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## Postural Control in Response to Unilateral and Bilateral External Standing Perturbations in Young and Older Adults

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## **ABSTRACT**

Balance is an important determinant of physical function and falls risk. This study sought to determine the effect of unilateral and bilateral perturbations, with and without cognitive load, on leg muscle activity in healthy young and older adults, as well as identify the influence of ankle power on postural and functional performance. Using a split-belt treadmill system, participants experienced unilateral and bilateral accelerations of the treadmill, without and with the Stroop test. Surface electromyography (EMG) from eight lower limb muscles was recorded from the right leg. EMG onset latency following perturbation onset, and root mean square of the muscle bursts were calculated for each perturbation. Unlike young adults, older adults did not demonstrate a distal to proximal muscle activation, suggesting that older adults adopt a unique response to postural perturbations – a response prioritized over cognitive load. Further, a higher level of ankle muscle power favoured better balance in older adults.

**Keywords:** balance, external perturbations, muscle power, cognitive load, older adults, EMG

## **LAY ABSTRACT**

Balance is an important determinant of physical function and falls risk. This study sought to determine the effect of slips (single [unilateral] or double [bilateral] limb), with and without a cognitive task, on leg muscle activity in healthy young and older adults. We also sought to identify the influence of ankle power (force x velocity) on postural and functional performance. Using a split-belt treadmill system, participants experienced unilateral and bilateral accelerations of the treadmill (i.e. accelerating one belt or both belts), without and with a cognitive test. Muscle activity from eight lower limb muscles were recorded from the right leg. The timing of muscle activity following acceleration onset, and magnitude of the muscle bursts were calculated for each acceleration. Young and older adults demonstrate different patterns of muscle activity, suggesting that older adults adopt a unique response to postural accelerations – a response prioritized over cognitive load. Further, a higher level of ankle muscle power favoured better balance in older adults.

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## Chapter 1 – Introduction

### 1.1 Background and Rationale

Falls are the primary cause of injury in individuals over the age of 65 (Kurz et al. 2016). The risk of falling increases with aging as a result of age-related neurological and muscular changes (Reid & Fielding, 2011). Aging is characterized by a decrease in muscle size as well as neuromuscular function (Vandervoort, 2002). A decline, specifically, in lower limb muscle power has been associated with functional impairments characterized by a decrease in mobility and an increase in the risk of falling (Reid & Fielding, 2011). The changes that occur in muscle size and function not only affect an individual's ability to perform daily functional activities but can be detrimental to postural control and gait efficiency (Paillard, 2017).

Balance is an important determinant of physical function and falls risk. The maintenance of upright balance requires the centre of mass (COM) to stay within the base of support (BoS; Maki & McIlroy, 1997). In a dynamic environment, the relationship between the COM and BoS is controlled by anticipatory postural adjustments and compensatory postural adjustments (APAs and CPAs, respectively; Maki & McIlroy, 1997). While both types of adjustments play a role in the maintenance of upright stance, compensatory control is the main method used to regain balance following an unexpected loss of body equilibrium, or perturbation, while standing (Maki & McIlroy, 1997). Compensatory responses use whole-body techniques triggered by the central nervous system (CNS) to restore balance (Bolton, 2015).

The use of perturbations has been a common method to investigate balance in previous studies. For example, support surface translations have been used to study reactive responses, (Norrie, Maki, Staines, & McIlroy, 2002; Dijkstra, Horak, Kamsama, & Peterson, 2015; Zemkova et al., 2017; Wang, Watanabe, & Asaka, 2017; Martelli et al., 2017; Inkol, Huntley, & Vallis, 2018; Shim, Harr, & Waller, 2018) as well as perturbations applied to the upper body (Santos, Kanekar, & Aruin, 2010; Kanekar & Aruin, 2014). While the use of perturbations has been extensively researched in regard to postural control, there is little information regarding how balance is affected when perturbations are induced unilaterally compared to bilaterally in older adults. The results of this study may identify areas of importance for balance training protocols and determine factors with the greatest influence on balance performance.

## **1.2 Objectives and Hypotheses**

### Objectives:

The primary objective of this study is to determine the effect of unilateral and bilateral perturbations on postural muscle activity in the leg, as well as to identify any muscle activation changes with the introduction of a cognitive load.

A secondary objective is to identify any relation between muscle power output around the ankle joint to the level of muscle activation in response to the postural perturbation, as well as functional performance.

A tertiary objective is to compare the postural responses between young and older adults.

### Hypotheses:

The primary hypotheses of this study are 1) that responses will differ between perturbation types, such that unilateral and bilateral accelerations will demonstrate different patterns of muscle activation; and 2) the addition of a cognitive load will increase the latency of response and muscle activity in both young and older adults.

The secondary hypotheses of this study are that, in older adults, an increase in ankle muscle power will have a positive influence on a clinical measure of balance and mobility. An increase in muscle power will be accompanied by an increase in the amplitude of muscle activity in response to perturbations. In young adults, it is hypothesized that ankle muscle power will demonstrate a lesser influence on functional performance and postural control than in older adults.

The tertiary hypotheses are that older adults will demonstrate an increase in postural response time, as well as a decrease in the amplitude of the muscular response when compared to young adults. The effect of a cognitive load will be more pronounced in young adults, as older adults will prioritize the balance task to the detriment of the cognitive task.

## Chapter 2 – Review of the Literature

This chapter will provide an overview of postural perturbations, muscle activation in balance recovery, perturbation types, aging and muscle function, aging and functional performance, aging and external perturbations, and the effect of a cognitive load.

### 2.1 Postural external perturbations

A postural perturbation can be defined as an action that shifts the body away from equilibrium (Horak, Henry, & Shumway-Cook, 1997). There are a wide variety of perturbation-inducing techniques that can be used to examine standing balance. Examples of external perturbations include rotating or translating support surfaces or applying a force to a specific body part (Rasman, Forbes, Tisserand, & Blouin, 2018). Perturbation studies have demonstrated that balance strategies develop as the CNS is exposed to challenges to equilibrium (Horak et al., 1997). It is, therefore, necessary for perturbations to be unpredictable, in order to limit any learning effect by the CNS (Maki & McIlroy, 2006). Responding to an external perturbation requires the CNS to adjust for the change in the COM to keep it within the BoS (Inkol et al., 2018).

The mechanisms required to keep the COM within the BoS may vary depending on the magnitude of the perturbation. Evidence of stereotypical patterns of muscle activation following platform translations led to the identification of muscle synergies (Horak et al., 1997). These patterns of muscle activity have provided insight into the concept of motor coordination and have allowed researchers to distinguish between normal and abnormal coordination, which may be useful when identifying neurological diseases (Horak et al., 1997). The unpredictability of perturbations is an essential component in simulating a real-life scenario in which a fall often occurs unexpectedly (Maki & McIlroy, 2006). Maki and McIlroy (1997) also proposed the “change-in-support” strategy, which involves the use of a step, in order to broaden the BoS (Inkol et al., 2018).

### 2.2 Muscle activation in balance recovery

Maintaining a stable base of support following a perturbation will require the activation of muscles around the ankle and/or hip joints (Inkol et al., 2018). In response to perturbations where maintaining a fixed base of support is feasible, the ankle and hip strategies are used to control motion in the sagittal plane (Ogaya, Okita, & Fuchioka, 2016). The ankle strategy employs a distal-to-proximal order of muscle activation, while the hip strategy requires proximal hip and trunk activation (Horak et al., 1997). Under control of the CNS, these strategies can be used independently of one another or

work together to regain control (Hwang et al., 2009). It has been suggested that the ankle strategy will be employed first, followed by activation at the knee, and then hip as the perturbation intensity increases (Horlings et al., 2009). This suggests larger amplitude perturbations often require activation of the muscles around the hip as ankle strategies are insufficient (Duclos, Maynard, Barthelemy, & Mesure, 2014). According to previous studies, both strategies require plantar flexor strength to regain control following an anterior displacement of the COM (Ogaya et al., 2016). The hip strategy, however, requires less ankle plantar flexion torque as it relies heavily on hip flexion to move the COM backwards (Ogaya et al., 2016). Therefore, the maintenance of muscle strength and power surrounding the ankle joint may be an important factor in reducing the movement of the COM in response to a perturbation.

Co-activation of the leg muscles is another common strategy that has been observed during perturbations (Santos et al., 2010). At the ankle, this strategy increases joint stiffness to generate the forces required to maintain a fixed BoS, following a perturbation. Evidence of this strategy is demonstrated by the co-contraction of the tibialis anterior and lateral gastrocnemius muscles found in response to disruptions of balance (Santos et al., 2010). In response to an unpredictable perturbation (pendulum impact to extended arms at shoulder level), older adults demonstrate larger compensatory postural adjustments (CPAs) and use different strategies and sequences of muscle activation to regain balance, when compared to younger adults (Kanekar & Aruin, 2014).

During bilateral stance perturbations in predictable conditions, both younger and older adults demonstrate muscle activation prior to the perturbation to reduce the overall movement of the COM (Kanekar & Aruin, 2014). This decreases the muscle activation required during the compensatory phase of control following the perturbation. In this scenario, younger and older adults use a distal to proximal muscle recruitment strategy (Kanekar & Aruin, 2014). A reciprocal pattern of activation is also evident during predictable perturbations (Kanekar & Aruin, 2014). When the COM moves in an anterior to posterior direction, the ventral muscles are activated while the dorsal muscles are inhibited (Kanekar & Aruin, 2014). In unpredictable conditions, anticipatory strategies are negligible, resulting in larger CPAs to compensate for the movement of the COM. In this scenario, younger adults have demonstrated a proximal to distal recruitment strategy to maintain balance when responding to unexpected perturbations. (Santos et al., 2010; Kanekar & Aruin, 2014). This sequence of activation is not maintained in older adults (Santos et al., 2010; Kanekar & Aruin, 2014). As well,

the reciprocal pattern of activation is replaced by a co-activation pattern in unpredictable conditions (Kanekar & Aruin, 2014).

### **2.3 External perturbation types**

The majority of studies examining balance recovery mechanisms using external perturbations have focused on bilateral translations of support surface platforms (e.g. Norrie et al., 2002; Zemkova et al., 2017; Inkol et al., 2018; Wang et al., 2017). However, it may be important to investigate the effect of unilateral perturbations, as disruptions to balance during daily living often occur unilaterally (Duclos et al., 2014). In fact, in a clinical population with chronic ankle instability, bilateral CPAs have been demonstrated following unilateral perturbations (Sousa, Silva, Gonzalez, & Santos, 2018).

Duclos et al., (2014) showed that in response to unilateral tendon vibration of the gastrocnemius-soleus complex, the non-perturbed limb was critical in limiting the displacement of the centre of pressure (COP). The original antero-posterior position of the COP was restored faster following unilateral tendon vibration than during bilateral tendon vibration. This demonstrates the importance of the unperturbed limb in the restoration of balance after a perturbation (Duclos et al., 2014).

