for the change in postural control. We postulate that the presence of fatigue affected the central plan for movement, resulting in a modified postural strategy. This modification can be explored through the central governor theory, which states

that central control of human performance is modulated by afferent feedback from the peripheral system (Noakes et al. 2005; Amann and Dempsey 2008). In this theory peripheral fatigue leads to a change in motor output that is designed to prevent catastrophic failure and injury to the muscle. This approach is supported by several studies examining the post-fatigue response to postural perturbations (Wilson et al. 2008; Davidson et al. 2009). For example, in a discrete, externally initiated perturbation postural muscle fatigue may cause the participants to shift to a hip response (Davidson et al. 2009), which is a more stable, although less energy efficient, response to a postural perturbation. Studies using discrete self-initiated postural perturbations also reveal that some young adults use a more conservative muscle activation pattern when they are fatigued than when they are rested (Strang and Berg 2007; Kanekar et al. 2008; Strang et al. 2009). This response includes an increased muscle co-activation, an earlier muscle onset, and a smaller muscle burst amplitude (Kanekar et al. 2008).

Further analysis of the postural response to the self-initiated, continuous perturbations used in this study revealed that participants modified their response in two distinct ways when the platform translated backwards after the ankle fatigue protocol. Participants in subgroup 1 initially increased their COP displacement and decreased their BF muscle activity. Although the same amount of fatigue was created in the ankle muscles of the participants in subgroup 2, their post-fatigue postural response was distinct from that used by subgroup 1. Important differences included a significantly higher rate of TA/MG muscle co-activation compared to subgroup 1, a continued activation of the BF muscle throughout the ten minutes post-fatigue and a significantly decreased COP displacement relative to the pre-fatigue trial. Although it is unclear why two different strategies were used post-fatigue, we do know that postural control is based on a combination of pre-existing biomechanical constraints, cognitive processes, and sensorimotor

coordination that work together with previous experience to shape an individual's motor response (Horak 2006). In some participants, the addition of fatigue may have increased the level of postural anxiety, resulting in an increased muscle co-activation (Okada et al. 2001), decreased muscle activity (Kanekar et al. 2008), decreased COP displacement (Adkin et al. 2000) and an overall increase in the rigidity of the postural response (Carpenter et al. 2004). Research on threatening postural tasks has demonstrated that previous experience with a high level of postural threat improves the postural response in less threatening situations, allowing a larger COP displacement relative to participants without this experience (Adkin et al. 2000). It is possible that a similar process occurred in this study, affording participants who had previously dealt with neuromuscular fatigue a higher level of confidence in their ability to overcome fatigue and maintain postural stability. This increased experience and confidence may have allowed the participants to use a more fluid and efficient postural response to deal with the internal perturbation caused by fatigue. Unfortunately, interpretation of this data is limited by the lack of information regarding the level of fear and experience of each participant.

The postural response to the forward displacement of the platform differed from both of the strategies used in the backwards direction. For example, when the platform moved forwards none of the participants altered their postural muscle onset latency or their COP or COM displacement relative to the trial performed immediately pre-fatigue (Pre-F10). Instead participants moved onto their toes to compensate for the forward movement of the platform, allowing them to remain stable immediately post-fatigue without altering their muscle activity. Although additional information is required to be sure, an increased level of postural anxiety caused by the backwards postural perturbation may have contributed to the postural strategy selection used immediately post-fatigue in this direction.

The second aim of this study was to follow the evolution of the postural response as the ankle muscle fatigue recovered over a ten-minute post-fatigue period. Our hypothesis that the COP displacement and muscle activity would return to the pre-fatigue values as the ankle force production capacity recovered was not supported. Instead, the postural trials performed once the ankle muscle force production had fully recovered, e.g. at F10, remained significantly different than the pre-fatigue trials. Previous research has identified a similar delayed recovery of postural control strategies (Strang et al. 2008) and even of overall postural stability (Nardone et al. 1998; Fox et al. 2008) after neuromuscular fatigue; however, the modality of these changes and the progression of their return to the pre-fatigue state is not well understood. This ambiguity is related in part to the task dependent nature of the manifestation of central and peripheral fatigue. Without a clear quantification of the impact of neuromuscular fatigue on the peripheral and central systems it is difficult to assess the impact on neuromuscular control of complex motor tasks.

Therefore, the recovery of the postural response in this study was assessed in conjunction with the recovery of the fatigue-induced changes occurring within the peripheral and central systems. Previous characterization of the fatigue created by the bi-directional ankle fatigue protocol revealed that by the second postural trial, performed at F5, the measurable central fatigue had subsided but the peripheral fatigue was still quantifiable in the dorsi-flexor muscles and the force production capacity was still reduced in the plantar-flexor muscles (Kennedy et al. 2011a). Generally, at F5 the COP returned to the pre-fatigue anterior-posterior location within the base of support indicating that the participants were more comfortable with the postural task at this point. However, the co-activation of the TA and MG muscles had not return to pre-fatigue

levels suggesting that the postural response was still modified to compensate for the effects of fatigue at F5.

The directionally specific data also suggested lingering fatigue effects at F5. In the backwards direction the participants in subgroup 2 began to activate their MG muscles earlier in anticipation of the perturbation relative to the pre-fatigue trial at F5. Interestingly, this subgroup also began to use their BF muscles again at this time, indicating a clear modification of the postural strategy. Although there was no change in the onset latency of the postural muscles in subgroup 1, participants began to decrease their COP displacement around this time. When the platform moved forwards the TA and RF muscles were activated earlier at F5 than they were before the fatigue protocol. In this direction participants also demonstrated a progressively smaller displacement of the COP. It is likely that the recovery of the central fatigue combined with the increased experience with the fatigued postural task both contributed to the evolution of the postural response found between F1 and F5.

The postural response continued to evolve further away from the pre-fatigue response as the ankle force production capacity recovered. After ten minutes of rest the COP displacement was significantly reduced in both subgroups in the backwards direction and for all participants in the forward direction relative to the pre-fatigue trial. Postural changes have been previously demonstrated to linger for 15 (Pline et al. 2006) and 20 (Yaggie and McGregor 2002) minutes after postural muscle fatigue; however, the mechanisms behind the delayed recovery have not been explored. Work performed in our laboratory revealed that the peripheral fatigue created in this study lingered throughout the ten-minute recovery period (Kennedy et al. 2011a). Although it is likely that the peripheral fatigue did not directly impact the postural response, it is possible that afferent information from the lingering peripheral changes caused the central nervous system

to continue to mediate the postural response. Several researchers have postulated that this type of central mediation plays an important role in postural control, regardless of the postural muscle that is fatigued (Strang and Berg 2007; Kanekar et al. 2008), and have demonstrated that fatigue of one muscle may cause both the fatigued and un-fatigued postural muscles to be activated earlier in advance of a postural perturbation post-fatigue (Strang et al. 2009).

In summary, fatigued participants modified their postural response to successfully control the displacement of their COM throughout the 10 minute recovery period. Although the fatigued individuals initially achieved postural stability using different strategies, they all decreased their COP displacement relative to the pre-fatigue trial after ten minutes of rest despite the full recovery of the ankle force production capacity and any quantifiable central fatigue. We postulate that afferent feedback from the lingering DF peripheral fatigue was an important factor in the postural modifications found in this study.

#### 4.6 References

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**Chapter 5: Fatiguing handgrip exercise alters maximal force-generating capacity of plantar-flexors**

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# **Fatiguing handgrip exercise alters maximal force-generating capacity of plantar-flexors**

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## 5.1 Abstract

Exercise induced fatigue causes changes within the central nervous system that decrease force production capacity in fatigued muscles. The impact on unrelated, non-exercised muscle performance is still unclear. The primary aim of this study was to examine the impact of a bilateral forearm muscle contraction on the motor function of the distal and unrelated ankle plantar-flexor muscles. The secondary aim was to compare the impact of maximal and submaximal forearm contractions on the non-fatigued ankle plantarflexor muscles. Maximal voluntary contractions (MVC) of the forearm and ankle plantar-flexor muscles as well as voluntary activation (VA) and twitch torque (TT) of the ankle plantar-flexor muscles were assessed pre-fatigue and throughout a 10-minute recovery period. Maximal (100% MVC) and submaximal (30% MVC) sustained isometric handgrip contractions caused a decreased handgrip MVC (to  $49.3 \pm 15.4\%$  and  $45.4 \pm 11.4\%$  of the initial MVC for maximal and submaximal contraction, respectively) that remained throughout the 10-minute recovery period. The fatigue protocols also caused a decreased ankle plantar-flexor MVC (to  $77 \pm 8.3\%$  and  $92.4 \pm 6.2\%$  of pre-fatigue MVC for maximal and submaximal contraction, respectively) and VA (to  $84.3 \pm 15.7\%$  and  $97.7 \pm 16.1\%$  of pre-fatigue VA for maximal and submaximal contraction, respectively). The plantar-flexor MVC recovered after the first minute post-fatigue while the VA recovered after the initial post-fatigue testing session. These results suggest central fatigue created by the fatiguing handgrip contraction translated to the performance of the non-exercised ankle muscles. Our results also show that the maximal fatigue protocol affected ankle plantar-flexor MVC and VA more severely than the submaximal protocol, highlighting the task-specificity of neuromuscular fatigue.

**Keywords:** central fatigue, peripheral fatigue, recovery, voluntary activation

## 5.2 Introduction

Neuromuscular fatigue is defined as a progressive reduction in the ability of a muscle to produce power or force regardless of whether the task can be sustained (Bigland-Ritchie and Woods 1984; Gandevia 2001). Fatigue affects the entire neuromuscular system from the muscle fibres and neuromuscular junction, i.e. peripheral fatigue, to the higher planning centres in the brain, i.e. central fatigue. Although it is difficult to quantify directly, central fatigue is defined as the decrease in central drive to the motoneurons (Gandevia 2001). Central fatigue contributes significantly to the decreased force production capacity of an exercised muscle (Gandevia et al. 1996; Smith et al. 2007; Sogaard et al. 2006) and is hypothesized to modulate the planning and execution of motor tasks beyond those involving the fatigued muscle group (Amann and Dempsey 2008; Forestier et al. 2002).

The manifestations of central fatigue are highly task specific (Enoka 2008), making it important to characterize the type of fatigue produced by the exercise before assessing how this fatigue alters motor performance. Although both maximal and submaximal contractions elicit central and peripheral changes (Bilodeau 2006; Sogaard et al. 2006; Taylor and Gandevia 2008), low-intensity, continuous exercise is often associated with central failure while maximal contractions are more associated with peripheral failure (Place et al. 2008). Eichelberger and Bilodeau (2007) proposed that these difference may not only be caused by the intensity of the contractions but that disparate stopping criteria and contraction duration may also contribute to the differences found post-fatigue (Eichelberger and Bilodeau 2007).

Researchers have been able to examine central fatigue more closely by examining the impact of exercise induced fatigue on the motor performance of a muscle group that is not involved in the exercise (i.e. “non-exercised muscle”). Using this approach McLean and

Samorezov (2009) found that the central fatigue created during single leg squats crossed over to the non-exercised leg resulting in a less efficient strategy when landing on that leg. They postulated that central fatigue, possibly caused by the inhibitory action of the fatigued leg muscles, decreased the proprioceptive abilities and altered the decision-making and movement execution of the central nervous system (CNS) (Mclean and Samorezov 2009). Unfortunately, it is not clear if the fatiguing exercise performed in this study also created fatigue within the muscles surrounding the hip joint and lower back. If these muscles were fatigued they could have been responsible for the post-exercise changes in postural control. Furthermore, the amount of central fatigue and the duration of the central changes were not quantified in this study making it difficult to assess the relationship between central fatigue and the execution of the motor task immediately after the exercise and as fatigue subsided.