Another study investigating the role of the stance limb during unilateral perturbations found that the thigh muscles of the stance limb were critical in maintaining balance (Hyodo, Saito, Ushiba, Tomita, & Masakado, 2010). These findings are supported by a study by Marigold, Bethune and Patla (2003), which compared muscle activity of the perturbed limb to that of the unperturbed limb. They demonstrated co-contraction of the rectus femoris and biceps femoris muscles in the unperturbed limb to regain control. Co-contraction around the ankle joint (i.e. tibialis anterior and medial gastrocnemius) has also been established in the unperturbed limb, in response to anticipation of a slippery surface (Chambers & Cham, 2006). It is suggested that ankle co-contraction may allow for better control of foot position, as well as increase joint stiffness. Overall, co-contraction strategies may be beneficial in decreasing the risk of falling (Chambers & Cham, 2006).

### **2.4 Aging and muscle function**

A loss of muscle mass and function as a result of aging, also defined as sarcopenia, is especially relevant to balance because sarcopenia particularly affects muscles of the lower limb (Montero-Fernandez & Serra-Rexach, 2013). In addition to muscular changes, aging also results in many functional deficits that may challenge balance and increase the risk of falling (Granacher, Gollhofer, Hortobagyi, Kressig & Muehlbauer, 2013).

Previous studies examining the effect of aging on postural control have found that older adults are less effective at regaining balance following an external perturbation than younger adults (Martelli et al., 2017; Dijkstra et al., 2015; Tsai, Hsieh, & Yang, 2014). Martelli et al. (2017) compared the motor responses of young ( $24\pm 2.7$  years) and older ( $65\pm 4.8$  years) adults subjected to slip-like perturbations while walking. They found that older adults had a slower reaction time and, in general, had a lower margin of stability than younger adults (Martelli et al. 2017). Another study analyzing muscle synergies during a forward perturbation found that older adults required more muscle activation and were more likely to use co-contraction to regain balance than younger adults (Wang et al., 2017). Dijkstra et al. (2015) found that older adults took more compensatory steps to regain balance following a perturbation than young adults; however, they were able to reduce the number of steps required following a perturbation training protocol.

The majority of studies examining the effects of aging focus on the loss of muscle strength demonstrated in older adults; however, changes in muscle power may have a larger impact on postural stability and control (Hruda, Hicks, & McCartney, 2003). Previously, resistance training has been used to counter-act age-related deficits in balance and increase strength. However, it has been demonstrated that improvements in strength do not result in significant improvements in functional performance (Granacher et al., 2013).

Muscle power is defined as the product of force and velocity (McKinnon, Connelly, Rice, Hunter, & Doherty, 2017). A recent review article suggests that a decrease in muscle power is related to a decrease in mobility and an increase in the risk of falls (McKinnon et al., 2017). In aging, muscle power is lost at a faster rate than muscle strength, which may be due to the selective denervation of fast-twitch muscle fibres (McKinnon et al., 2017) and subsequent reinnervation by slow motoneurons, resulting in an increase in slow twitch muscle fibres (Inacio, 2016). In reference to the ability to control posture following an external perturbation, a high percentage of type II muscle fibres is associated with a faster reaction time (Paillard, 2017). Therefore, a loss of type II muscle fibres in older adults may contribute to an increased risk of falling, due to the inability to produce force rapidly (Paillard, 2017). Reactive responses to a perturbation require force and velocity (i.e. power) to counteract the movement of the COM (Paillard, 2017). It has been suggested that older adults are at a higher risk of falling, when compared to young adults, because they are unable to generate the power required to maintain balance following an unexpected slip during walking (Chambers & Cham, 2006). A loss of muscle power is relevant to postural control, as a positive

correlation between muscle power output and the limits of stability scores has been demonstrated (Shim et al., 2018).

## **2.5 Aging and functional performance**

Functional outcomes assess the ability to perform everyday tasks (i.e. eating, rising from a chair, using a telephone) in a safe and effective manner (Quinn, McArthur, Ellis, & Stott, 2011).

Neuromuscular changes influence activities of daily living, such as rising from a chair and ascending stairs (Paillard, 2018). A loss of muscle power as a result of aging is especially relevant to physical function, as performance-based outcomes are largely influenced by power (Reid & Fielding, 2011). In community-dwelling women over the age of 65, plantarflexor muscle power has been shown to be an independent predictor of performance during a chair rise task, while dorsiflexor power was an independent predictor of an 8-stair climbing task (Suzuki, Bean, & Fielding, 2001). Conversely, plantar- and dorsiflexor strength were not independently associated with chair rise or stair climbing performance (Suzuki et al., 2001). When accounting for self-reported measures of health and physical function, data suggested that ankle muscle power is an essential component of functional performance (Suzuki et al., 2001). Regardless of training method, an increase in leg muscle power was more effective in improving performance-based outcomes (i.e. Short Physical Performance Battery; SPPB) than an increase in leg muscle strength, in older adults (Bean et al., 2010). When comparing types of resistance training, high-velocity resistance training has been shown to be more effective at improving functional outcomes (i.e. adapted arm curl, 30-s chair stand test, 8-ft up-and-go test) than low-intensity resistance training (Bottara, Machado, Nogueira, Scales, & Veloso, 2007). It is, therefore, evident that an important relationship exists between lower extremity muscle power and functional performance and that muscle power training in older adults is critical in the performance of activities of daily living.

## **2.6 Aging and external perturbations**

Millie et al. found that older adults were twice as likely to take a step when responding to an external perturbation (2003). When preparing to take a step, older adults demonstrated excessive muscle co-contraction and a low stability margin for COP displacement (Wang et al., 2017). Taking a step may therefore, be an inefficient strategy to regain balance, as the act of making a step has been associated with an increased risk of falling among older adults (Wang et al., 2017). The action of taking a recovery step requires a momentary shift from double-leg stance to single-leg stance. A recent study

has shown that this brief moment of single-leg support can result in limb collapse and ultimately result in a fall (Wang, Liu, & Pai, 2019).

There are a number of studies investigating perturbations while walking and have generally focussed on the action of the perturbed limb (Senden et al., 2014; Martelli et al., 2017; McCrum, Gerards, Karamanidis, Zijlstra, & Meijer, 2017). However, the unperturbed limb may play a critical role in maintaining balance because muscles of the unperturbed limb are activated quickly ( $> 180$  ms) following a perturbation. These onset latencies are similar to those found in the perturbed limb (Marigold et al., 2003).

The coordination between limbs in response to a perturbation is critical in the maintenance of balance as the actions of the unperturbed limb allow for a wider BoS, which increases stability (Marigold et al., 2003). A study investigating the effects of unilateral training on the trained and contralateral limb found that neuromuscular responses improved in both limbs following the unilateral training protocol. These results are indicative of a cross-education effect, which is beneficial in maintaining postural control (Oliveria, Brito Silva, Farina, & Kersting, 2013). This study suggests that balance training results in faster reaction time (muscle onset) and a longer burst of muscle activity. These adaptations are critical in effectively responding to disruptions to balance (Oliveira et al., 2013).

## **2.7 Effect of a cognitive load**

Postural responses are distinct from stretch reflexes; stretch reflexes can be identified 40-50 ms following a perturbation, whereas a postural response occurs 70-180 ms after a loss of equilibrium (Horak et al., 1997). As balance control does not occur as an automatic reflex, recovery from an unexpected disturbance requires attention (Cheng, Tsang, Schooling & Fong, 2018). In a real-life scenario, a loss of balance often occurs when the mind is focused on another task. Generally, daily motor tasks are performed simultaneously with a cognitive task (Tomas-Carus et al., 2019). Therefore, an appropriate manner to train balance is in a dual-task setting.

Dual-task paradigms offer a better understanding of the attention required to react to a challenge to balance (Patel & Bhatt, 2015). The capacity sharing theory, proposed by Pashler, explains how attentional resources are allocated to one task at the detriment of the second task (1994). The effect of a cognitive task, however, has been shown to vary depending on the task chosen (Inkol et al., 2018). A study by Worden and Vallis (2016) investigated the effects of performing a cognitive



(auditory Stroop task) and locomotor (obstacle avoidance) task on stability control and found no change in stability during the locomotor task when a cognitive task was introduced, indicating a prioritization of the motor task. Conversely, another study investigating allocation of attentional resources (balancing on an ankle-disc board and performing a memory task) found a decline in performance in both tasks when they were performed simultaneously (Schaefer, Krampe, Lindenberger & Baltes, 2008). Many previous studies have examined postural control using a dual-task paradigm (e.g. Patel & Bhatt, 2015; Norrie et al., 2002; Inkol et al., 2018).

In older adults, a decline in cognition has been associated with a reduced ability to effectively perform activities of daily living, resulting in an increased risk of falling (Fischer et al., 2014). Previous studies have used a cognitive-motor dual-task paradigm in order to assess the risk of falling in older adults (Tomas-Carus et al., 2019; Asai et al., 2018), as dual-task protocols are more successful at identifying functional deficits than single-task protocols (Tomas-Carus et al., 2019). As previously stated, the ability to perform tasks simultaneously requires an allocation of attentional resources. Similar to young adults, there seems to be a lack of consensus regarding which task (i.e. motor or cognitive) older adults will prioritize (Nnodim, Kim, Ashton-Miller, 2016). During the simultaneous administration of a gait perturbation and an auditory stimulus (i.e. vocal choice reaction test), older adults maintained postural control at the detriment of the cognitive task (i.e. significant increase in response time; Nnodim et al., 2016). Conversely, another study demonstrated a decline in dynamic postural performance during a dual-task protocol (Bernard-Demanze, Dumitrescu, Jimeno, Borel, & Lacour, 2009). It is postulated that the lack of agreement in the literature can be attributed to the varying complexity of the postural and cognitive tasks among studies (Bernard-Demanze et al., 2009).

## **2.8 Summary**

Ageing is associated with many muscular and functional changes (McKinnon et al., 2017; Reid & Fielding, 2011). The use of external perturbations has been identified as a useful tool in analyzing balance strategies in older adults (e.g. Martelli et al., 2017; Inkol et al., 2018; Shim et al., 2018). It is important to investigate postural control strategies in older adults to determine appropriate treatment techniques to limit the loss of mobility and adapt to the neuromuscular changes associated with aging. In a natural environment, a loss of balance may occur unilaterally or bilaterally, and when the mind is focused on another task (Tomas-Carus et al., 2019).

## **Chapter 3 - Methods**

### **3.1 Study design**

This is a cross-sectional study observing healthy young and older adults. The methodology used a quantitative analysis to examine physiological measurements and functional performance to identify differences between young and older adults. All outcomes were assessed during a single testing session lasting approximately 60 minutes.

This study was conducted within the Wolf Orthopaedic Biomechanics Laboratory (WOBL) at Western University. The Western University Research Ethics Board approved the methods used in this study. All participants signed an informed consent prior to participation in the study.

### **3.2 Participants**

Participants recruited for this study were between the ages of 18-30 years or 70+ years. To be included in the study, participants were required to meet the following inclusion criteria:

1. Be able to understand oral and written English
2. No physical injuries (e.g. leg fracture) sustained within the last 6 months
3. Have not been diagnosed with a respiratory and/or neurological disorder

### **3.3 Experimental set-up and procedure**

Ambulatory balance was assessed using the Community Balance and Mobility Scale (CB&M, /96; Knorr, Brouwer & Garland, 2010) – as the performance-based functional outcome measure for this study. The CB&M consists of 13 tests designed to analyze balance and mobility performance. Examples of these tests include unilateral stance, tandem walking, and descending a flight of stairs. A detailed description of each the CB&M tests can be found in Appendix II.

Participants completed maximal muscle power measurements using the Biodex System 3 isokinetic dynamometer. The set up and positioning of the Biodex protocol were performed according to the application and operation manual (Biodex Manual Systems Inc., Shirley, New York, USA). Participants were provided with verbal instructions and encouragement through the testing. All measurements were recorded unilaterally on the right side, which was the unperturbed (stance) limb during unilateral perturbations. The right side was chosen because it is generally the dominant limb for the majority of the population.

### Isometric ankle plantarflexion/dorsiflexion

Unilateral isometric ankle plantarflexion and dorsiflexion were assessed to determine maximum isometric torque about the right ankle and the maximal EMG was used for normalization of the EMG during perturbations. Participants were seated with the seat tilted back at 85°, with a limb-support pad securing the thigh and holding the knee at 30° of knee flexion (0° being full knee extension). The dynamometer's axis of rotation and ankle attachment were identical to the isotonic protocol (see above). At an ankle angle of 90°, participants alternated between isometric plantarflexion contractions and isometric dorsiflexion contractions. A total of three maximum plantarflexion and three maximum dorsiflexion contractions were performed, with a contraction time of three seconds and a rest period of twenty seconds between each contraction (Biodex Medical Systems Inc., Shirley, New York, USA). The percent difference across the three maximal contractions was less than 10% in order to be considered a true representation of a maximal contraction.

### Isotonic ankle plantarflexion/dorsiflexion

Unilateral isotonic ankle plantarflexion and dorsiflexion were assessed to determine average power around the ankle joint on the right side. Plantarflexion and dorsiflexion torque were set at 10% of the maximum torque assessed during the isometric contractions (see below). The axis of rotation of the dynamometer was aligned with the participant's lateral malleolus, with an ankle and foot strap securing the foot to the ankle attachment. Participants completed a total of three concentric plantarflexion contractions and three concentric dorsiflexion contractions, moving through their full ROM.

### Perturbation protocol

The Gait in Real time Analysis Interactive Lab (GRAIL) system was used for the standing perturbation tests. The GRAIL system (Motekforce Link, Amsterdam, Netherlands) consists of a dual-belt treadmill system set within a virtual reality environment. The treadmill belts are able to accelerate independently of one another, or in synchrony. In this study, accelerations were used to simulate a slip. A posteriorly-directed acceleration of the treadmill caused an anterior displacement of the COM. For the purpose of this study, unilateral and bilateral accelerations shifted the body away from equilibrium but did not induce a stepping reaction. Participants were instructed to stand in a comfortable standing position with one foot on each treadmill belt (i.e. shoulder width apart), while looking straight ahead for the duration of the perturbation testing. The duration of each perturbation

was 200 ms. As the duration of each perturbation was kept constant, an increase in perturbation intensity (i.e. increase in treadmill velocity; m/s) also caused an increase in the distance travelled by the treadmill belts. The intensity of all accelerations were set for each participant. Participants were secured by a safety harness attached to the ceiling, which did not provide any body weight support.

Participants experienced 20 unilateral (left belt only) and 20 bilateral backward accelerations of the treadmill. During unilateral accelerations, the right belt remained stationary, with the right leg being the stance leg. Both unilateral and bilateral accelerations of the treadmill caused anterior movement of the body's COM but no stepping reaction. To determine the appropriate perturbation intensity, participants were subjected to each perturbation type at an increasing intensity, until a step was required. The intensity was then decreased just below that required a step. Participants were unaware of the timing of the perturbations, which were delivered at least two seconds apart. Participants were instructed to keep their gaze on the virtual reality screen and to avoid taking a step when responding to the perturbation when possible. Any trials in which the participant stepped were excluded from analysis. Perturbations were delivered in sets, starting with five unilateral accelerations, followed by five bilateral accelerations. This set was repeated four times.

Participants performed the balance perturbation tests for a second time while simultaneously performing the Stroop cognitive task (Stroop, 1992). The Stroop cognitive task involves the name of a colour appearing on the screen but written in a font of a different colour. Participants were instructed to call out the colour in which the word was written, and not simply read that word that appeared on the screen. For example, if the word BLUE appeared in green font, participants would call out green. The Stroop cognitive task appeared on the centre of the virtual reality screen, at a rate of three seconds per word. The number of correct and incorrect responses were documented.

A visual representation of the split-belt treadmill system set within the virtual reality environment showing the Stroop test is demonstrated in Figure 1.



*Figure 1. The GRAIL system with the Stroop test presented on the virtual reality screen.*

### 3.4 Instrumentation/Data collection

EMG activity was recorded from eight lower limb muscles on the participant's right side (stance limb). After the skin was cleaned using *NuPrep* skin gel, bi-polar surface electrodes were placed according to the Surface ElectroMyography for the Non-Invasive Assessment of Muscles (SENIAM) guidelines (Hermens et al., 1999). The surface EMGs (Trigno™ Avanti wireless sensors, Delsys Inc., Natick, Massachusetts, USA) were recorded from: rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF), lateral gastrocnemius (LG), medial gastrocnemius (MG), soleus (Sol) and tibialis anterior (TA) muscles. EMG signals were sampled at 2000 Hz.

The treadmill perturbations were triggered using an application created in the GRAIL software D-flow (Motekforce Link, Amsterdam, Netherlands). To synchronize data collection, the treadmill belt speeds were recorded on all systems. The speed of each treadmill belt was outputted as an analog signal using a Phidget Analog 4-output #1002\_0B (Phidgets, Inc., Calgary, Alberta, Canada) and collected on Spike2 6.03 (Cambridge Electronic Design Limited, Milton, Cambridge, England) and Cortex-64 (version 5.0.1.1497; Motion Analysis Corporation, Rohnert Park, California, United States) at 2000 Hz.

### 3.5 Data analysis

All analyses were performed using Spike2 8.13 (Cambridge Electronic Design Limited, Milton, Cambridge, England). The onset of each perturbation and the onset of EMG activity was determined by threshold crossing on the filtered left treadmill belt speed signal. The threshold was calculated as the point the signal reached two standard deviations (SD) above the mean of a 500 ms epoch prior to the perturbation. EMG signals were band-pass filtered (Butterworth 4<sup>th</sup> order, 10-400 Hz) and then full wave rectified. After rectification, EMG signals are filtered again with a low-pass filter (Butterworth 2<sup>nd</sup> order, 0.7 Hz) to determine the EMG onset. The root mean square (RMS) EMG amplitude was calculated for 500 ms prior to the perturbation onset (baseline EMG) and for 100 ms after the onset of the muscle activity. Only trials in which the EMG burst exceeded 1.5 times the baseline were included in analyses. The latency of muscle activation was calculated as the difference between the timing of the muscle burst onset and the onset of the corresponding perturbation. The EMG amplitude during the burst was normalized to the baseline EMG amplitude. A schematic of the data analysis process is depicted by Figure 2. The EMG amplitude of the burst was also represented as a percentage of the EMG during the plateau phase of the isometric MVC. To examine the level of EMG pre-activation, the RMS for a 500 ms epoch was calculated during the static trials when no

perturbations were delivered. Pre-activation was considered present if the baseline EMG during the perturbation trial was larger than the EMG during the static trial.

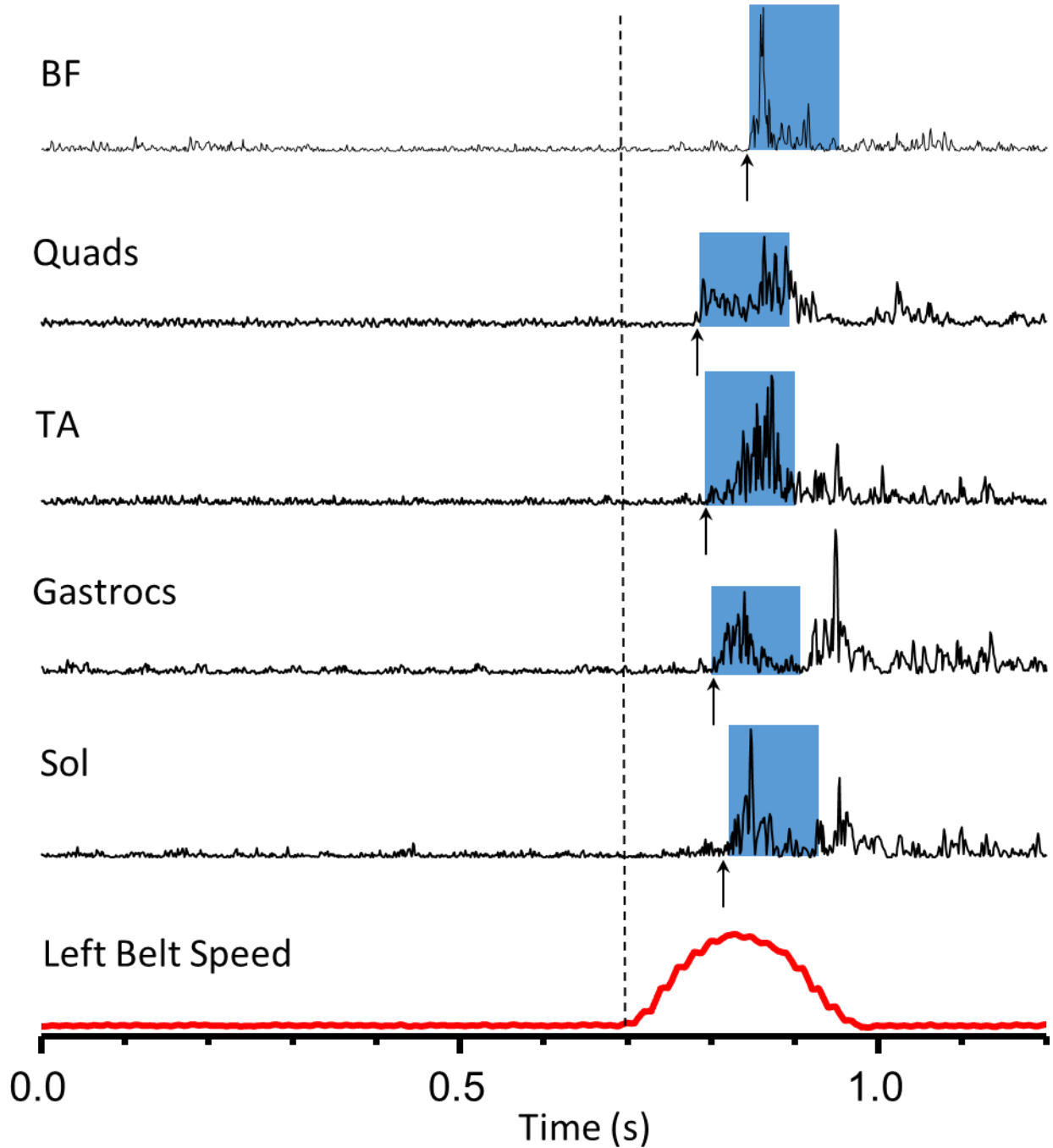


Figure 2. EMG recordings for a single perturbation from representative older adult. Perturbation onset taken from the treadmill signal (bottom row, dashed line) and EMG burst onset (arrow) are shown. Blue rectangles denote the area where RMS amplitude is calculated.