The influence of central fatigue can be more clearly assessed during a simple motor task where the level of voluntary muscle activation (VA) and/or cortical excitability is examined. The VA is a measure of central fatigue that is quantified by measuring the additional force produced by neuromuscular stimulation performed during a maximal voluntary contraction (Belanger and McComas 1981). This basic measure has been used to explore the cross-over effect that central fatigue created in one limb has on the contralateral, homogeneous muscle group (Benwell et al. 2006; Humphry et al. 2004; Post et al. 2008; Todd et al. 2003). One such study found that the central fatigue created during an unilateral upper arm task was powerful enough to decrease the force production of the non-exercised arm (Post et al. 2008). Another study examined the impact of unilateral leg fatigue on the contralateral limb (Rathey et al. 2006). Although the force production and the peripheral measures of fatigue, i.e. the twitch torque and M-wave properties, of the non-exercised leg were unchanged, the level of voluntary activation was significantly

decreased in this leg after the unilateral fatigue protocol. The authors concluded that central fatigue crossed-over to the non-exercised limb but that it did not affect their basic force production capacity.

Presently, it is unclear whether the central fatigue created by an upper limb exercise would also cross-over to and/or affect the motor performance of distal and unrelated lower limb muscles. An investigation into this relationship may increase our understanding of the impact that central fatigue has on the motor control of unrelated, non-fatigued muscle groups. Therefore, the aim of the present study was to determine whether the neuromuscular fatigue created during an upper limb fatigue protocol would be transferred to an unrelated muscle group at the ankle. More specifically, we investigated how fatigue induced by a sustained isometric handgrip exercise affected the ability to voluntarily activate and produce force in ankle plantar-flexor muscles immediately post-fatigue and throughout a 10 min recovery period. Since neuromuscular fatigue is highly dependent on the type of exercise (Enoka and Duchateau 2008), the secondary aim was to determine if the effects of neuromuscular fatigue differed between a maximal and submaximal fatigue task. It was hypothesised that the central fatigue created by a sustained sub-maximal fatigue protocol would affect the motor performance of an unrelated, non-fatigued muscle group more severely than that produced by a sustained maximal contraction.

### **5.3 Methods**

**Participants.** Fourteen young healthy, habitually active participants (6 women, 8 men; ranged from 20 to 30 years; female height  $170.5 \pm 3.9$  cm; weight  $60.5 \pm 4.5$  kg, male height  $176.8 \pm 4.9$  cm; weight  $71.8 \pm 6.7$  kg) volunteered to participate in two separate testing sessions; one testing a maximal fatigue protocol and the other a submaximal fatigue protocol. Participants were informed as to the nature of the experiment and the study was approved by the local ethics committee and was conducted according to the Helsinki declaration.

**Experimental Setup.** As shown in Fig 1A, participants sat on an isokinetic dynamometer (Biodex System 3 Research, Biodex Medical, Shirley, USA) with their torso reclined by  $15^\circ$  from upright and both legs extended in front of them. Their right foot was strapped into an ankle attachment that held the foot at  $10^\circ$  plantar flexion. The torso, waist and right thigh were strapped to the dynamometer chair to ensure that the participant's body position did not change throughout the experiment. The participant's forearms were placed on a table in front of them in a supinated position. Their hands were strapped to the table and an instrumented handgrip (Pinch/Grip Digital Analyzer; MIE Medical Research Ltd, Leeds, UK) was placed in each hand. The width of the handgrip was adjusted to each participant's hand size so that the proximal interphalangeal joints of the 4 fingers rested on one side of the handgrip and that of the thumb rested on the other side. The fingers of the right hand were taped to the handgrip to ensure that the finger placement did not change between trials, that the basal grip force remained stable throughout the testing period and that the grip was relatively constant between participants. The torque signals from the ankle attachment on the isokinetic dynamometer (Biodex) and each of the handgrips were digitized at a sampling rate of 4 kHz (Bagnoli 16, Delsys Inc., Boston, USA), low-pass filtered at 50 Hz and displayed on a monitor in front of the participant.

**EMG recording.** Surface electromyography (EMG) was recorded from the, *flexor digitorum superficialis* (FDS) and *biceps brachii* (BB) of the right arm. The BB EMG was recorded to ensure that its recruitment did not change during the fatigue protocol and that the putative changes observed at the level of PF were only due to handgrip muscles. EMG was also recorded from the *medial* (GM) and *lateral* (GL) *gastrocnemius*, and *soleus* (SOL) of the right leg. For each muscle, a dry-surface electrode (Delsys DE 2.1, Delsys Inc, Boston, USA; 1 cm interelectrode distance) was attached to the skin. Prior to electrode application, the skin was shaved and cleaned with a mixture of alcohol and ether to minimize impedance. Each electrode was placed in accordance with the SENIAM recommendations (Hermens et al. 2000). The FDS electrode was placed on the muscle belly located in the lateral component of the forearm approximately half way between the medial epicondyle and the base of the 4<sup>th</sup> finger. Placement of the FDS was verified by an intense handgrip contraction. A ground electrode was placed on the pisiform bone of the right hand. The EMG signals were amplified (x 1000) and digitized (bandwidth of 6-400 Hz) at a sampling rate of 4 kHz (Bagnoli 16, Delsys Inc., Boston, USA)

**Electrical stimulation.** Twitch contractions of the right ankle plantar-flexors were elicited by electrical stimulation of the tibial nerve found in the popliteal fossa (Scaglioni and Martin 2009). The cathodes were placed 10 cm distal to the popliteal fossa. A conductive probe was used to determine the precise stimulation location that provided the largest mechanical response in the ankle. A 2 × 2 cm anode was placed on this location and a constant current stimulator (Digitimer DS7A, Digitimer Ltd., Letchworth Garden City, UK) delivered single electric pulses to the tibial nerve (pulse duration = 200µs). To determine the appropriate stimulation intensity, stimuli began at low level and were increased in incremental steps of 20 mA until the force produced by the stimulation no longer increased (mean maximum current = 173.0 ± 30.5 mA). To ensure the

reliability of our stimulation technique we checked that the force produced by the stimulation performed at rest was equal to or greater than 25% of the participant's MVC (Bulow et al. 1993).

## **Procedure**

Each participant performed two separate testing sessions. One session examined the impact of handgrip muscle fatigue created by a bilateral maximal isometric handgrip contraction while the other examined that created by a bilateral submaximal handgrip contraction. The order of the sessions was randomly assigned and there were 48 to 72 hours separating the two sessions. Each session consisted of a warm-up, pre-fatigue maximal voluntary isometric contractions (MVCs), a bilateral handgrip fatigue protocol, consisting of either a sustained maximal or a submaximal contraction, and a series of post-fatigue MVCs (Fig 1B). During the pre and post-fatigue MVCs the handgrip and ankle plantar-flexor contractions were performed in sequence. For clarity this sequence was called a 'contraction set'. Each 'contraction set' consisted of a 4 second long isometric handgrip contraction followed 15 seconds later by a 4 second plantar-flexion of the right ankle. The warm-up and fatiguing contractions were performed bilaterally in order to fatigue as much forearm muscle mass as possible. The MVCs performed pre and post-fatigue were performed unilaterally with the participants right arm.

The warm-up was performed with both handgrips simultaneously and consisted of 4 contraction sets performed at 25%, 4 at 50% and 4 at 75% of the participants perceived maximal handgrip and ankle MVC. Fifteen seconds of rest were given between the contraction sets and 1 minute was afforded between the 3 different levels.

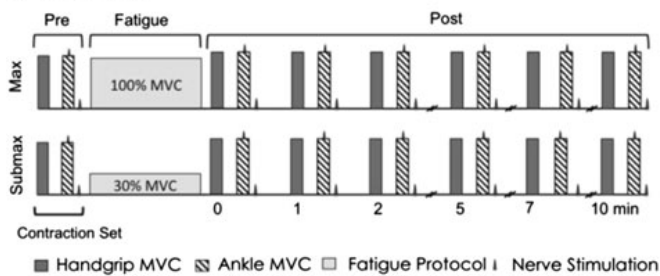
*Pre-fatigue.* Maximal contraction sets were repeated twice for both hands and the right ankle. The largest initial handgrip force produced (MVC) was used to calculate the stopping criterion

(20% MVC) used in the submaximal and maximal fatigue protocols, as well as the level of force to be maintained in the both hands during the submaximal fatigue protocol (30% MVC).

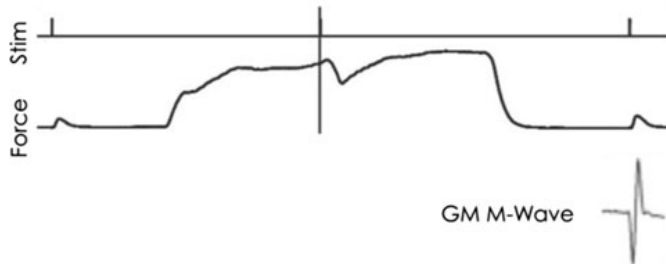
### A Experimental setup



### B Protocol



### C Representative Data



**Fig 1 Submaximal and maximal experimental protocols performed on separate testing days.** *A) Experimental setup. Participants sat on a dynamometer with their shoulders and waist strapped to the chair, their hands strapped to the table in front of them and their right ankle and foot strapped to an ankle attachment. B) Submaximal and maximal fatigue protocol. The participants performed pre-fatigue maximal voluntary contractions (MVCs) with the right hand and ankle, a fatiguing contraction with both hands simultaneously, and a series of post-fatigue contractions performed with the right hand and ankle. During and immediately after each ankle plantarflexor MVC performed pre and post-fatigue, electrical stimuli were delivered to the tibial nerve. C) Representative data from the neuromuscular stimulation. The top trace represents the timing of the stimulation (stim). The bottom trace represents the ankle PF force from which the VA and TT were calculated. The inset image is a close up of the GM M-wave.*

Next, the participants performed two more contraction sets in which the right hand and right ankle plantar-flexor were maximally contracted. The larger of these two contractions was used as the pre-fatigue value in the statistical analysis. During these contraction sets the ankle plantarflexors were superimposed with electrical stimulations. The stimulations were performed during the ankle MVCs as soon as the individual reached a stable force plateau and immediately after each of the contractions. Two minutes of recovery was given between each contraction set and 15 seconds was afforded between the handgrip and stimulated ankle plantar-flexor contractions.

*Fatigue Protocol.* After 3 min of rest the participants began either the maximal or submaximal handgrip fatigue protocol. These fatiguing contractions were performed bilaterally to increase the amount fatigue created within the forearm muscles in order to maximize the central changes occurring in reaction to the peripheral changes (Noakes et al. 2005). The force produced was visualized separately for both hands throughout the fatigue protocols. During the maximal isometric handgrip protocol the participants were verbally encouraged to produce the maximal amount of force possible with both hands. During the submaximal isometric handgrip protocol the participants were verbally encouraged to maintain their hand force production at 30% MVC, which was visually indicated on each of the graphs, for as long as possible with both hands. The fatigue protocol was stopped in both the maximal and submaximal conditions when the force production was reduced to 20% of MVC previously determined for the right hand. The participants were unaware of the stopping criteria.

A ten point Borg Scale was used to determine the perceived exertion of participants throughout the maximal and submaximal handgrip fatigue protocols (Adkin et al. 2002). Every 30 s the

participants were asked to assess their perceived effort on a scale of 0 to 10 where 0 represented the resting state and 10 represented the strongest contraction that fingers could perform.

*Post-Fatigue.* Immediately after the fatigue protocol (R0) the handgrip was removed from the left hand and the participants were asked to perform a set of MVCs with their right hand followed by one with their right ankle plantar-flexors. Electrical stimuli were delivered during and after each of the ankle contractions. This process was repeated after 1, 2, 5, 7 and 10 min of rest.

### **Data Analysis**

Data processing was performed using Matlab<sup>®</sup> scripts (The Mathworks, Natick, USA). Before data analysis was performed the EMG data was band-pass filtered (20-450 Hz). The forearm and ankle MVCs, as well as the ankle twitch torque (TT) and level of voluntary muscle activation (VA) were calculated for the largest of the two contractions performed pre-fatigue and for the contractions occurring immediately post-fatigue (R0), and throughout the recovery period (R1, R2, R5, R7, R10). The VA level was estimated by Eq. 1:

$$VA = [1 - (\text{extra torque} / \text{control twitch torque})] \quad (1)$$

The M-wave peak-to-peak amplitude was calculated for the GM and SOL using Spike2 (v5.06, Cambridge Electronic Design, UK) to investigate the possibility of peripheral fatigue in the ankle PF muscles (Figure 1 c).

### **Statistics**

A t-test assessed the difference between the duration of the maximal and submaximal fatigue protocols. A two-way repeated measure ANOVA [factors = trial type (submaximal and maximal)]

and fatigue (pre and post-fatigue)] was performed to determine the effect of fatigue on the handgrip MVCs, ankle PF MVC, VA, TT and the Sol and GM M-wave amplitudes. Next, a two-way repeated measure ANOVA [factors = trial type (submaximal and maximal) and recovery time (R0, R1, R2, R5, R7 and R10)] was used to assess the duration of the fatigue effects throughout the 10-minute post-fatigue testing session. Post-hoc analyses were performed when appropriate using Bonferroni corrected paired t-tests. Bivariate Pearson correlations compared the reduction of the handgrip and PF MVC to the changes in PF VA caused by the maximal and submaximal fatigue protocols.

A p-value below 0.05 was considered significant. Values are reported as mean  $\pm$  standard deviation (SD) throughout the text and the figures.

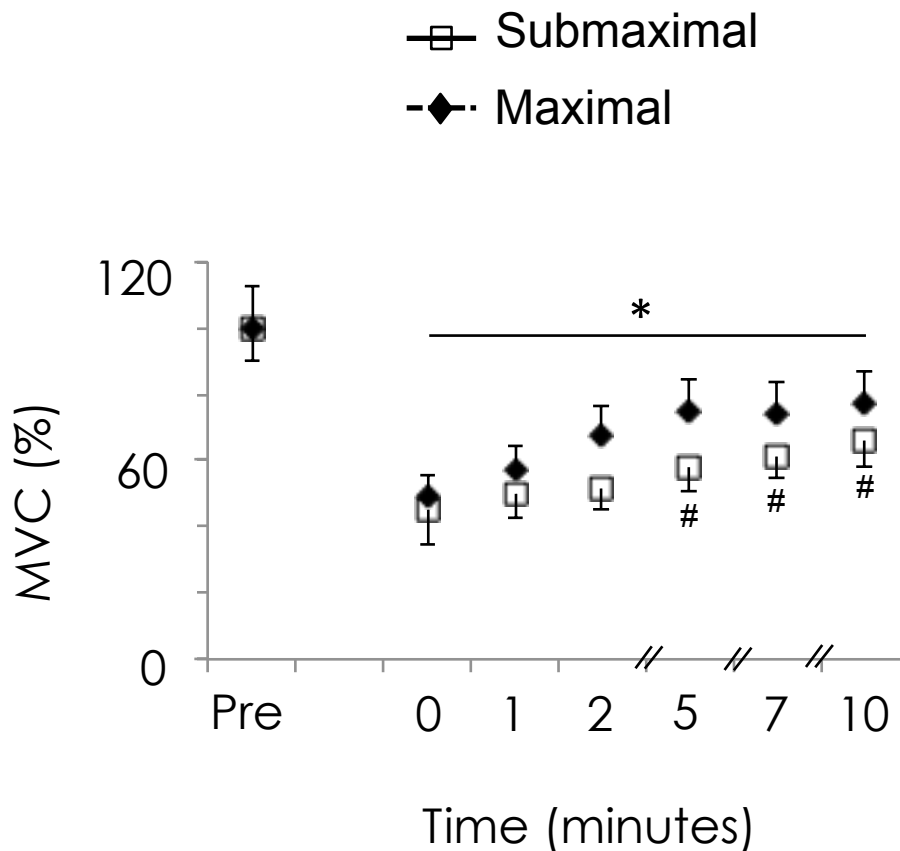
#### **5.4 Results**

*Fatiguing Contraction.* The maximal fatigue protocol was significantly shorter than the submaximal fatigue protocol ( $t(14) = 10.08$ ,  $p = 0.0001$ ;  $134 \pm 31$  vs.  $234 \pm 36$ s). While the perception of effort increased from  $2.2 \pm 0.9$  (fairly light) at the start of the submaximal fatigue protocol to  $6.1 \pm 1.2$  (hard) halfway through the protocol and  $10 \pm 0$  (“very very hard”) at the end of the protocol, it remained at 10 throughout the maximal protocol

#### *Handgrip*

There was a main effect of the fatigue protocols on the handgrip MVC ( $F(1, 13) = 32.78$ ,  $p = 0.001$ ) but no main effect of trial type (i.e. maximal or submaximal) ( $F(1, 13) = 0.25$ ,  $p = 0.627$ ) or interaction ( $F(1, 13) = 0.61$ ,  $p = 0.448$ ) indicating that the MVC was similarly affected by the two exercises immediately post-fatigue (R0). The maximal fatigue protocol decreased the MVC

to  $49.3 \pm 15.4\%$  MVC while the submaximal protocol decreased the value to  $45.4 \pm 11.4\%$  MVC. However, post-fatigue there was a main effect of recovery time ( $F(6, 72) = 27.91, p = 0.001$ ), trial type ( $F(1, 12) = 5.18, p = 0.040$ ) and interaction ( $F(6, 72) = 2.78, p = 0.017$ ), indicating that MVC did not recover in the same way after the maximal and submaximal forearm contractions. Post-hoc analysis revealed that the post-fatigue values were significantly lower than the pre-fatigue values throughout the entire post-fatigue testing session ( $p < 0.05$ ) and that the handgrip MVC values were lower after the submaximal fatigue protocols relative to the maximal values at R5 ( $p = 0.018$ ), R7 ( $p = 0.01$ ) and R10 ( $p = 0.034$ ) (Fig. 2).



**Fig 2 Handgrip Force Production.** Maximal voluntary contractions (MVC) of the handgrip are depicted pre and post-fatigue for the submaximal (solid diamonds) and maximal (open squares) fatigue protocols. The data are shown as mean  $\pm$  SD pre-fatigue (pre), immediately post-fatigue (0) and throughout the 10 min recovery period (1-10). \* indicates a significant difference from

*the pre-fatigue value and # indicates a difference between the maximal and submaximal data ( $p < 0.05$ ).*

#### *Ankle Plantar-flexors*

There was a main effect of the handgrip fatigue protocols on the ankle force production (F (1, 13) = 9.32  $p = 0.009$ ), trial type (F (1, 13) = 92.15  $p = 0.001$ ) and interaction of fatigue x trial type (F (1, 13) = 9.32  $p = 0.009$ ) indicating that the two fatigue protocols affected the ankle PF MVC differently. The maximal fatigue protocol decreased the ankle PF MVC to  $77 \pm 8.3\%$  of pre-fatigue MVC while the submaximal fatigue protocol decreased the value to  $92.4 \pm 6.2\%$  MVC. Post-fatigue there was a main effect of recovery time (F (6, 72) = 4.34,  $p < 0.05$ ) and trial type (F (1, 12) = 6.49,  $p < 0.05$ ). Post-hoc analysis revealed that the ankle PF MVC was reduced for the first two post-fatigue trials performed at R0 ( $p = 0.001$ ) and R1 ( $p = 0.019$ ) before it returned to the pre-fatigue values. However, there was no main effect for the interaction (F (6, 72) = 2.17,  $p > 0.05$ ).

There was a main effect of both fatigue protocols (F (1, 13) = 6.33,  $p = 0.026$ ) and trial type (F (1, 13) = 7.07,  $p = 0.02$ ) on the ankle PF VA. The interaction fatigue protocols  $\times$  trial type was significant (F (1, 13) = 6.33,  $p = 0.026$ ) indicating that the maximal and submaximal fatigue protocols affected the PF VA differently immediately post-fatigue (R0). More precisely, the maximal fatigue protocol caused a decrease in the ankle PF VA to  $84.3 \pm 15.7\%$  and the submaximal protocol to  $97.7 \pm 16.1\%$ . Two-way repeated measure ANOVAs performed on the post-fatigue data showed that there was a main effect of recovery time (F (6, 72) = 3.05,  $p = 0.010$ ) but not trial type (F (1, 12) = 0.15,  $p = 0.70$ ) or interaction (F (6, 72) = 0.94,  $p = 0.47$ ). The ankle VA was significantly lower at R0 ( $p = 0.007$ ) than it was before the fatigue protocols. After this point the ankle VA returned to the pre-fatigue values (i.e. R1,  $p = 0.072$ ).

There was no main effect of fatigue ( $F(1, 13) = 0.029, p = 0.87$ ), trial type ( $F(1, 13) = 2.30, p = 0.153$ ) or interaction ( $F(1, 13) = 0.29, p = 0.601$ ) on the ankle PF TT. Furthermore, no main effect of recovery time ( $F(6, 72) = 1.39, p = 0.231$ ), trial type ( $F(1, 12) = 0.58, p = 0.46$ ) or interaction ( $F(6, 72) = 0.49, p = 0.81$ ) was found. There was no main effect of fatigue on the peak-to-peak M-wave amplitude recorded from the GM ( $F(1, 13) = 0.050, p = 0.828$ ) or SOL ( $F(1, 13) = 0.17, p = 0.69$ ) muscles. Similarly there was no main effect of trial type ( $F(1, 13) = 0.84, p = 0.377, F(1, 13) = 0.97, p = 0.76$ ) or interaction ( $F(1, 13) = 1.72, p = 0.22, F(1, 13) = 3.0, p = 0.11$ ) on either muscle. The repeated measure two-way ANOVA revealed that there was no main effect of the recovery time ( $F(6, 72) = 0.28, p = 0.95, F(6, 72) = 0.083, p = 0.99$ ) trial type ( $F(1, 12) = 0.35, p = 0.57, F(1, 12) = 0.008, p = 0.93$ ) or interaction ( $F(6, 72) = 0.21, p = 0.98, F(6, 72) = 0.24, p = 0.97$ ) for either the GM or the SOL muscles. Overall, these results indicate that no peripheral fatigue occurred in PF.

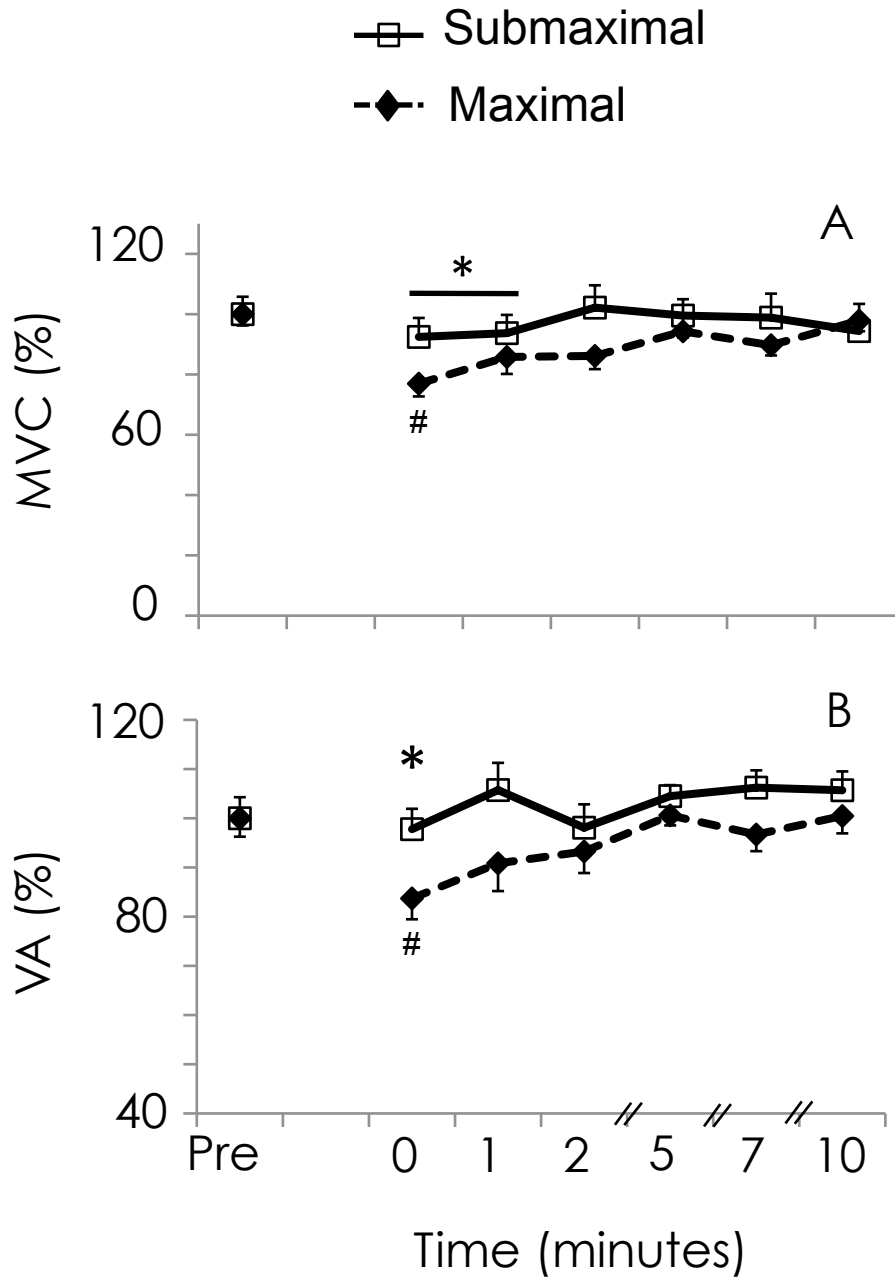
No significant correlation was found between the handgrip MVC and the PF VA after both the maximal ( $r(12) = 0.138, p = 0.638$ ) and the submaximal fatigue protocol ( $r(12) = 0.004, p = 0.988$ ). Similarly, no significant correlation between the ankle PF MVC and PF VA was found for both the maximal ( $r(12) = -0.297, p = 0.303$ ) and the submaximal ( $r(12) = 0.144, p = 0.623$ ) fatigue protocol.