### 3.6 Statistical analysis

Statistical analyses were conducted using SPSS v.25 (IBM Corp, Armonk, NY). All muscle activity data were collected for each muscle separately to obtain a robust sampling of lower extremity muscles. Based on physiological function and individual muscle activity, it was concluded that RF, VL and VM exhibited similar behaviour, as did LG and MG. These muscles were grouped together as the Quads and Gastrocs, respectively. Grouping these muscles together also limited the number of ANOVAs performed, thereby increasing the strength of the ANOVA. The mean latency and RMS were calculated for each group (young and older adults).

To determine differences between EMG latency and RMS amplitude during unilateral and bilateral accelerations in young and older adults with and without the Stroop test, a comparison was done using a three-way mixed measures analyses of variance (ANOVAs) with perturbation type (unilateral acceleration and bilateral acceleration), and cognitive load type (No Stroop and Stroop) as the repeated measures and group (young adults and older adults) as the independent factor. Statistical significance was considered at  $p \leq 0.05$ . EMG amplitudes as a percentage of MVC EMG were also analyzed using independent (comparing age groups) and paired (comparing acceleration types within groups) t-tests. As each muscle was subjected to four comparisons, the corrected p value was  $p \leq 0.0125$ .

Any outliers, assessed by examination of studentized residuals for values greater than  $\pm 3$  standard deviations (SDs), were removed. When a significant interaction between factors was found, paired and independent t-tests were performed with Bonferroni corrections as post hoc analysis. For two factor interactions, four comparisons (t-tests) were performed and the corrected p value was  $p \leq 0.0125$ .

The order of muscle recruitment was assessed using a one-way repeated measure ANOVA with Bonferroni corrections for each condition (unilateral acceleration, bilateral acceleration, No Stroop and Stroop). Twenty comparisons were performed in each condition and the correction p value was  $p \leq 0.0025$ .

To determine the relationship between muscle power and functional performance, and latency and amplitude of muscle response to a perturbation, data were first tested for normality using the Kolmogorov-Smirnov test. Normally distributed data were analyzed using Pearson correlations ( $r$ ). Data that were not normally distributed were analyzed using Spearman correlations ( $\rho$ ). All



correlations were performed using a two-tailed test of significance. Statistical significance for all analyses was considered at  $p \leq 0.05$ .

A three-way mixed measures ANOVA was used to analyze any differences in EMG amplitude recorded during a static trial and the baseline EMG collected 500 ms prior to the perturbation onset. Muscle and trial type (static trial or perturbation) were the repeated measures and group (young adults and older adults) was the independent factor.

In order to determine the influence of the cognitive load, the number of correct responses during the Stroop test (as a percentage of total responses) were compared between young and older adults using an independent t-test ( $p \leq 0.05$ ).

## Chapter 4 – Results

### 4.1 Participants

Twenty healthy young adults (eleven male and nine female, mean age  $22.8 \pm 2.7$  years; mean height  $175.2 \pm 6.2$  cm; mean body mass  $71.1 \pm 11.7$  kg) and twenty healthy older adults (eleven male and nine female; mean age  $76.6 \pm 5.5$  years; mean height  $170.9 \pm 7.5$  cm; mean body mass  $76.8 \pm 9.0$ ) with no prior musculoskeletal injuries that would affect balance testing, neurological disorders, or respiratory diseases participated in the study.

### 4.2 Perturbation Protocol Outcomes

#### 4.2.1 EMG Latency

The results of the three way mixed methods ANOVA demonstrated no interaction between the three independent variables (age, perturbation type and cognitive load type) in any muscle group. There was a significant two-way interaction between perturbation type and age in the Quads, Gastroc, Sol and TA muscles and a significant two-way interaction between cognitive load type and age in the Quads muscles (Table 1). In BF there were no significant interactions, however there is an overall significant main effect of age ( $p=0.02$ ).

*Table 1. EMG Latency: The F-statistic (F), p-value (p) and degrees of freedom (df) from the interaction between perturbation and age, and cognitive load and age.*

Muscle	Perturbation type and age interaction			Cognitive load type and age interaction		
	F	p	df	F	p	df
Quads	17.99	$p<0.001^*$	1	11.18	$p=0.002^*$	1
BF	0.891	$p=0.35$	1	1.46	$p=0.24$	1
Gastrocs	15.34	$p<0.001^*$	1	0.87	$p=0.36$	1
Sol	9.48	$p=0.004^*$	1	0.53	$p=0.47$	1
TA	11.24	$p=0.002^*$	1	3.20	$p=0.08$	1

Significance is denoted by \*

Post hoc analyses demonstrated a significant difference in latency of muscle activation between young and older adults during both unilateral and bilateral accelerations in the Quads, and only during bilateral accelerations in the Gastrocs, Sol and TA muscles. In the Quads, older adults demonstrated a shorter latency of muscle activity than young adults during both unilateral and

bilateral accelerations. In the Gastrocs, Sol and TA muscles, young adults were quicker to respond to the bilateral perturbations than the older adults (Figure 3)

Young adults demonstrated a significant difference in latency of muscle activation between unilateral and bilateral perturbations, such that there was a shorter latency of activation during bilateral accelerations, in the Quads, Gastrocs, Sol and TA muscles. The older adults had similar latencies across all perturbation types (Figure 3).

In the Quads, there was a significant difference in the latency of muscle activation between young and older adults during both the No Stroop and Stroop condition, with the Quads being activated earlier in the older than the young adults (Figure 4). Young adults demonstrated a longer latency of muscle activation in the Stroop versus the No Stroop in the Quads; whereas the latency was not affected by the Stroop test in the older adults.

Regardless of perturbation type or cognitive load type, young adults demonstrated a distal to proximal muscle activation pattern, with Sol, Gastrocs and TA being activated before BF and Quads (Figure 3 and 4). During unilateral accelerations, Sol was activated significantly earlier than all muscles and Quads were activated significantly later than all other muscles ( $p < 0.0025$ ). When both legs were perturbed, there was no significant difference between Quad and BF latency. In all conditions, the onset of Gastrocs and TA activity was similar (Figure 3). The Stroop test had minimal influence on the order of muscle activation (Figure 4)

Older adults activated Sol first, followed by Quads, with Gastrocs and TA, and BF activated last during both perturbation types and cognitive load types. (Figure 3 and 4). Regardless of perturbation type, older adults activated BF significantly later than all other muscles ( $p < 0.0025$ ). As well, there was a significant difference between the onset of Sol activity and the burst of activity produced by the other distal muscles ( $p < 0.0025$ ). There was not, however, any difference in the onset of TA, following Gastroc activation (Figure 3). Similar to young adults, the addition of the Stroop test had minimal effect on the pattern of muscle activation in older adults (Figure 4).

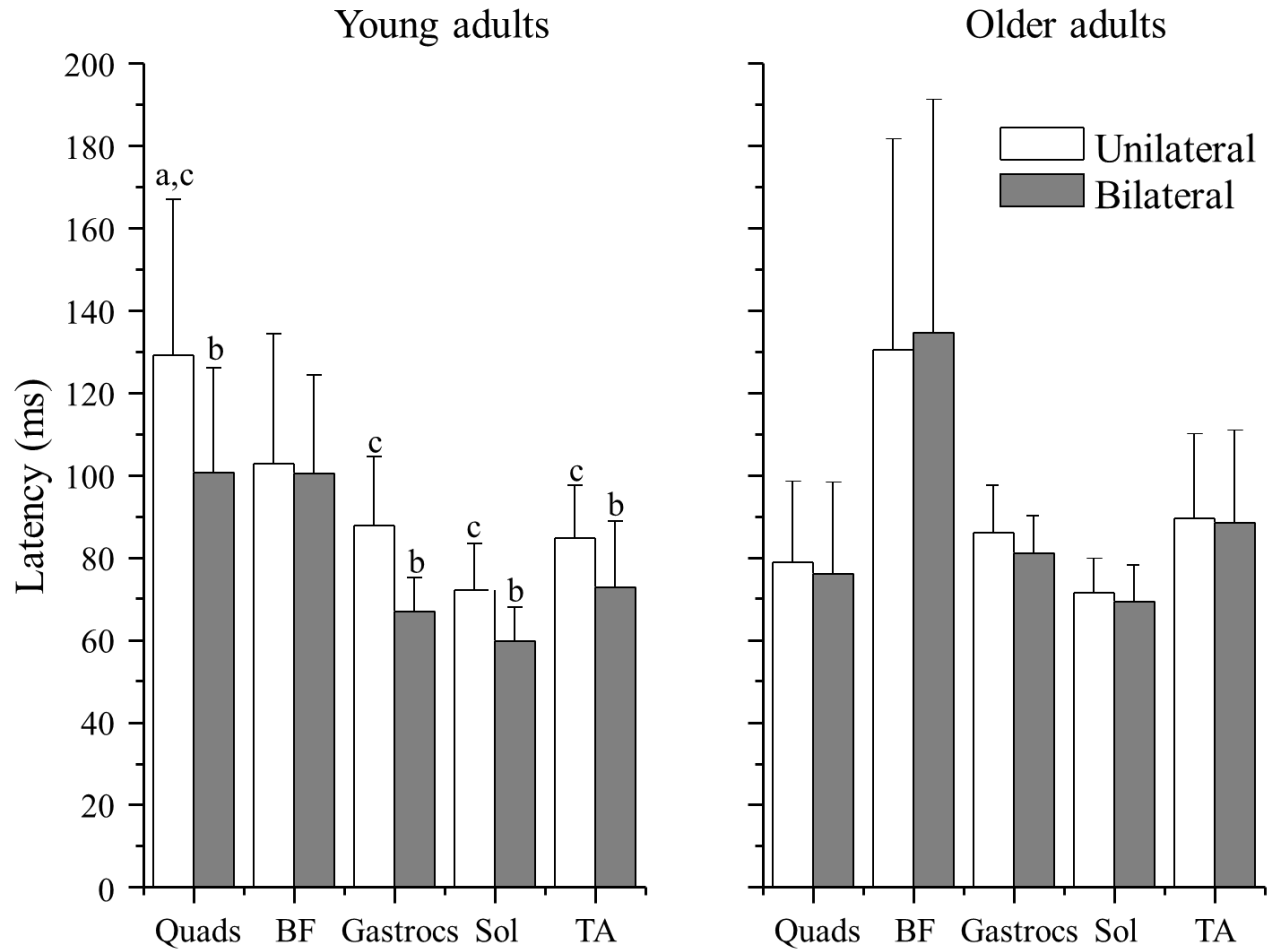


Figure 3. Latency of muscle activation, denoted by mean and SD, of combined cognitive load tests describing the interaction between perturbation type and age.