## **5.5 Discussion**

The present study investigated whether the neuromuscular fatigue induced by a sustained maximal and submaximal isometric handgrip contraction would result in decreased voluntary muscle activity and force production capacity of non-exercised ankle plantar-flexor muscles. The results indicate that the forearm fatigue protocols caused a temporary decrease in the maximal voluntary contraction and level of voluntary muscle activation of the non-fatigued ankle plantar-

flexor muscles. Moreover, the ankle PF MVC and VA were more affected by the maximal fatigue protocol relative to the submaximal protocol.

Twitch interpolation was used to assess the central and peripheral changes that occurred in the non-exercising ankle PF muscles. While the number of stimuli best suited for twitch interpolation has been disputed, single pulse stimuli were used to quantify the fatigue found in this study because it is the least painful method and has been shown to give a reliable measure of the participant's level of maximal voluntary activation (Behm et al. 1996; Merton 1954; Scaglioni and Martin 2009; Taylor 2009). Using this methodology we found that the MVC and VA of the non-exercising ankle plantar-flexor muscles were significantly decreased by the sustained handgrip contractions (Fig 3). Since there was no peripheral fatigue found within the plantar-flexor muscles (i.e. no change in TT or in GM or SOL M-wave amplitudes), we argue that fatigue created by the handgrip exercise was responsible for the impaired motor performance at the ankle. More precisely, the decreased VA and MVC as well as the substantial increase in perceived effort demonstrated that changes within the central nervous system temporarily prevented full activation of the muscles involved in the ankle plantar-flexion.



**Fig 3 Ankle plantarflexor muscle fatigue.** The maximal voluntary contraction (MVC) (A) and level of voluntary activation (VA) (B) are depicted for the ankle plantar-flexors pre and post-fatigue for the submaximal (solid diamonds) and maximal fatigue (open squares) protocols. All data are shown as mean  $\pm$  SD pre-fatigue (pre), immediately post-fatigue (0) and throughout the 10 min recovery period (1-10). \* indicates a significant difference from the pre-fatigue value and # indicates a difference between the maximal and submaximal data ( $p < 0.05$ ).

Recovery of the ankle MVC and VA and handgrip MVC were assessed throughout a 10-min post-fatigue recovery period. The data demonstrated that the ankle PF VA recovered after the first test performed post-fatigue (R0) and that the ankle PF MVC recovered after a minute of rest (R1). These changes occurred despite the lingering impairment of the handgrip MVC found throughout the 10-min post-fatigue testing period. The disparity in recovery time between the ankle MVC and the handgrip MVC can be explained by the type of fatigue causing the impairment. The decreased handgrip MVC was caused by both peripheral and central changes while the ankle MVC was only affected by systemic central fatigue. Recovery of the central changes, which occurs more quickly than recovery of peripheral fatigue (Søgaard et al. 2006), allowed the ankle MVC to return to the pre-fatigue levels rapidly post-fatigue. We postulate that slower recovering peripheral changes within the forearm muscles were responsible for a large proportion of the decreased forearm MVC found throughout the 10-minute post-fatigue testing period.

The second aim of this study was to examine the effect of a maximal and a submaximal (30% MVC) handgrip contraction on the muscle performance of the non-fatigued ankle plantar-flexors. The maximal and submaximal contractions were both performed until the force production capacity was reduced to 20% MVC to ensure that the exhaustion/stopping criteria did not influence the data (Eichelberger and Bilodeau 2007). The results indicated that even when the stopping criteria were controlled, the maximal and submaximal forearm contractions did not impact ankle performance in the same way. More specifically, the ankle PF MVC and VA were both decreased further immediately after the maximal fatigue protocol relative to the submaximal protocol. Furthermore, the PF MVC recovered more slowly after the maximal protocol than after the submaximal protocol. These differences did not support our initial hypothesis, which

predicted that the submaximal fatigue protocol would create more central fatigue than the maximal protocol. It is possible that the energy required to drive the forearm muscles maximally created more severe central changes than the submaximal contraction; however, it is difficult to support this theory without a precise quantification of central/peripheral fatigue created at the level of handgrip muscles.

In conclusion, this study was the first to demonstrate that fatigue created by a forearm muscle contraction resulted in a decreased motor performance of the functionally unrelated and distally located ankle plantar-flexor muscles. Specifically, we reported that isometric handgrip contractions briefly decreased the ankle plantar-flexor MVC and VA. Since peripheral fatigue was not found in the ankle plantar-flexors, we suggest that the changes found in the ankle PF were caused by the central fatigue developed during the handgrip exercise. Further analysis revealed that the maximal handgrip fatigue protocol caused a larger decrease in the ankle MVC and VA than the submaximal protocol. The results from this study increase our understanding of how central fatigue affects simple motor performance of a non-exercised and functionally unrelated muscle group. Additional research is required to explore how this systemic change affects more complex motor tasks that involve the lower limb such as postural stability and locomotion.

## **Acknowledgements**

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## 5.8 Unpublished Findings

Although the results regarding peripheral and central fatigue developed within the forearm muscles were not published with the rest of the data from this experiment, it is important to mention these findings here as they contribute to the understanding of the central fatigue in the subsequent postural study (Figure 1.4). These data were not published because the stimulation techniques had not been previously validated and we could not confirm that median nerve was stimulated in isolation from the ulnar nerve. The stimulation (200 $\mu$ s with a mean maximum current of  $124 \pm 26.3$ ) occurred 10 cm proximal to the medial epicondyle with a cathode placed 10 cm distal to the medial malleolus.

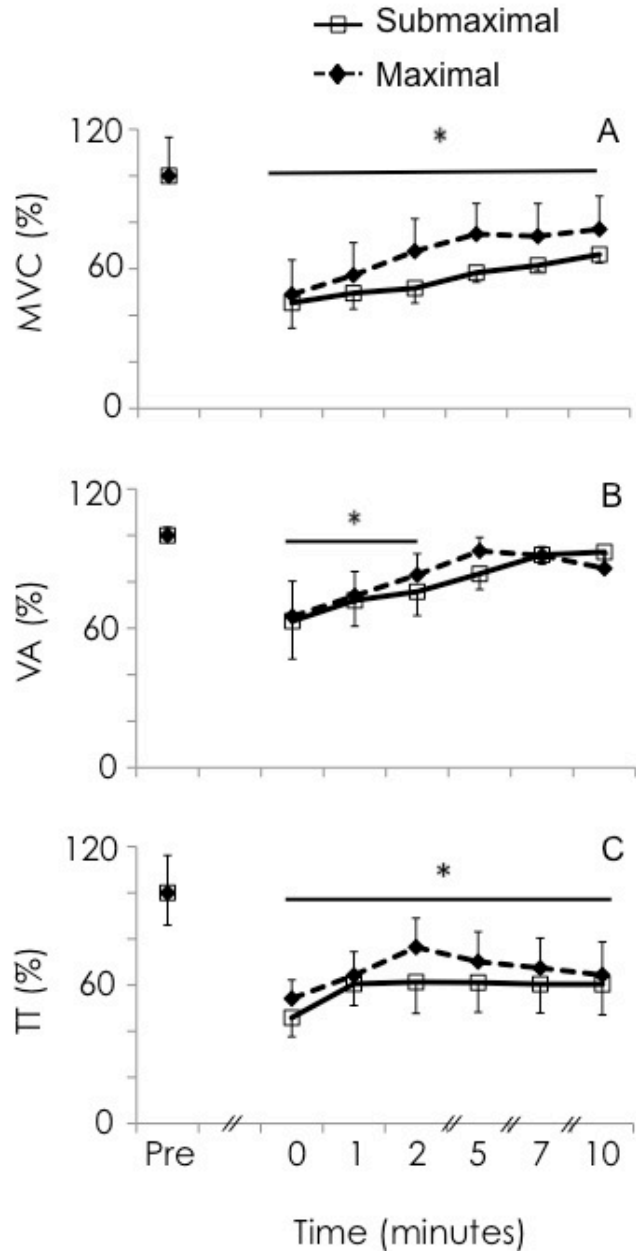
*Statistical Analysis.* Two-way repeated measure ANOVAs [factors = time (i.e. pre-fatigue or post-fatigue at R0, R1; R2; R5; R7 or R10) and type of exercise (i.e., submaximal vs. maximal)] were used to assess the impact of fatigue on MVCs, VA and TT for the right forearm muscles. A p-value below 0.05 was considered significant. If significant main effects were detected Bonferroni *post hoc* tests comparing the post-fatigue values to the pre-fatigue value determined how long the post-fatigue changes remained.

*Results:* The two-way repeated measures ANOVA revealed that there was no interaction effect (fatigue  $\times$  type of exercise:  $F(6, 150) = 1.129, p = 0.35$ ) of fatigue on the maximal voluntary contraction (MVC) of the handgrip and no main effect of the type of exercise ( $F(1, 25) = 0.72, p = 0.40$ ). However, there was a main effect of time ( $F(6, 150) = 39.87, p < 0.001$ ) on MVC. More precisely, the force was significantly decreased from  $22.6 \pm 6.2$  to  $9.6 \pm 2.3$  kg after the sustained handgrip contractions. The handgrip MVC remained significantly lower than the pre-fatigue condition throughout the ten-min post-fatigue recovery period (Figure. 4 A).

There was no interaction fatigue  $\times$  type of exercise ( $F(6, 150) = 0.49, p = 0.82$ ) and no main effect of type of exercise ( $F(1, 25) = 1.54, p = 0.24$ ) on the voluntary activation level (VA) found in the handgrip muscles post-fatigue. There was a main effect of time ( $F(6, 150) = 10.80, p < 0.001$ ) on the VA found post-fatigue. The VA was significantly reduced from  $95.9 \pm 13.2\%$  pre-fatigue to  $61.5 \pm 18.5\%$  after the fatigue protocol. The VA remained significantly reduced throughout the first 2 min post-fatigue (R0, R1, R2  $p < 0.05$ ) (Figure. 4 B).

There was no significant interaction fatigue  $\times$  type of exercise ( $F(6, 156) = 0.58, p = 0.75$ ) on the twitch torque in the handgrip muscles measured post-fatigue and no main effect of type of exercise ( $F(1, 26) = 0.02, p = 0.88$ ); however there was a main effect of fatigue ( $F(6, 156) = 18.61, p < 0.001$ ). The TT was decreased to  $49.8 \pm 9.1\%$  of the  $MVC_i$  after the handgrip contraction. The TT remained significantly decreased throughout the ten-min recovery period (Figure. 4 C).

*Summary:* The results depict that both the maximal and submaximal forearm muscle fatigue protocols caused the forearm muscle MVC to be decreased throughout the ten-minute post-fatigue period relative to the pre-fatigue MVC. Both protocols also caused a decreased VA in the forearm muscles that remained for the first two minutes after the forearm contraction. Finally, the forearm TT was decreased by both the maximal and submaximal fatigue protocols throughout the entire ten-minute recovery period relative to the pre-fatigue values.



**Fig 4. Handgrip muscles fatigue.** % maximal handgrip force production (MVC) (A), level of voluntary activation (VA) (B) and twitch torque (TT) (C) are depicted for both pre and post-fatigue for the maximal (solid diamonds) and submaximal (open squares) fatigue protocols. All data are shown as mean  $\pm$  SD pre-fatigue (pre), immediately post-fatigue (0) and throughout the ten min recovery period (1-10). \* indicates a significant difference from the pre-fatigue value ( $p < 0.05$ ).

**Chapter 6: Impact of Forearm Fatigue on the Postural  
Response to an Externally Initiated, Predictable  
Perturbation**

Submitted to Neuroscience Letters

# Impact of Forearm Fatigue on the Postural Response to an Externally Initiated, Predictable Perturbation

Impact of Forearm Fatigue on the Postural Response to an Externally Initiated, Predictable  
Perturbation

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## **6.1 Abstract**

### **Objective**

To examine the impact of central fatigue on the anticipatory postural response to continual oscillations of the support platform throughout a ten-minute recovery period.

### **Methods**

Central fatigue was isolated from the changes occurring within the muscle by inducing fatigue in non-postural muscles, in this case the forearm muscles involved in a bi-lateral handgrip contraction. Postural control, including the center of mass (COM) and center of pressure (COP) displacement and muscle activity, was quantified pre-fatigue and throughout a ten-minute post-fatigue period.

### **Results**

Immediately post-fatigue the COP displacement decreased and the postural muscles were activated earlier in anticipation of the perturbations. These changes returned to the baseline values as the central fatigue recovered despite the lingering peripheral feedback from the fatigued non-postural muscles.

### **Conclusion**

These findings suggest that central fatigue created by the fatiguing forearm contraction modified the postural strategy used to maintain stability. This is the first study to clearly demonstrate that central fatigue impacts dynamic postural control.

## **6.2 Highlights**

1. Fatigue within the central nervous system was isolated from the fatigued muscles.
2. Central fatigue modified the postural response to the predictable postural perturbation.
3. The postural response returned to baseline values as central fatigue subsided.

### **6.3 Introduction**

Postural control is a dynamic process that is dependant on pervious experience, postural confidence and afferent feedback from the sensory systems to maintain balance. Exercise induced fatigue decreases postural control, causing an increased sway in quiet stance [5, 17, 23]. In dynamic postural tasks participants adjust their motor response to compensate for the local impairment [3, 6, 7]. More specifically, the anticipatory postural responses to self-initiated postural perturbations causes both the fatigued and non-fatigued muscles to be activated earlier in anticipation of the perturbation with a smaller muscle burst amplitude relative to pre-fatigue trials [6, 13]. These findings suggest that the change in postural response is centrally mediated; however, the involvement of fatigued muscles in the postural task makes it difficult to be certain. Work in our laboratory has demonstrated that postural changes caused by fatigue outlasted the recovery of postural muscle force production [7]. We found that as the ankle plantar and dorsiflexor muscles recovered from alternating isometric contractions many participants continued to activate their postural muscles further in advance of the perturbation and all showed a smaller center of pressure (COP) displacement than they did pre-fatigue. We hypothesized that the modification of the postural response was caused by a progressive change in the central nervous system's (CNS) motor plan based on afferent feedback from the muscle rather than by a decreased muscle capacity caused by fatigue-induced muscle failure. Presently it is unclear whether this central modification only occurs in response to fatigue of muscles that are directly involved in the motor task or whether it is a general fatigue response.

To examine this central modification more closely, researchers typically fatigue one muscle group and analyze the impact on the muscle activation and motor performance of non-fatigued muscle groups [18, 19]. In this way it is possible to analyze the impact of the fatigue protocol on

the central nervous system and on the performance of the non-fatigued muscles in isolation from any peripheral changes occurring within the fatigued muscles. In single limb quiet stance this experimental approach demonstrated that fatigue of one thigh decreased the postural stability on the contralateral, non-fatigued leg [17]. The maximal voluntary contraction (MVC) of the non-fatigued leg was not affected by the fatigue protocol and so it was hypothesized that the postural changes originated within the central nervous system. However, the muscle activity was not quantified in this experiment and so it is difficult to determine if and how the postural response was modified to compensate for the general destabilizing effects of the fatigue protocol.

In dynamic or perturbed postural tasks the CNS mediates and reorganizes the motor strategy used to compensate for the destabilizing effects of fatigue. Strang et al. (2009) investigated central mediation in detail by fatiguing the thigh muscles of one leg and quantifying the impact on postural sway and muscle onset latency of non-fatigued postural muscles during a self-initiated postural perturbation in which the participants rapidly reached both of their arms out in front of their bodies. The fatigued and non-fatigued postural muscles were activated earlier in anticipation of the self-initiated perturbation while the postural sway characteristics remained unchanged. These findings confirmed the hypothesis that the CNS modifies the postural strategy to overcome the destabilizing effects of fatigue when a postural muscle is fatigued. However, it is unclear whether the central changes occurred in response to afferent feedback from the fatigued postural muscles in order to protect the individual from injury, as would be suggested by the central governor theory [15], or as a result of a temporary impairment of the complex central output required to maintain postural control as might be suggested by researchers examining fatigue-induced impairment within the brain [11, 14].

The primary aim of this study was to build upon the work of Strang et al. (2009) and Paillard et al. (2010) to investigate the impact of fatigue induced central changes on the postural response to a predictable external perturbation. To do this we isolated the central fatigue caused by a fatiguing handgrip exercise and examined the impact on the postural response, including muscle onset latency, muscle burst amplitude and COP/COM displacement, to external predictable postural perturbations. We have previously shown that a maximal forearm contraction resulted in a decreased handgrip strength through a ten-minute recovery period, caused measureable central fatigue in ankle plantarflexor muscles immediately post-fatigue and affected ankle plantarflexor force production capacity throughout the first minute post-fatigue [8]. The secondary aim of this study was to compare the recovery of the postural response in conjunction with the recovery of the neuromuscular fatigue found within the forearm muscles and central nervous system.

Overall, we hypothesized that the postural response would be centrally mediated by the presence of forearm fatigue despite the fact that the forearms were not used in the motor task. We postulated that after the forearms were fatigued the COP displacement would decrease and the postural muscles would be activated further in advance of the perturbation. We expected that the postural strategy would not return to the pre-fatigue baseline as long as the CNS was receiving afferent information signalling fatigue within the forearm muscles [7].

#### **6.4 Methodology**

Twelve young, active, healthy men (6) and women (6) participated in this study. Their average height and weight was  $180.8 \pm 62.6$  cm and  $77.8 \pm 10.4$  kg for the men and  $166.8 \pm 70.7$  cm and  $57.6 \pm 9.4$  kg for the women. There were no neurological impairments or recent injuries. The experimental procedures were approved by the ethics board at the University of Ottawa and were performed in accordance with the Tri-Council Policy Statement [21].

Electromyography (EMG) electrodes were placed on the medial gastrocnemius (MG), tibialis anterior (TA), biceps femoris (BF), rectus femoris (RF), erector spinae (ES), rectus abdominus (RA), trapezius (TR) and flexor digitorum superficialis (FDS) according to the SENIAM recommendations [12]. The EMG data were captured at 1000 Hz (bandwidth of 6–400 Hz) and full wave rectified (Delsys DE 2.1, Delsys Inc, Boston, USA; 1 cm inter-electrode distance). The ground reaction forces were captured with a Kistler force plate at 500Hz (Type 9286, Kistler Instrument Corp, New York, USA), which was fixed to an oscillating support surface [1]. Seven VICON cameras (Vicon Peak, Oxford, UK) were used in conjunction with thirty-six retro-reflective markers that were placed on anatomical landmarks and 4 corners of the force plate to capture the center of mass (COM) displacement. The kinematic data were captured at 200 Hz and the ground reaction forces were captured at 500Hz. Instrumented handgrip dynamometers (Noraxon TeleMyo DT System, Arizona, USA) were used to determine the force produced by both hands during the forearm fatigue protocol [8].

## Procedure

The participants performed a brief warm-up, a series of ten pre-fatigue posture trials, a maximal bilateral fatiguing handgrip contraction and a series of ten post-fatigue posture trials. Warm up and fatiguing contractions were performed while the participant was seated in a chair placed beside the force plate with their backs resting against a backrest and their hands resting on their knees in a supine position.

The forearm/handgrip warm-up consisted of 3 sets of 4 handgrip contractions performed at 25%, 50% and 75% of the individual's perceived maximal force output. Each contraction lasted for ten seconds. Fifteen seconds rest was provided between contractions and 30 seconds between sets [8]. Throughout this warm-up period participants were instructed to relax the muscles that were

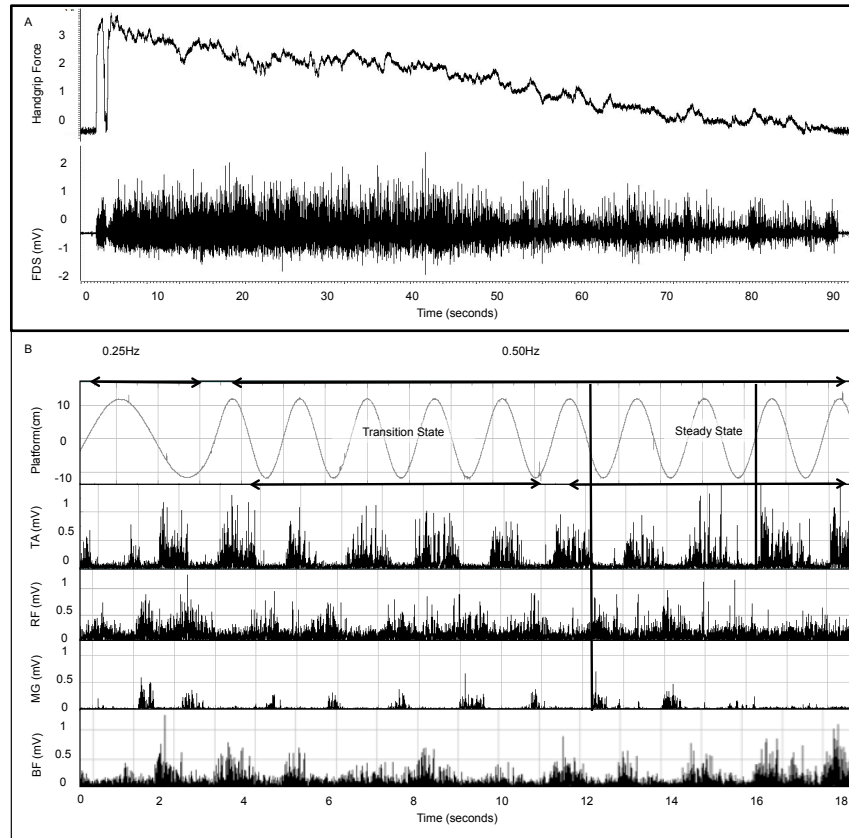
not involved in the contraction, while still producing maximal force with their hand/forearm muscles. EMG from the ES, RA, TR, and RF muscles were visualized for the researcher to ensure that the activity from these muscle groups was negligible during the contractions. Next, the participants performed three maximal voluntary contractions with both hands simultaneously. The contractions were separated by 1 minute of rest. These MVCs were used to determine the stopping criterion for each individual.

Next participants performed ten pre-fatigue postural trials. Each trial lasted for 60 seconds and consisted of continuous anterior/posterior (A/P) oscillations of the support surface. The oscillations began at 0.25 Hz before being increased to 0.50 Hz approximately halfway through the testing period [7]. Ten seconds of rest were provided between postural trials. Participants stood with their feet hip-width apart, arms relaxed at their sides and their heads up. None of the participants took a step or fell in any of the posture trials. During this pre-fatigue postural testing period the participants' postural response adapted to control the displacement of the COM in a reliable and efficient manner [9]. Although the participant performed postural trials for ten minutes, the response no longer changed after the seventh minute. We postulated that at this point the central set, a plan generated by the CNS in reaction to contextual feedback [4], was tailored to meet the requirements of the motor task, allowing the participants to reliably attain the appropriate postural response in an efficient manner [9]. The tenth and last pre-fatigue postural trial was used as the baseline for comparison with the fatigued postural trials.