<sup>a</sup> denotes a significant difference from older adults during unilateral accelerations; <sup>b</sup> denotes a significant difference from older adults during bilateral accelerations; <sup>c</sup> denotes a significant difference between unilateral and bilateral accelerations

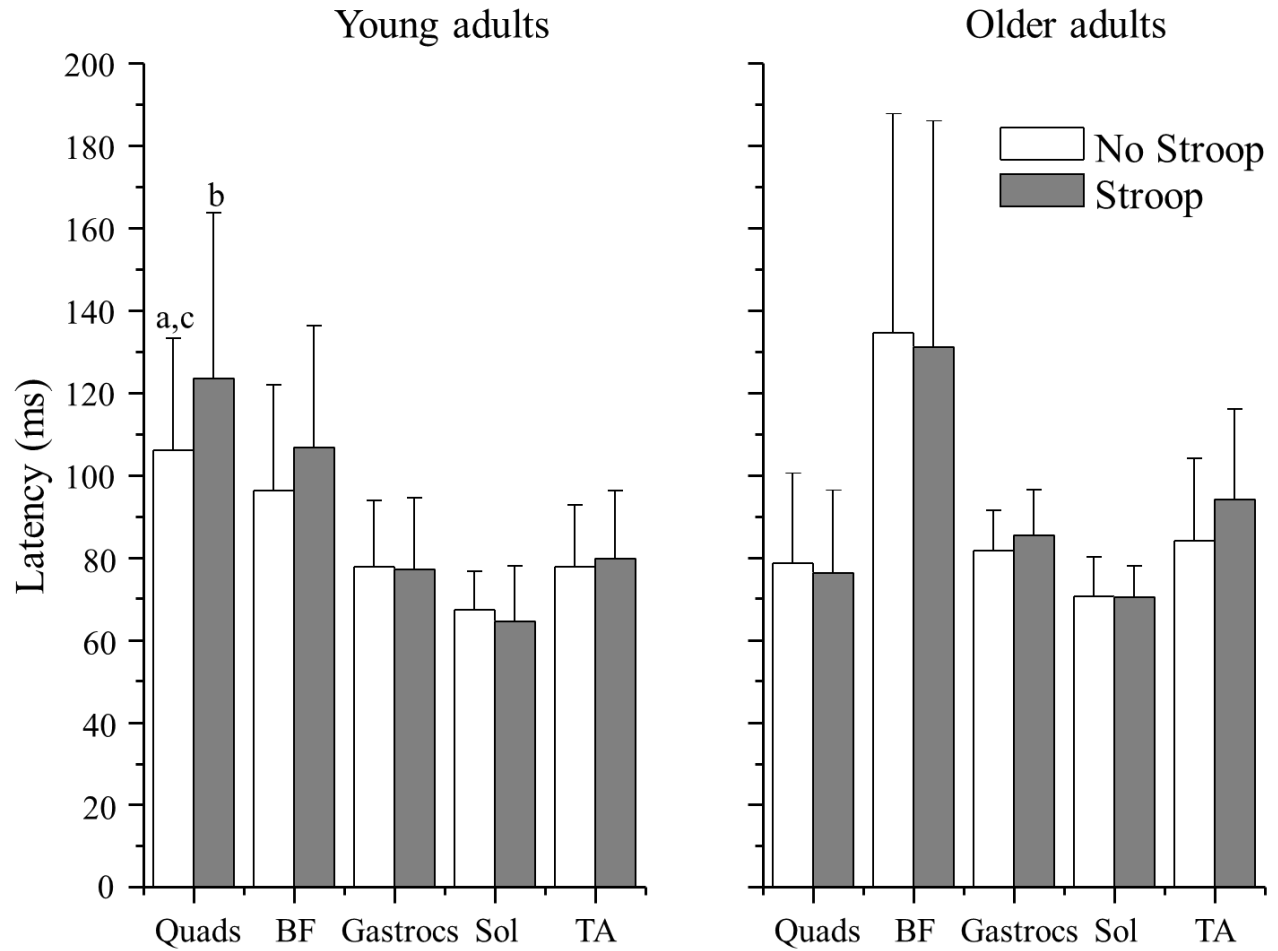


Figure 4. Latency of muscle activation, denoted by mean and SD, of combined acceleration types describing the interaction between cognitive load and age.

<sup>a</sup> denotes a significant difference from older adults during No Stroop; <sup>b</sup> denotes a significant difference from older adults during Stroop; <sup>c</sup> denotes a significant difference between No Stroop and Stroop

#### 4.2.2 EMG burst amplitude:

The results of the three way mixed methods ANOVA demonstrated a significant interaction between the three independent variables (age, perturbation type and cognitive load type) only in the Quads muscles. There was a significant two-way interaction between perturbation type and age in the Quads, Gastrocs, and Sol muscles and a significant two-way interaction between cognitive load type and age in the Quads and TA muscles (Table 2). In BF there were no significant interactions, however there was an overall significant main effect of perturbation ( $p < 0.001$ ).

*Table 2. EMG Amplitude: The F-statistic (F), p-value (p) and degrees of freedom (df) from the interaction between perturbation and age, and test and age.*

Muscle	Perturbation type and age interaction			Cognitive load type and age interaction		
	F	p	df	F	p	df
Quads	10.56	$p=0.002^*$	1	7.91	$p=0.008^*$	1
BF	3.94	$p=0.055$	1	0.40	$p=0.53$	1
Gastrocs	12.38	$p=0.001^*$	1	0.17	$p=0.68$	1
Sol	37.60	$p < 0.001^*$	1	0.10	$p=0.75$	1
TA	0.01	$p=0.91$	1	5.65	$p=0.02^*$	1

Significance is denoted by \*

Post-hoc analyses demonstrated that young adults produced a larger amplitude of muscle activity than older adults during unilateral accelerations and bilateral accelerations in the Quads, Gastrocs and Sol muscles. In both age groups, a significantly larger burst of muscle activity was seen following bilateral accelerations in these muscles. There were no significant differences in BF or TA as a function of age or perturbation type. In the Quads and TA muscles, young adults demonstrated a significantly larger amplitude of muscle activity in both cognitive load conditions when compared to older adults (Figure 5). Also in the Quads and TA muscles in young adults, a larger burst of muscle activity was seen during the Stroop test when compared to the No Stroop test (Figure 6).

In young and older adults, the degree of muscle activity, denoted as a percentage of MVC EMG (% MVC EMG), was larger during bilateral accelerations than during unilateral accelerations in Gastrocs and Sol. Older adults also demonstrate an increase in BF activity during bilateral accelerations. The EMG amplitude (% MVC EMG) decreased significantly in the TA during bilateral accelerations when compared to unilateral accelerations, only in young adults. Regardless of acceleration type, older adults demonstrated larger EMG (% MVC EMG) values in BF than young

adults. During unilateral accelerations only, older adults also demonstrated a larger degree of muscle activation in Quads and Sol than young adults (Table 3).

*Table 3. The percentage of muscle activity, denoted as the average percentage of MVC, during the burst of activity following perturbations without a cognitive load.*

	Young adults		Older adults	
	Unilateral acceleration (% of max)	Bilateral acceleration (% of max)	Unilateral acceleration (% of max)	Bilateral acceleration (% of max)
Quads	12.45 <sup>+</sup>	14.72	25.21	23.39
BF	14.96 <sup>+</sup>	21.78 <sup>+</sup>	41.44 <sup>*</sup>	51.48
Gastrocs	37.57 <sup>*</sup>	60.64	80.32 <sup>*</sup>	108.23
Sol	32.38 <sup>*,+</sup>	63.67	67.94 <sup>*</sup>	86.38
TA	23.09 <sup>*</sup>	17.63	29.31	27.15

\* denotes a significant difference from bilateral accelerations; <sup>+</sup> denotes a significant difference from older adults