After the pre-fatigue postural trials the participants sat on a chair placed beside the force plate and completed the bilateral maximal handgrip fatigue protocol. They were instructed to relax any muscles that were not involved in the contraction and, similar to the warm-up, EMG from the ES, RA, TR and RF was visualized to minimize activation of these muscles during the fatiguing

contraction. The force produced by both hands was also visualized for the participants throughout the fatigue protocol to ensure that they produced a similar amount of force with each hand. The handgrip contraction continued until the force production capacity of the dominant hand was reduced to 20% of the largest pre-fatigue MVC (Figure 1A). We have previously shown that this forearm fatigue protocol affects the forearm force production capacity for ten minutes, reduces the ankle plantar-flexor force production for one minute and creates measureable central fatigue within this muscle for 30 seconds post-fatigue [8].

Immediately after the fatiguing protocol, participants stood on the force plate and performed the post-fatigue series of ten dynamic postural trials. The first post-fatigue postural trial began one minute from the end of the fatigue protocol and a postural trial was performed every minute after that for ten minutes.



**Figure 1** A. The force trace produced by a participant's dominant hand and the electromyographic activity of the flexor digitorum superficialis throughout the fatigue protocol. B. Posture Protocol. Platform oscillation trace and EMG signals from the tibialis anterior (TA), rectus femoris (RF), medial gastrocnemius (MG) and biceps femoris (BF) muscles during the transition and steady state phase of the platform oscillations occurring at 0.50 Hz during the last pre-fatigue trial (BL-1). Example of muscle onset provided by vertical lines extending from sinusoidal wave to MG and TA muscle bursts (Kennedy et al. 2012 reprinted with permission from *Experimental Brain Research*).

## Data Analysis

### *Fatigue Protocol.*

The root mean-square (RMS) and the mean power frequency (MPF) of the EMG signal from the RF, ES, RA, TR and FDS muscles as well as the force produced by the dominate hand were calculated over 50 ms epochs at 10% intervals throughout the fatigue protocol using a Matlab<sup>®</sup> script (The Mathworks, Natick, USA). The duration of the fatigue protocol was also recorded.

### *Postural trials.*

The muscle onset latencies and muscle burst amplitudes were calculated for the TA, MG, RF and BF muscles in BioProc 3 (Bioproc 3 version 3.06, D.G.E. Robertson). Muscle onset latencies were determined by a 2 standard deviation threshold and were temporally coded relative to the maximum or minimum A/P displacement of the support surface (Figure 1B). The TA and RF muscles were coded relative to the onset of the forwards translation and the MG and BF muscles were coded relative to the onset of the backwards displacement of the platform. If a muscle was activated in advance of the perturbation it was coded as negative and if it was activated after the peak displacement of the support surface it was coded as positive (see Bugnariu and Sveistrup 2006 and Kennedy et al. 2012a for more details). If a muscle was activated in less than 15% of the oscillations it was not included in individual or group calculations of onset latencies to avoid the involvement of random muscle bursts in the data analysis. The incidence of ankle muscle co-contraction was also determined in BioProc 3 by locating the occurrence of a simultaneous activation of the TA and MG muscles lasting longer than 50ms during the last 5 cycles of each trial.

The anthropometric measurements and kinematic data were used to calculate the maximal peak-to-peak anterior/posterior displacement of the COM. The anterior/posterior movement of the force plate was subtracted from the COM displacement to get a true representation of the movement of the COM. The anterior/posterior COP displacement was calculated from the ground reaction forces using VICON's plug-in-gait software. The COM and COP displacements were analyzed independently for the forward and backward displacements of the support surface.

For all posture variables, data were processed for the last pre-fatigue postural trial (BL-1) and for the trials performed one (F1), two (F2), five (F5), seven (F7), and ten (F10) minutes after the end of the fatigue protocol. These time points were selected so that the postural data could be compared to the data from the fatigue characterization study previously published by our laboratory [8]. The data were averaged over the last five oscillations performed at 0.50 Hz for each of these trials to ensure that the participants had reached a steady state postural response. The data were then ensemble averaged between participants.

### Statistical Analysis

For the fatigue protocol a repeated measure analyses of variances (ANOVAs) were performed to determine if there was a main effect of fatigue on the level of handgrip force production as well as on the RMS and MPF of the RF, ES, RA, TR and FDS muscles. For the posture trials repeated measure ANOVAs were also used to compare the pre-fatigue values to those recorded throughout the ten minute post-fatigue testing session for the COM and COP displacement as well as the onset latencies and burst amplitudes of the TA, MG, RF and BF muscles and probability of TA/MG co-contraction. Separate ANOVAs were performed for the forward and backwards perturbations. Pre-planned paired t-tests were performed to determine how long the effects of fatigue remained after the fatiguing handgrip contractions. Results considered significant for  $p < 0.05$ .

## 6.5 Results

### *Fatigue Protocol.*

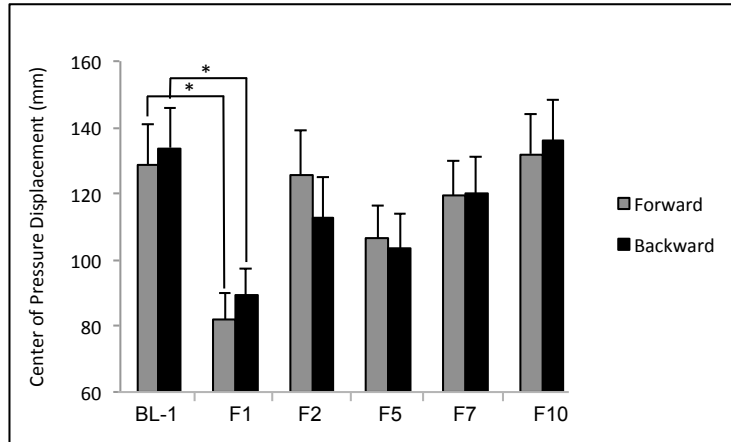
The maximal isometric forearm fatiguing contraction lasted for  $65.7 \pm 11.2$  seconds and resulted in a significant decrease in the force production capacity of the forearms ( $p < 0.05$ ). The forearm

force became significantly lower 30% of the way through the fatigue protocol than it was at the start ( $p = 0.001$ ), after which it continued to decline until it fell below 20% MVC at the end of the fatigue protocol.

The RMS of the RF, TR, ES and RA muscles did not vary throughout the fatigue protocol relative to the start of the fatiguing contraction ( $p > 0.05$ ). The FDS was affected by fatigue ( $p < 0.05$ ), showing a slightly increased RMS at the start of the forearm contraction followed by a steady decrease starting 30% of the way through the fatigue protocol. The FDS RMS was significantly lower at the end of the fatigue protocol relative to the start of the contraction ( $p < 0.05$ ). Fatigue did not affect the MPF of the RF, TR, ES and RS muscle relative to the start of the fatigue protocol ( $p > 0.05$ ). The FDS MPF was affected by the fatigue protocol ( $p < 0.05$ ), showing a statistically lower value 30% of the way through the fatigue protocol relative to the start of the sustained handgrip contraction ( $p = 0.001$ ). The FDS MPF continued to decrease throughout the rest of the fatigue protocol.

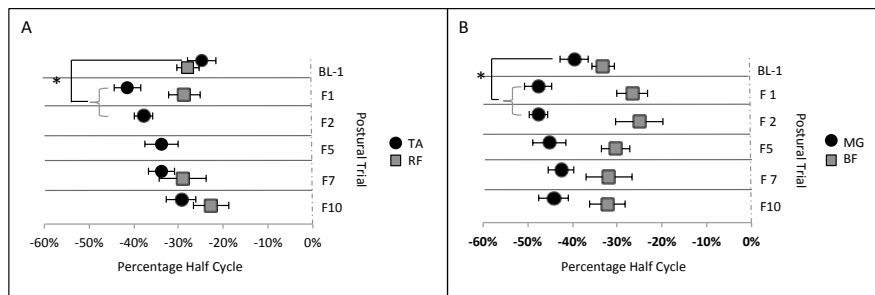
#### *Postural Trials.*

The COM displacement did not change significantly following the fatigue protocol in either the forward ( $p > 0.05$ ) or backwards ( $p > 0.05$ ) directions. The COP displacement decreased significantly immediately post-fatigue during both the forwards ( $p < 0.05$ ) and backwards ( $p < 0.05$ ) platform translations before returning to the pre-fatigue values after 2 minutes (F2: forwards  $p = 0.452$ , backwards  $p = 0.0995$ ) (Figure 2).



**Figure 2.** Center of pressure displacement (mm) during the forward (grey) and backward (black) translation of the support surface pre-fatigue (BL-1) and post-fatigue after one (F1), two, (F2), five (F5) seven (F7) and ten (F10) minutes of rest. \* indicates statistically different than BL-1 ( $p < 0.05$ ).

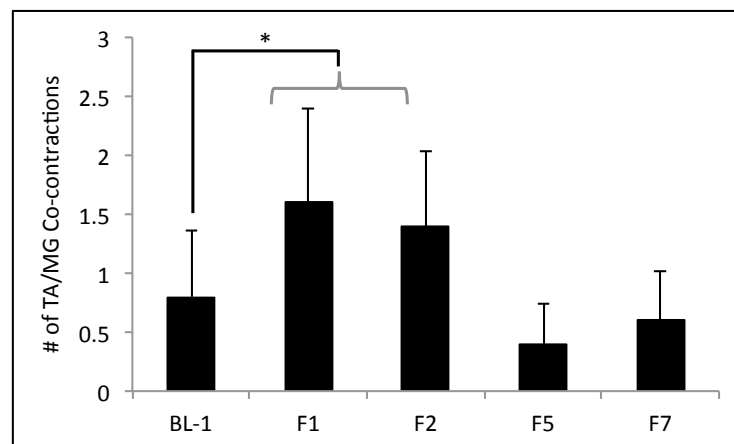
There was a significant main effect of fatigue on the muscle onset latency for the TA ( $p < 0.05$ ) (Figure 3a) and MG ( $p < 0.05$ ) (Figure 3b) muscles but not for the RF ( $p > 0.05$ ) and BF ( $p > 0.05$ ) muscles. The TA and MG muscles were both activated significantly earlier at F1 (TA  $p = 0.001$ , MG  $p = 0.028$ ) and F2 (TA  $p = 0.014$ , MG  $p = 0.046$ ) minutes post-fatigue before returning to and remaining at the pre-fatigue onset latency time by F5 (TA  $p = 0.674$ , MG  $p = 0.322$ ).



**Figure 3.** Tibialis anterior (TA), rectus femoris (RF), medial gastrocnemius (MG) and biceps femoris (BF) muscle onset latency relative to the maximal displacement of the support surface in the forwards (A) and backwards (B) directions. Postural trials performed pre-fatigue (BL-1) as well as throughout the post-fatigue recovery period after one (F1), two, (F2), five (F5) seven (F7) and ten (F10) minutes of rest. \* indicates statistically different than BL-1 ( $p < 0.05$ ).

There was a significant main effect of fatigue on muscle burst amplitude for the TA ( $p < 0.05$ ) and MG ( $p < 0.05$ ) muscles but not for the RF ( $p > 0.05$ ) and BF ( $p > 0.05$ ) muscles. The TA muscle burst amplitude was significantly lower at F1 ( $p = 0.01$ ), F2 ( $p = 0.003$ ), F5 ( $p = 0.014$ ) and F7 ( $p = 0.007$ ) minutes post-fatigue relative to the pre-fatigue condition. By ten minutes post-fatigue (F10) the TA muscle burst amplitude had returned to the pre-fatigue values ( $p = 0.115$ ). The MG muscle amplitude was larger at F1 ( $p = 0.049$ ) than pre-fatigue and returned to and remained at the pre-fatigue values by F2 ( $p = 0.253$ ).

There was a main effect of fatigue on the co-contraction of the TA and MG muscles ( $p < 0.05$ ). The incidence of co-contraction increased immediately post-fatigue ( $p = 0.044$ ) and remained elevated at F2 ( $p = 0.022$ ) relative to the pre-fatigue values (Figure 4). By 5 minutes of post-fatigue the rate of co-contraction had returned to pre-fatigue levels (F5:  $p = 0.461$ ).



**Figure 4.** Co-contractions of the tibialis anterior (TA) and medial gastrocnemius (MG) over the last 5 platform oscillations performed at 0.50 Hz. These data were quantified for the trials performed pre-fatigue (BL-1) and throughout the post-fatigue recovery period after one (F1), two, (F2), five (F5) seven (F7) and ten (F10) minutes of rest. \* indicates statistically different than BL-1 ( $p < 0.05$ ).

## 6.6 Discussion

This study examined the impact of forearm muscle fatigue on the postural response to a predictable but externally initiated perturbation. We chose to fatigue the forearm muscles to ensure that peripheral fatigue created by the exercise was isolated from the muscles involved in the postural task. The results support the hypothesis that the post-fatigue postural response would be modified after the forearm muscles were fatigued, despite the fact that fatigue was not found in the postural muscles assessed in this study. This finding suggests that, at least initially, a general fatigue induced central change is responsible for the modification of the postural response. There were several notable factors concerning the fatigue induced modifications to the postural response including the similarity of the response found immediately after the forearm muscle fatigue to that found after fatigue of the ankle plantar and dorsiflexor muscles as well as the temporal recovery of these changes.

The postural changes found immediately after the forearm fatigue protocol were similar to those found in studies that fatigued muscles directly involved in the postural task [6, 7, 20] and include an increased rate of TA, MG muscle co-contraction (Figure 4) [6, 7], a decreased COP displacement (Figure 2) [7] and an earlier activation of the postural muscles [7] (Figure 3) with a smaller muscle burst amplitude [20]. The increased co-contraction of postural muscles is a sign of postural stiffening [10], a change in motor response often associated with anxiety [16]. The decreased COP displacement [2] and earlier activation of postural muscles, normally accompanied by a decreased muscle burst amplitude [20, 22], also indicate a shift to a more conservative or anxious postural strategy. These parallels exist despite the fact that the forearm contractions did not induce fatigue in the postural muscles assessed in this study. We postulate

that the central fatigue created during the forearm fatigue protocol was at least partly responsible for the shift towards the more conservative postural strategy found immediately post-fatigue.

It is possible to explore the impact of the forearm fatigue protocol on postural control further by analyzing the recovery of the postural response in conjunction with the recovery of peripheral and central components of neuromuscular fatigue. The second hypothesis of this study predicted that the postural response would return to the pre-fatigue characteristics as the afferent feedback from the fatigued forearm muscle subsided. Previous analysis performed in our laboratory determined that the forearm muscles continued to be affected by the fatigue protocol throughout the entire 10-minute recovery period [8]. Contrary to our hypothesis, the results from the present study demonstrated that the majority of the postural changes returned to baseline within minutes of the forearm muscle fatigue protocol; with the COP displacement taking 1 minute and the muscle onset latencies taking 2 minutes to return to the values recorded pre-fatigue. The recovery of this postural response coincided closely with the dissipation of central fatigue quantified in the ankle plantarflexor muscles [8]; suggesting that the postural changes were caused by a brief fatigue-induced impairment within the CNS and not in response to afferent information from the fatigued muscle group.

The difference between the impact of the ankle and forearm muscle fatigue on postural control suggests that once the initial central fatigue subsides, the CNS is able to modify the motor performance to meet the specific internal and external requirements of the motor task as opposed to continuing to respond with a general fatigue-induced response. In a previous study we found that when the ankle plantar and dorsiflexors muscles were fatigued the postural response to the predictable, externally initiated perturbation did not recover throughout the ten minute post-fatigue period despite the rapid recovery of the quantifiable central fatigue [7]. We postulated

that this lack of change in the post-fatigue postural response was caused by continued afferent feedback from the peripheral fatigue measured in the ankle dorsiflexor muscles. It is likely that this afferent information prevented the participant's central set, and thus the postural response, from returning to the pre-fatigue state. It is important to note that the forearm muscle was also affected by the fatigue protocol throughout the entire ten-minute post-fatigue period [8] but that this impairment did not prevent the postural response from recovering. Taken together, these findings suggest that once the initial central fatigue diminished, the CNS determined that the remaining peripheral fatigue in the forearm muscles was not a threat to postural stability and so modified the postural response accordingly.

In conclusion, we found that fatigue created by sustained, bilateral, maximal forearm contractions altered the postural response to predictable, external perturbations. Similar to studies that fatigued local postural muscles, the handgrip muscle fatigue protocol caused the postural response to be more conservative immediately post-fatigue. Since fatigue was not created in any of the postural muscles, central changes must be proposed as the origin of these postural changes. This theory is further supported by the fact that the recovery of the postural changes coincided temporally with the recovery of central fatigue, not with the subsiding afferent feedback from the fatigued arm muscles. This secondary finding suggests that once central fatigue subsides, the CNS is able to modulate the postural response to meet the requirements of the type and location of fatigue found within the system as opposed to continuing to use a general fatigue-induced postural modification.

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## **Chapter 7: General discussion**

## **7.1 Major findings and their significance**

This thesis provides a more complete understanding of the contribution of central and peripheral fatigue to the decreased motor performance found immediately post-fatigue as well as throughout a ten-minute recovery period. Since neuromuscular fatigue is highly task specific, it was important to first quantify the development and recovery of the central and peripheral changes before assessing their impact on more complex motor tasks. To accomplish this overarching goal five separate experiments were designed and implemented to quantify the fatigue developed by two separate fatigue protocols and to assess their impact on the postural response to externally initiated, predictable postural perturbations (Figure 1.1). The data from each of these studies have been addressed in detail in the five manuscripts presented in this dissertation and so the focus of this discussion section will be to consider the individual findings with respect to the general aims and hypotheses of the studies presented in the introduction section as well as in conjunction with one another. Finally, conclusions and future research directions will be proposed in this section of the dissertation.

### **Adaptation of the postural response**

The results from the adaptation study clearly demonstrated that young healthy participants were able to rapidly adapt to the postural task used in this experiment. The data from this study showed a two-step adaptation process that is described in several motor learning or adaptation theories. Many of these theories, including the Fitts and Posner 3-stage model (Fitts and Posner 1976), the Vereijken 3-stage model (Vereijken, van Emmerik et al. 1992), the Gentile's 2-stage model (Gentile 1972) and the systems theory model (Shumway-Cook and Woollacott 2007)

describe a rapid early improvement of the motor performance during which the learner constrains their movement to meet the requirements of the motor task. This first phase is followed by a more progressive refinement of the motor performance to improve the postural efficiency.

In the adaptation study the first phase of learning, during which the participants quickly decreased the displacement of their COP, reached a steady state after 5 platform oscillations. Subsequently, participants began to activate their postural muscles earlier in advance of the perturbation with smaller muscle burst amplitudes. This evolution continued until the seventh postural trial, after which the response no longer evolved with further practice. **These results established that a series of at least seven, minute-long postural trials is necessary to allow the participants to adapt to the postural task before examining the impact of neuromuscular fatigue on the motor response.**

The first fatigue characterization study performed in this dissertation was designed to quantify the manifestation and recovery of neuromuscular fatigue caused by bi-directional ankle plantar (PF) and dorsiflexor (DF) muscle contractions. The fatigue protocol reduced the MVC of both muscle groups to less than 50% of their initial MVC for at least three seconds. It was hypothesized that the force of these two muscle groups would be decreased by central and peripheral fatigue (Kent-Braun 1999) and that the contribution of each would be different for the ankle plantar and dorsiflexor muscles.

The muscle fiber type (Mannion, Dumas et al. 1998) and co-ordination (Prilutsky 2000) of ankle PF and DFs caused these two muscles groups to be fatigued differently. The results from this study indicated that peripheral fatigue was a major contributor to the impaired performance in

the DF muscles and that central fatigue contributed to the changes found in the PF. The force production capacity of the ankle DF muscle recovered 30 seconds after the fatigue protocol; however, measurable peripheral fatigue was quantified in this muscle group throughout the entire ten-minute recovery period. Although it is surprising that the MVC could recover while peripheral fatigue was still measured in a muscle, this finding can be explained by central compensation. More specifically, the CNS may have increased the motor unit firing frequency of the DF muscles to increase the force production above what would be expected (Edwards, Hill et al. 1977). This improved force production is a functional asset as the DF muscles are essential to balance recovery and must be able to produce a large and rapid muscle burst to compensate for a postural perturbation.

Contrarily, the ankle PF MVC was reduced for the first five minutes after the fatigue protocol while central fatigue lingered in this muscle group for only the first two minutes. It is possible that this decreased MVC was caused by a centrally orchestrated inhibition of the antagonistic muscles groups designed to protect the ankle joint from injury. This central change would have been caused by the lingering peripheral fatigue of the DF muscles. Alternatively, is it possible that the fatigue characterization techniques used missed any peripheral fatigue that developed within the ankle PF muscles. This is a possibility because multiple muscles are involved in the ankle PF force production, allowing compensation and muscle rotation to maintain a high level of peripheral functionality.

**This fatigue characterization study demonstrated that different types of fatigue are created in different muscle groups despite similar stopping criteria.** It was essential to perform this characterization before assessing the impact of the fatigue protocol on dynamic postural control.

With a good understanding of the type of fatigue produced by the ankle contractions we were able to determine how the ankle muscle fatigue created by this fatigue protocol impacted the motor response to a complex postural task. The first posture study was designed to characterize the postural response, including the COM and COP displacement and muscle activity of key postural muscles, to predictable, externally initiated oscillations of the platform immediately post-fatigue and throughout a ten-minute recovery period. It was predicted that the postural response would return to the pre-fatigue baseline as the force production capacity of the ankle plantar and dorsiflexor muscles recovered. It was also predicted that the COM displacement, an important control variable in posture (Scholz, Schoner et al. 2007), would not be affected by the ankle muscle fatigue but that the COP displacement (Vuillerme, Sporbert et al. 2009) and muscle onset latency (Strang and Berg 2007, Kanekar, Santos et al. 2008) would be altered to compensate for the destabilizing effects of fatigue.

The postural response to the externally initiated, predictable postural perturbations was indeed affected by the ankle fatigue protocol. Immediately post-fatigue all of the participants shifted their COP further onto their toes and increased the incidence of tibialis anterior/medial gastrocnemius co-activation. Similar subtle changes in the postural response have previously been described as indicators of postural anxiety (Okada, Hirakawa et al. 2001), suggesting that the participants in this study were more uncomfortable with the postural task after the fatigue protocol than they were before. These changes in the postural strategy likely helped to stabilize the ankle joint and worked to control the COM effectively.

Further analysis of the postural response occurring immediately post-fatigue (F1) revealed that the participants used two different approaches to compensate for the ankle muscle fatigue when

the platform shifted backwards and a third when the platform shifted forward. In the backwards direction one subgroup increased their COP displacement and reduced the incidence of biceps femoris muscle bursting while the second subgroup decreased their COP displacement without changing their muscle activity. **Although the two groups used slightly different strategies to compensate for neuromuscular fatigue when the platform shifted backwards, they were both able to maintain control of their COM displacement post-fatigue.** In addition to personal preference and postural anxiety, it is possible that previous experience with neuromuscular fatigue was involved in the disparity between the two subgroups found immediately post-fatigue. The sub-group that used a more conservative postural strategy resembles that used by older participants (Bugnariu and Sveistrup 2006) and those who have a higher level of postural anxiety (Carpenter, Frank et al. 2001)

**When the platform shifted forwards all of the fatigued participants used the same postural strategy to maintain the displacement of their COM.** In this direction the participants did not change their postural strategy immediately post-fatigue; however, during the recovery period they altered their muscle activity and COP displacement to compensate for the destabilizing effects of fatigue. I postulate that only one strategy was used in this direction because of the anatomical and biomechanical limitations of the ankle and the foot shape.