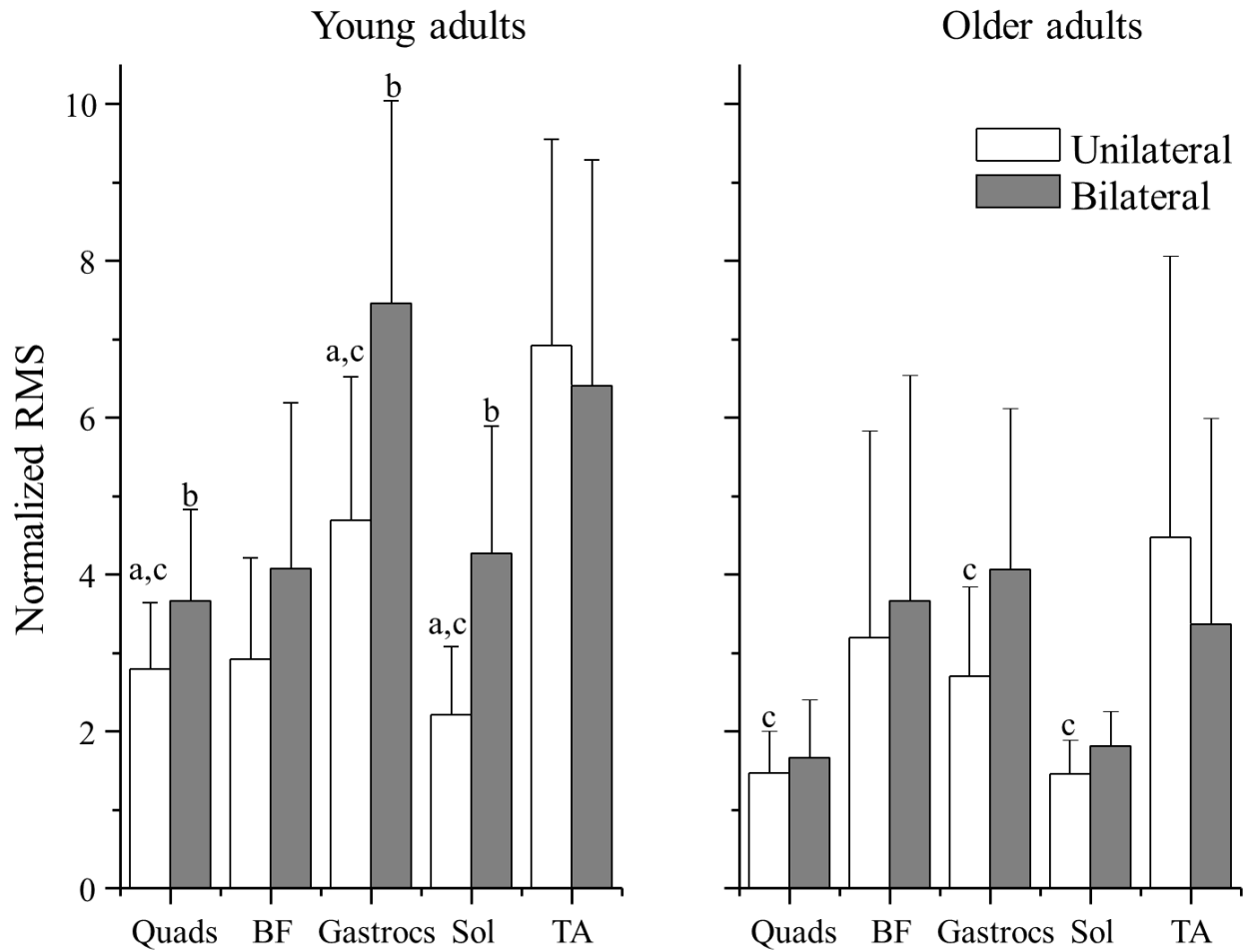


Figure 5. EMG burst amplitude normalized to baseline EMG, denoted by mean and SD, of combined cognitive load types describing the interaction between perturbation type and age.

<sup>a</sup> denotes a significant difference from older adults during unilateral accelerations; <sup>b</sup> denotes a significant difference from older adults during bilateral accelerations; <sup>c</sup> denotes a significant difference between unilateral and bilateral accelerations



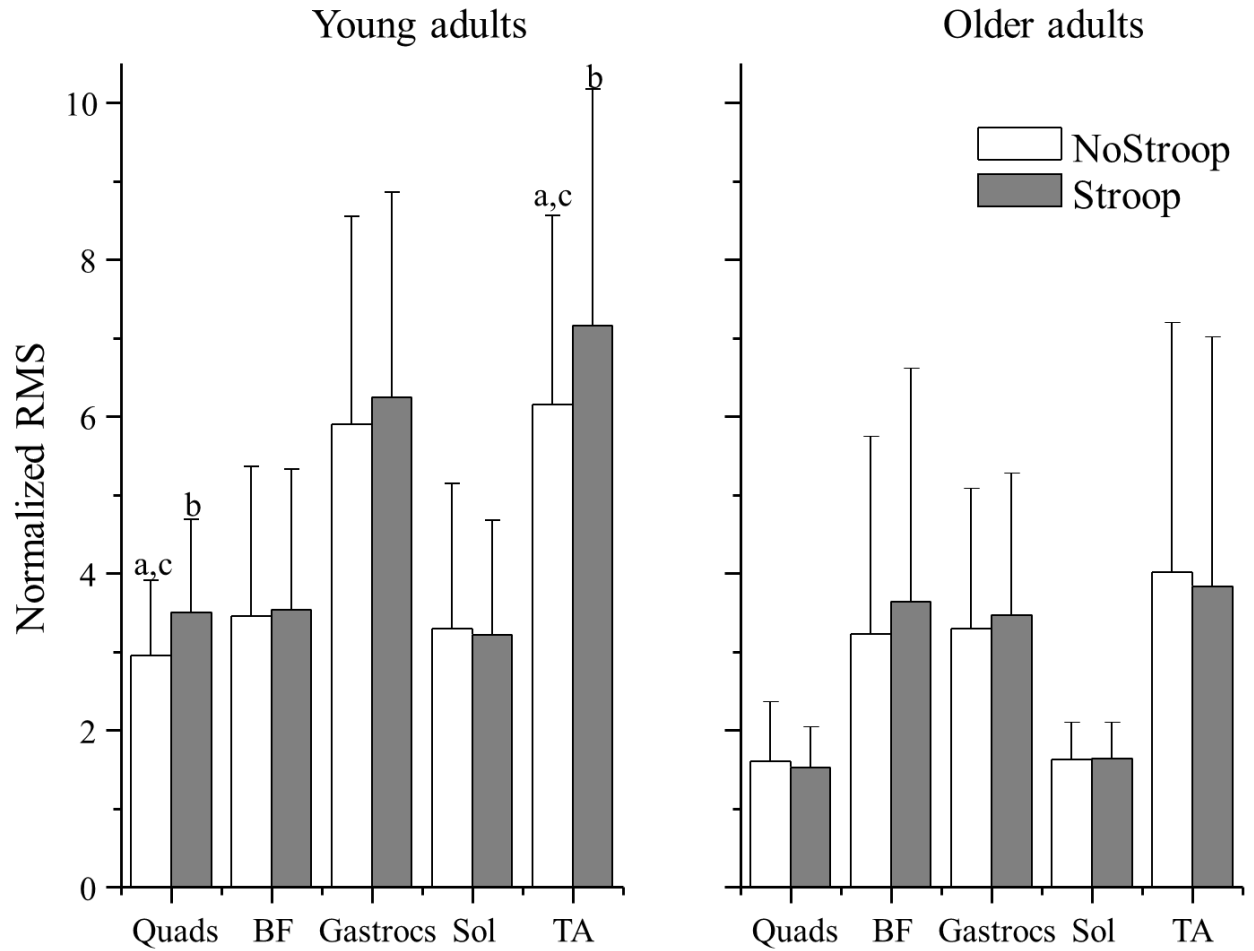


Figure 6. EMG burst amplitude normalized to baseline EMG, denoted by mean and SD, of combined acceleration types describing the interaction between cognitive load and age.

<sup>a</sup> denotes a significant difference from older adults during No Stroop; <sup>b</sup> denotes a significant difference from older adults during Stroop; <sup>c</sup> denotes a significant difference between No Stroop and Stroop

### 4.2.3 EMG Pre-activation

In both young and older adults, the baseline EMG collected just prior to the perturbation onset was significantly larger than the EMG amplitude collected during static trials when no perturbation was delivered or expected by the participant. Older adults demonstrate larger EMG pre-activation than young adults in all muscles except BF ( $p < 0.01$ ; Table 4).

Table 4. Baseline EMG measures, denoted by mean (SD).

	Baseline EMG	Young adults (mV)	Older adults (mV)
Quads	Static trial EMG	0.008 (0.007) <sup>+</sup>	0.04 (0.05)
	Perturbation baseline EMG	0.02 (0.008) <sup>*,+</sup>	0.08 (0.07) <sup>*</sup>
BF	Static trial EMG	0.01 (0.008)	0.02 (0.008)
	Perturbation baseline EMG	0.02 (0.007) <sup>*</sup>	0.03 (0.02) <sup>*</sup>
Gastrocs	Static trial MG	0.02 (0.01)	0.02 (0.008)
	Perturbation baseline EMG	0.03 (0.02) <sup>*,+</sup>	0.07 (0.03) <sup>*</sup>
Sol	Static trial EMG	0.01 (0.006) <sup>+</sup>	0.06 (0.04)
	Perturbation baseline EMG	0.06 (0.02) <sup>*,+</sup>	0.12 (0.06) <sup>*</sup>
TA	Static trial EMG	0.01 (0.006)	0.01 (0.008)
	Perturbation baseline EMG	0.03 (0.01) <sup>*,+</sup>	0.09 (0.1) <sup>*</sup>

\* denotes a significant difference from static trial;

+ denotes a significant difference from older adults

### 4.2.4 Stroop Accuracy

There was a significant difference in the number of correct responses (as a percentage of total responses) reported during the Stroop test between young and older adults ( $p = 0.001$ ), although both groups performed the task very well. Young adults demonstrated a greater percentage of correct responses than older adults (mean: 99.6% (0.75) and 94.7% (6.3), respectively).

### 4.3 Functional Balance and Ankle Muscle Power

Community Balance & Mobility scores and average plantarflexor and dorsiflexor power for the young and older adult groups are presented in Table 5. Older adults have lower CB&M scores and lower isotonic power than young adults.

*Table 5. CB&M scores, isotonic ankle plantarflexor and dorsiflexor power, denoted by mean (SD), in young and older adults.*

	<b>CB&amp;M score (/96)</b>	<b>Average isotonic ankle plantarflexor power (Watts)</b>	<b>Average isotonic ankle dorsiflexor power (Watts)</b>
<b>Young adults</b>	94.3 (1.5)	53.7 (24.6)	13.6 (7.2)
<b>Older adults</b>	63.1 (12.9)	23.9 (10.5)	4.9 (2.2)

The majority of the data used for the correlations between power and functional outcomes, EMG latency and RMS amplitude were not normally distributed ( $p > 0.05$ ), therefore, Spearman correlations were used in all cases.

### 4.3.1 Muscle Power and Functional Outcomes

Plantarflexor muscle power or dorsiflexor muscle power and CB&M score data for young and older adults are presented in Figure 7. Whereas there were no significant correlations between plantarflexor or dorsiflexor power and CB&M score in young adults ( $\rho=0.150$  and  $\rho=-0.098$  respectively), there was a significant correlation between plantarflexor power and CB&M score ( $\rho=0.464$ ;  $p=0.04$ ), in older adults but not between dorsiflexor power and CB&M score ( $\rho=0.314$ ;  $p=0.18$ ).

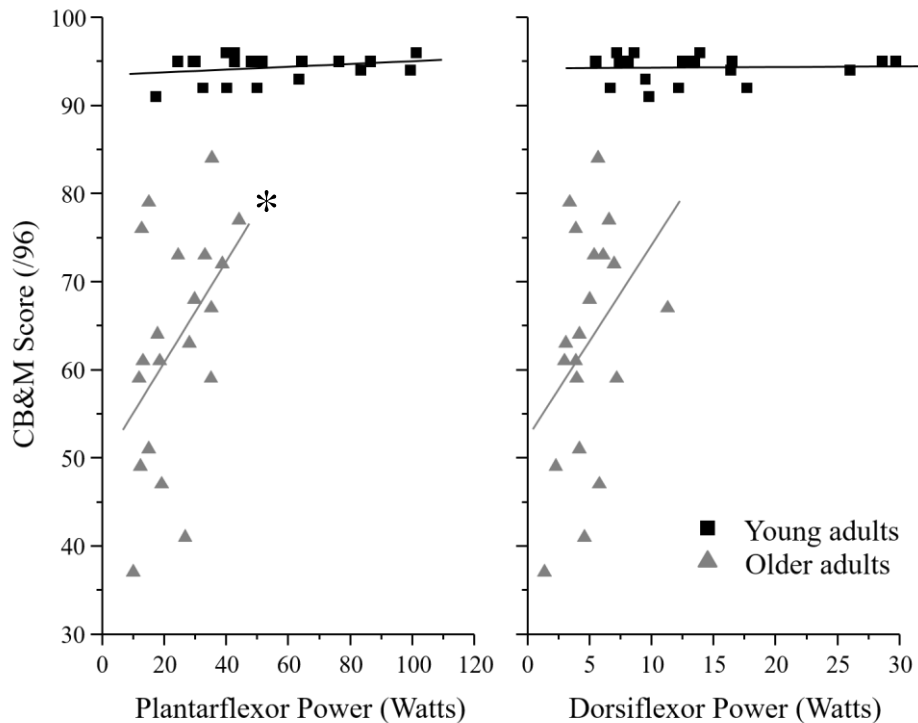


Figure 7. The correlation between plantarflexor and dorsiflexor power and CB&M score in young and older adults.