When the post-fatigue posture data was assessed in conjunction with the results from the ankle muscle fatigue characterization study it became clear that the changes in postural strategy were not simply caused by the decreased force production capacity of the ankle muscles. In fact, by the time the first postural trial was performed the ankle dorsiflexor MVC had fully recovered and the ankle plantarflexor MVC had returned to ~ 80% of the pre-fatigue value. Therefore, other

fatigue-induced changes must be considered as possible factors involved in the post-fatigue changes. The results from the ankle muscle fatigue characterization study indicate that central fatigue, measured by the level of voluntary activation of the muscle (VA), was quantifiable in the ankle plantarflexors for 1 minute post-fatigue. It is likely that the decreased VA contributed to forward shift in the COP found in both subgroups immediately post-fatigue. This forward lean is often found in participants who are uncomfortable with the postural task such as individuals with peripheral impairment (Horak and Hlavacka 2001). **I postulate that the postural response found immediately post-fatigue was a result of a slight central impairment that prevented the CNS from modifying the postural response to compensate for the destabilizing effects of fatigue in the most efficient way.**

Central fatigue subsided by the next postural trial occurring after five minutes of rest. At this time the postural response was different than the response found immediately post-fatigue, showing an earlier activation of some postural muscles and deactivation of others. Although the ankle muscle force production capacity had returned by this point, I hypothesis that the **remaining afferent feedback from the fatigued postural muscles prevented the CNS's motor plan from returning to the pre-fatigue state.** It is likely that this lingering modification occurred to prevent injury while the individual was in a compromised state. This hypothesis is loosely based on the work done by Hill (Edwards 1983), Noakes and St. Claire (Noakes, St Clair Gibson et al. 2005) which suggests that the central nervous system regulates the motor plan based on afferent feedback from the fatigued muscle to ensure that physical exertion does not threaten the body's homeostasis or place it at risk for injury.

After 10 minutes of recovery the COP displacement was significantly lower than it was pre-fatigue. This is an interesting finding since the muscle onset latency had returned to the pre-fatigue values by this point. I hypothesize that the decreased COP displacement may have been caused by a longer muscle burst duration of the muscles surrounding the ankle and hip. This increased duration was not quantified in this dissertation but has been found by other researchers as a post-fatigue strategy used to compensate for postural perturbations (Kanekar, Santos et al. 2008). It is hypothesized that a longer burst duration at a lower amplitude would prevent large and possibly destabilizing muscle activity when an individual is already unstable. In addition to longer muscles burst duration an increased level of tonic activity could have been responsible for the decreased COP displacement found 10 minutes after the ankle muscle fatigue protocol. I hypothesize that the lingering peripheral fatigue from the ankle PF continued to play an important role in the altered postural strategy used at this time point.

The next phase of this dissertation focused on the development of exercise induced central fatigue of non-postural muscles and examined the impact on postural control. The forearm characterization study examined the impact of bi-lateral forearm contractions on the motor performance of the ankle plantarflexor muscles. Since peripheral fatigue was quarantined to the fatigued muscle fibers, this experimental design allowed a thorough investigation into the impact of the central fatigue created by forearm muscle activity on the ankle plantarflexor muscles. It was hypothesized that the central fatigue produced in the forearm muscles would cross over to the non-fatigued ankle plantarflexor muscles but that the force production capacity of the ankle would not be impaired. It was also predicted that a longer, submaximal contraction would produce more central fatigue than the shorter maximal contraction (Bilodeau, Henderson et al. 2001), despite a similar stopping criteria used for both experiments.

**The results from this study indicated that the central fatigue created by the bilateral forearm contractions translated to the ankle plantarflexors in the form of a decreased ankle VA and MVC.** This is the first study to show that central fatigue affects distal, unrelated muscle groups; however, previous work has demonstrated that central fatigue created in one limb can be transferred to the contralateral homologous muscle group (Todd, Petersen et al. 2003, Rattey, Martin et al. 2006). Rattey et al. used transcranial magnetic stimulation to demonstrate that the impaired performance of the contralateral limbs was associated with a decreased cortical output. This is likely the case in the present study as well; however, further research is required to determine whether this decreased cortical excitability is caused by a physiological impairment within the CNS or in response to afferent feedback from the fatigued muscle group.

The unpublished results from this study also found that peripheral fatigue was measured in the forearm muscles throughout the ten-minutes after the maximal and submaximal fatigue protocols. This recovery time was similar to the duration of peripheral fatigue measured in the ankle dorsiflexor muscles after the ankle fatigue protocol. Impairment of the excitation-contraction coupling mechanisms in the fatigued muscles is likely an important factor in the delayed recovery of these peripheral factors (Raastad and Hallen 2000).

Contrary to the initial hypothesis, the maximal forearm contraction had a greater impact on the ankle VA and MVC than the submaximal protocol. This finding can be partly explained by fact that both fatigue protocols had the same stopping criteria of 20% of the initial MVC, a constraint not usually applied when comparing submaximal and maximal contractions. It is likely that the increased energy and mental effort required to maintain the maximal contraction contributed to

the differences found between the maximal and submaximal protocols (Marcora, Staiano et al. 2009).

The last study in this dissertation assessed the impact of the central fatigue created during the bilateral forearm contraction on the motor response to a predictably and externally initiated postural perturbation. The initial hypothesis that the central fatigue created by the forearm contraction would affect postural control was supported. More specifically, after the fatigue protocol the COP displacement was decreased and the postural muscles were activated further in advance of the perturbation with a higher incidence of co-contraction between the TA and MG muscles. These post-fatigue changes were similar to those found after fatigue of the ankle muscles and also seem to represent an increased postural anxiety found immediately post-fatigue. **I postulate that the central fatigue created by the forearm muscle fatigue protocol caused the CNS to move from the efficient postural strategy used pre-fatigue to a safer and less efficient strategy used immediately post-fatigue.**

In the next postural trial, performed after 2 minutes of rest, the central fatigue had subsided and the postural strategy had returned to the pre-fatigue characteristics. Although afferent information from the fatigued forearm muscle was still present, the recovery of the central fatigue allowed the CNS to assess the postural requirements and tailor the response accordingly. Comparing the recovery of the postural response found after the forearm muscle fatigue protocol to the changes found after the ankle muscle fatigue supports the argument that once central fatigue has recovered the CNS is able to meet the requirements of the postural task, ensuring that the postural response is as efficient as possible. In this study the fatigue produced by the forearm

contraction did not threaten postural control and so the postural response returned to the pre-fatigue characteristics established during the ten-minute pre-fatigue practice period.

Overall the two posture studies demonstrated that immediately post-fatigue, while central fatigue persisted, there was a general shift towards a more conservative postural strategy. This conservative strategy included an increased incidence of muscle co-contraction, forward displacement of the COP, and smaller muscle burst amplitudes. It may have been caused by physiological changes within the brain such as altered levels of brain serotonin, increased cerebral glucose metabolism and an increased uptake of ammonium ions among other factors. Alternatively, the conservative postural strategy could have been caused by an intentional shift in the postural response to maximize stability given peripheral fatigue. This central regulation would occur at both the spinal and supraspinal level and would affect cortical excitation as well as the selection of the overall motor plan.

Once central fatigue recovered, the postural strategy was adjusted further to accommodate for residual, relevant peripheral fatigue. This final conclusion is based on a comparison of the recovery data from the two postural studies performed in this dissertation. The ankle fatigue study demonstrated that the postural strategy used to maintain balance did not return to the pre-fatigue values throughout the ten-minute recovery period despite the full recovery of the force production of the fatigued muscles. I hypothesize that the lingering peripheral fatigue in the plantar-flexor muscles provided afferent information to the central nervous system that was responsible for the continued modulation of the response. Contrarily, the postural strategy used after the forearm muscle fatigue returned to the pre-fatigue state within 5 minutes post-fatigue despite continued peripheral fatigue in the forearm muscles. This finding suggests that once

central fatigue subsides, the CNS is able to tailor the movement strategies to meet the requirements of the individual and the motor task.

The findings from this study are applicable to several areas of health research including rehabilitation medicine. Rehabilitation medicine deals with individuals who are inherently at a higher risk for falls due to injury, age or stroke. Their rehabilitation programs likely involve repetition of motor skills designed to retrain the body and mind to plan and execute movement. While therapists understand the warning signs from fatigued muscles, they may be less cognizant of how the fatigue-induced changes within the central nervous system affect postural control and motor performance. An increased awareness of the impact of central fatigue on stability and movement would allow therapists to use extra caution as their patients become fatigued. Future research may also investigate the role of central fatigue on the efficacy of rehabilitation and motor learning. This, as well as other future research directions, will be examined in the next section of this dissertation.

## **7.2 Future Research Directions**

Although this research identified the importance of central fatigue on postural control, it was beyond the scope to identify the specific mechanisms behind the central changes. An important direction for future research would be to determine whether the central fatigue was caused by physiological impairment within the central nervous system or by a conscious shift in the postural strategy based on afferent feedback from the fatigued muscles. It would be possible to determine the role of this afferent feedback in isolation from physiological central changes by inducing fatigue in a postural muscle through electrical stimulation.

### **Does previous experience with a fatigued postural task improve postural control in subsequent postural tasks?**

The data from the ‘ankle muscle fatigue on posture’ study demonstrated that not all of the participants modified their post-fatigue postural response in the same way. It was not possible to investigate the mechanism responsible for the disparate postural responses to the ankle muscle fatigue protocol with the variables assessed in this series of studies; however, I believe that previous experience with fatigued postural control may be a contributing factor. I believe that this research question could be addressed by recruiting several subpopulations of young healthy adults with varying levels of experience with fatigue during standing motor tasks, i.e. soccer players and track athletes. These athletes would be compared to participants who had less experience with fatigued postural control such as swimmers and inactive participants of the same demographic. Alternatively, this research question could be answered by having a general population of young health participants perform the same fatigued postural task on two separate testing days. In this way the ‘previous experience’, i.e. first testing session, would be better controlled and the confounding variable of ‘sport specific fitness’ would be removed.

### **How does fatigue impair the ability to learn a new postural task?**

The present research suggests that central fatigue impairs the CNS’s ability to provide the most efficient response to an externally initiated but predictable postural perturbation. Future research endeavours should investigate whether the presence of central fatigue also impairs an individual’s ability to learn a new motor task. This work could be performed with a similar postural paradigm and would have implications in work safety, rehabilitation training programs and high-level athletic performance.

## **Does mental fatigue also impair motor performance of complex postural tasks?**

Although controversial, rigorous mental tasks have also been shown to affect motor planning (Lorist, Klein et al. 2000) and performance (Marcora, Staiano et al. 2009). There is very little research in this area although it could have important implications in the design and execution of rehabilitation and athletic training programs. This is particularly true in situations where the central nervous system is fatigued by both physical exercise and demanding cognitive tasks. The involvement of the CNS in the postural task used in this dissertation makes it a good tool to investigate the impact of mental fatigue on motor planning and control.

### **7.3 Conclusion**

In general, the fatigue characterization studies demonstrated that peripheral and central fatigue contributed to the overall decrease in performance differently depending on the muscle groups that were fatigued (i.e. the ankle plantar and dorsiflexors from study 2) and the intensity of the contractions (i.e. maximal vs. submaximal contractions from study 4). The forearm fatigue study is the first work to find that central fatigue created in one area of the body translates to the voluntary activation and force production of non-fatigued and unrelated muscle groups.

The ankle muscle fatigue protocol affected the postural response to the externally initiated, predictable postural perturbations. As hypothesized, the COM, an important control variable in posture, was maintained through a modification of the COP displacement and postural muscle activity. Immediately post-fatigue the postural strategy was inefficient relative to the strategy used pre-fatigue. I postulate that this decrease in efficiency was caused by the presence of central fatigue created during the ankle exercise. The postural response became more efficient as the central fatigue subsided; however, it did not return to the pre-fatigue values during the ten-

minute post-fatigue period. I suggest that this persistent postural modification is associated with continued afferent feedback from the dorsiflexor muscles as opposed to being caused by a reduced impairment within the postural muscles.

The forearm contractions also caused a modification of the postural strategy used immediately post-fatigue. These muscles were not involved in the postural task and so it can be assumed that central fatigue was an important factor in the postural changes found in this study. The central fatigue and post-fatigue postural changes both subsided rapidly after the forearm contractions despite the lingering afferent information from the fatigued forearm muscles. The difference in recovery time between the two postural studies suggests that the CNS was able to differentiate between feedback coming from local postural muscles and muscles that were superfluous to the motor goal.

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