\* denotes significance

### 4.3.2 Muscle Power and EMG burst amplitude

While there were no significant correlations between plantarflexor muscle power and RMS in the Gastrocs and Sol muscles during accelerations in young adults ( $\rho=-0.190$  to  $0.247$ ), there was a significant correlation between plantarflexor power and RMS in Gastrocs during bilateral accelerations ( $\rho=0.582$ ;  $p=0.007$ ) in older adults, but not during unilateral accelerations ( $\rho=0.394$ ; Figure 8).

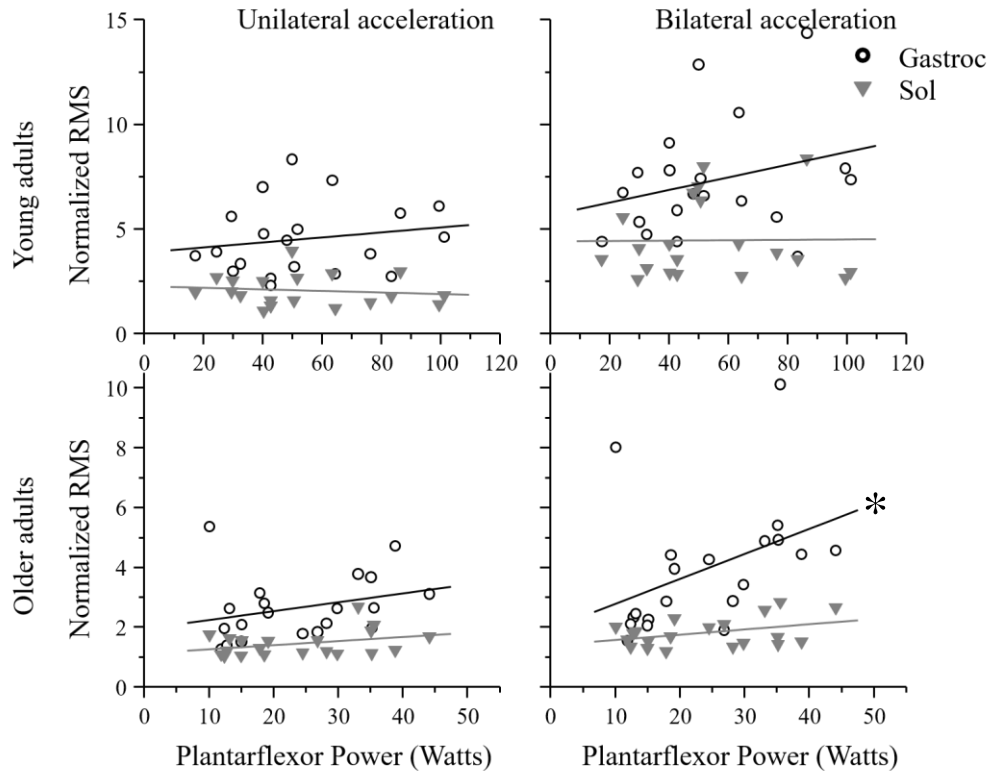


Figure 8. Correlations between plantarflexor power and EMG burst amplitude in the Gastrocs and Sol during unilateral and bilateral accelerations in young and older adults.

\* denotes significance

#### 4.3.4 Muscle Power and Perturbation Intensity

In young adults, there was no significant correlation between plantarflexor power and unilateral perturbation intensity ( $\rho = -0.018$ ). There was, however, a significant correlation between plantarflexor power and unilateral perturbation intensity ( $\rho = 0.486$ ;  $p = 0.03$ ) in older adults. In both young and older adults there was no significant correlation between plantarflexor power and bilateral perturbation intensity ( $\rho = 0.183$  and  $\rho = 0.293$  respectively; Figure 9).

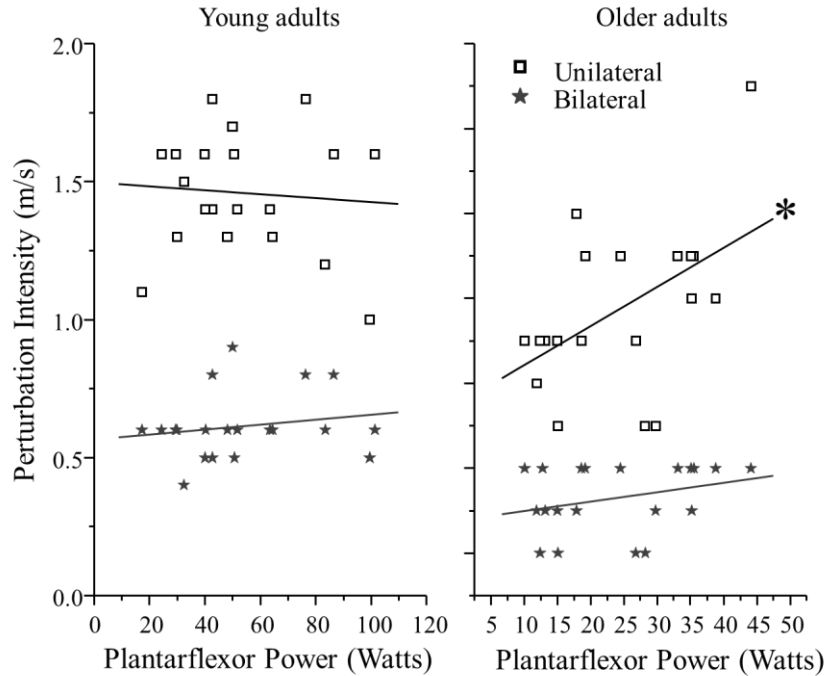


Figure 9. Correlations between plantarflexor power and perturbation intensity of unilateral and bilateral accelerations in young and older adults.

\* denotes significance

## Chapter 5 – Discussion

The main findings of this study are that, unlike young adults, older adults do not modulate their postural responses, depending on whether the perturbation occurs unilaterally or bilaterally. The addition of a cognitive load does not influence the postural response in older adults, suggesting they are prioritizing the postural task over the cognitive task. Further, an increase in muscle power proves beneficial for functional and postural performance in older adults.

### 5.1 Unilateral and Bilateral Accelerations

We hypothesized that unilateral and bilateral accelerations would produce different responses, and that the addition of a cognitive load would delay muscle activation and increase the burst of muscle activity required to regain balance. Additionally, we hypothesized that older adults would demonstrate a greater latency of muscle activity, a decreased amplitude of muscle activation and prioritize the balance task over the cognitive task when compared to young adults. The muscle activation patterns observed in this study indicate that young and older adults respond differently to perturbations to a support surface platform. Partially confirming our hypothesis, young adults adjusted their postural responses depending on whether the perturbation occurred unilaterally or bilaterally. Conversely, older adults responded in a similar manner regardless of perturbation type (Figure 3, 5). Contrary to our hypothesis, the addition of the Stroop test had minimal influence on latency or amplitude of the muscle bursts produced by young adults, and no influence in older adults (Figure 4, 6).

#### Young adults

Based on the latency of muscle activation, young adults demonstrated a distal to proximal order to muscle activation to regain balance following a perturbation (Figure 3). The use of support surface translations has been shown to elicit muscle activation quickly at the ankle joint, followed by involvement at the thigh and then trunk (Horak & Nashner, 1986). The burst of Sol activity was first, followed by the similar onset latencies of Gastrocs and TA, and lastly proximal muscle activation, further supporting the notion that ankle musculature is critical in the maintenance of balance in young adults (Horak & Nashner, 1986). While this recruitment order is different to the proximal to distal order found in randomly applied external perturbations Santos et al., (2010), it provides evidence that young adults rely on the ankle strategy (Horak et al., 1997), regardless of whether balance is challenged unilaterally or bilaterally. In the study by Santos et al. (2010), the perturbation

was delivered at shoulder level to the participants extended arm, whereas in our study the perturbation occurred distally. It is possible that the height at which the perturbation occurs (proximal or distal) can influence the muscular response, such that proximal perturbations rely on proximal muscle activation, whereas distal perturbations rely on distal muscle activation.

The type of acceleration (unilateral/bilateral) influenced the latency of response in the Quads, Gastrocs, Sol and TA, but not the BF. The quicker onset (decreased latency) of muscle activity during bilateral perturbations provides insight into the importance of the stance leg in limiting the loss of equilibrium (Duclos et al., 2014) and reducing the muscular response. The unperturbed limb has been shown to be activated at latencies between 140 and 250 ms (Marigold et al. 2003), whereas the perturbed limb has been shown to be activated at latencies between 70 and 110 ms (Horak & Nashner, 1986). Additionally, the contribution of the plantarflexor muscles (as a percent of MVC EMG) increases significantly during bilateral perturbations and demonstrates activity above 60% of MVC EMG, indicating that bilateral perturbations require more ankle musculature involvement. Therefore, it could be said that bilateral perturbations pose a greater threat to balance, and hence require a greater muscular response. Further, the decrease in Quad onset latency, as well as the increase in BF EMG activity as a percentage of MVC (although not significant) associated with bilateral perturbations is indicative of the muscle recruitment strategy proposed by Horlings et al., which states that knee and hip musculature are activated as the perturbation intensity increases (2009).

Again, in support of statement made by Horlings et al., (2009; see above), young adults demonstrated larger RMS EMG amplitudes during bilateral accelerations than during unilateral accelerations, further supporting the notion that bilateral perturbations pose a greater risk to equilibrium. It would seem, however, that young adults rely minimally on Quad activation, as although there is an increase in RMS amplitude during bilateral accelerations, the amplitude of EMG activity, denoted as a percentage of MVC is relatively low (Table 3). The plantarflexor muscles demonstrate a significant increase in RMS amplitude, as well as a greater percentage of MVC EMG during bilateral accelerations (Table 3), providing further support for the reliance on the ankle strategy regardless of perturbation condition. Previous studies have also demonstrated the maintenance of the ankle strategy for postural control in young adults (Mackey & Robinovitch, 2006; Boyas et al., 2017).



Although co-contraction has been previously reported as a mechanism for postural control using a fixed BoS strategy (Santos et al., 2010), based on the RMS values as a percentage of MVC EMG, there is limited evidence of a co-contraction strategy used by young adults in this study. BF demonstrates a greater degree of activation than the Quads, but overall the contribution is minimal (12-22%; Table 3). The greatest degree of activation is demonstrated in the plantarflexor muscles, however there is lesser activation in TA. There may be an indication of co-contraction around the ankle joint during unilateral perturbations, which is supported by a previous study demonstrating the co-contraction around the ankle joint in the unperturbed limb in response to a disruption to balance (Chambers & Cham, 2006). Previous evidence of co-activation has been reported in response to perturbations applied at the shoulder or during gait (Santos et al., 2010; Chambers & Cham, 2006). It is, therefore, possible that stance perturbations are more easily managed by young adults, and do not require a stiffening response strategy.

In response to forward sway, the dorsal muscles are expected to be the main contributors to the posterior movement of the COM to restore equilibrium (Horak et al., 1997). The addition of the Stroop test resulted only in an increase in EMG latency and amplitude in the Quads, as well as an increase in amplitude in TA in young adults. As the cognitive load affected only ventral muscles, this suggests that the Stroop test had a minimal effect on postural performance. These results are supported by a previous study by Worden and Vallis (2016), which found no change in motor performance, in young adults, when a cognitive task was introduced. The similarities in the results of our study to the results of Worden and Vallis (2016) may be attributed to the choice of cognitive task (visual Stroop task and auditory Stroop task, respectively). The lack of effect may also be attributed to the limited complexity of the cognitive task (Bernard-Demanze et al., 2009) and the relative ease in which young adults responded to postural perturbations.

Additionally, it has recently been suggested that the effect of a cognitive load may be altered depending on whether the response to a perturbation requires a fixed BoS or a change-in-support strategy (Inkol et al., 2018). Inkol et al. (2018) found a decline in motor performance but not cognitive performance when responding to perturbations in which balance was maintained using a fixed BoS strategy, but the opposite (i.e. decline in cognitive performance but not in motor performance) when the postural control required the execution of a step. As the current study required balance to be maintained without changing the dimensions of the BoS, this could explain the consistency of correct Stroop responses in young adults.

### Older adults

Older adults demonstrated a similar latency of muscular response regardless of whether the perturbation occurs unilaterally or bilaterally, suggesting that older adults are not able to modulate their response based on the task demands. In both acceleration types, there is no difference in the onset latencies between the first burst of muscle activity, produced by the Sol, and the activation of the Quads. While these results may indicate a greater reliance on the Quads for postural control, older adults generate a relatively small amplitude of muscle activity in the Quads, denoted as a percentage of MVC EMG (23-25%; Table 3). Early activation of the Quads, therefore, may be related to greater reliance on hip movements, which has previously been reported in older adults (Manchester, Woollacott, Zederbauer-Hylton, Marin, 1989; Okada, Hirakawa, Takada, & Kinoshita, 2001).

The immediate activation of the Sol and Quads followed by the activation of the Gastrocs, TA and BF indicates that older adults may adopt a mixed ankle and hip strategy in response to a disruption to balance. Older adults demonstrated an increased reliance on the dorsal muscles as evidenced through the large degree of muscle activation as a percentage of their MVC EMG (41-108%; Table 3). While older adults activated BF last, the burst of muscle activity is relatively large (41%-51%; Table 3). As it is expected that the dorsal muscles will be the main contributors to equilibrium following a forward loss of balance (Horak et al., 1997), older adults were able to maintain this pattern albeit with a slower onset of activation. The greater relative degree of activation demonstrated by older adults is not uncommon, as a previous study has also reported greater RMS values in older adults when normalized as percent of MVC EMG (Tsai et al., 2014). That is, relative to their MVC RMS EMG, older adults required a greater percentage of their maximal muscle activation capacity to return to a position of equilibrium (Tsai et al., 2014).

Based on the lower treadmill acceleration intensity in which balance can be maintained without taking a step, bilateral perturbations pose a greater threat to stability and therefore require more muscle activity to correct for the loss of equilibrium. As the stance limb (during unilateral perturbations) is now being perturbed, a greater loss of balance occurs. In the Quads, Gastrocs and Sol, the EMG amplitude increases during the bilateral perturbation when compared to the unilateral perturbation. The increase in EMG amplitude in the Quads is most likely related to a greater degree of movement at the hip joint during bilateral accelerations (Manchester et al., 1989), as the muscle burst as a percentage of MVC EMG remains relatively small (Table 3). Gastrocs and Sol activity has

been shown to reduce the movement of the COM in response to a forward loss of balance (Graham, Carty, Lloyd, & Barrett, 2017). Therefore, without a fixed stance limb, a greater reaction from the Gastrocs and Sol is required. The degree of activation in BF, Gastrocs and Sol (based on % MVC EMG) increases significantly during bilateral accelerations as well, further supporting the increased difficulty of bilateral perturbations.

The use of co-contraction strategies for postural control has previously been reported in older adults (i.e. Nagai et al., 2011; Wang et al., 2017). The use of co-contraction specifically around the ankle joint has been demonstrated as an ankle stiffening strategy during static and dynamic postural control tasks (Nagai et al., 2011; Donath, Kurz, Roth, Zahner, & Faude, 2016). While older adults demonstrated a large reliance on the dorsal muscles for postural control, the activity of the ventral muscles was relatively small (Table 3). The overall weak level of co-activation demonstrated in this study may be related to the nature of the postural task. In previous studies, co-contraction in older adults has been identified in response to tasks such as functional reach tests, standing on a foam balance pad and following anterior displacements of the support surface platform (posterior movement of the COM, but no stepping reaction; Nagai et al., 2011; Donath et al., 2016; Okada et al., 2001). As accelerations (or posterior translations) of the treadmill were used in our study, the need for co-activation may be limited, as the dorsal muscles alone (specifically the plantarflexor muscles) are capable of stabilizing the COM.

Older adults demonstrated a similar latency and amplitude of EMG response in the No Stroop and Stroop conditions. This could be indicative of a “posture first” strategy in older adults, meaning they will prioritize the balance task to the detriment of the cognitive task (Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997). These results are comparable to previous studies, in which older adults maintained postural control during a dual-task protocol, but demonstrated a decline in cognitive task performance (Nnodim et al., 2016). A previous study has also demonstrated the increased attentional demands of a step recovery compared to a fixed BoS recovery (Brauer, Woollacott, & Shumway-Cook, 2002), which may partially account for the lack of effect the addition of a cognitive load had on postural control in our study. As the fear of falling has been shown to increase with age, older adults may be more inclined to allocate attentional resources to the postural task, as it poses a greater risk to balance than the cognitive task (Scheffer, Schuurmans, van Dijk, van Der Hooft, & De Rooij, 2008).

### Young vs. Older adults

The use of platform perturbations to disturb standing balance in young and older adults has previously identified differences in postural control strategies (Alexander, 1994). There is a lack of consensus among perturbation studies when analyzing muscle activation patterns from the lower limb muscles (Chambers & Cham, 2007; Tsai et al., 2014; Kanekar & Aruin, 2014). During slip forward perturbations, young adults activated proximal leg muscles and TA sooner than older adults, but demonstrated a delayed activation in the gastrocnemius muscle when compared to older adults (Tsai et al., 2014). In young and older adults, the early activation of the knee flexors and distal muscles (TA and MG), followed by a significantly delayed activation of the knee extensors has been demonstrated in response to a slippery surface during gait (Chambers & Cham, 2007). Previous studies have also reported a delay in the activation of the distal muscles in older adults when compared to younger adults (Woollacott, Shumway-Cook, & Nashner, 1986).

The dissimilarities in postural responses observed in young and older adults in our study are in line with Kanekar & Aruin (2014), who found dissimilarities in postural responses between age groups. The onset timing of muscle activity reported in this study are comparable to previous studies using external perturbation techniques (Horak & Nashner, 1986; Forghani & Milner, 2017). These studies found early onset of ankle activity at 70-80 ms in young adults in response to a perturbation (Horak & Nashner, 1986; Forghani & Milner, 2017) followed by thigh and trunk latencies up to 110 ms (Horak & Nashner, 1986). The onset latencies demonstrated in our study are indicative of a long-latency stretch response (Forgaard, Franks, Maslovat, & Chua, 2016). Long latency responses have been shown to differ between young and older adults, such that older adults demonstrated a longer peak response time (Madhavan et al., 2009), which may explain the increased latency of response in the distal muscles and BF in older adults when compared to young adults. Although BF demonstrates no interaction effects, there is a significant difference between age groups, such that older adults demonstrate an increase in response time. The lack of any interaction effects may be explained by the reliance on ankle musculature in young adults and the lack of modulation in older adults. The short Quad latencies in older adults were most likely due to the differences in control strategies demonstrated by young (ankle strategy) and older (mixed strategy) adults.

The RMS of the first 100 ms of muscle activity following the burst onset is larger in the Quads, Gastrocs and Sol in the young adults compared to older adults. Larger amplitudes of muscle activity have previously been reported in young adults during hazardous slip conditions during gait, in which

young adults demonstrate a more powerful response (Chambers & Cham, 2007). As force must be generated quickly to stabilize the COM, the smaller EMG amplitude values demonstrated by the older adults may partially be attributed to the increase in motor unit size and a decrease in contraction velocity as a consequence of aging, (McKinnon et al., 2017) which results in a decreased ability to produce a great amount of force rapidly (i.e. the first 100 ms following a perturbation). While older adults demonstrate reduced RMS amplitudes when compared to young adults, they also demonstrate a higher percent of MVC when responding to perturbations, indicating a relatively greater degree of activation. In accordance with Tsai et al. (2014), who also reported greater RMS values in older adults when normalized as a percentage of MVC EMG, relative to their MVC EMG older adults required a greater percentage of their maximal muscle activation capacity to return to a position of equilibrium. In addition, results of the comparison between baseline EMG amplitudes demonstrated a higher pre-activation EMG activity in older adults (Table 4). This baseline activity could partially account for the decreased amplitude of EMG activity demonstrated by older adults following a perturbation, as all RMS values obtained in this study were normalized to baseline EMG. Finally, as the perturbation intensity is set relative to each participant, older adults are subjected to smaller perturbations than young adults, which may also explain the decreased EMG values.

The muscle recruitment patterns identified in young and older adults differed in each group. As young adults employed the ankle strategy, there was an emphasis on the plantarflexor muscles to regain control. In older adults, the mixed ankle and hip strategy incorporated ankle and thigh muscles. Differences in postural strategies have been identified in a previous study investigating the effects of different standing balance tasks (Donath et al., 2016). However, in the study by Donath et al. (2016), older adults demonstrated a relatively larger degree of muscle activity from the TA than did young adults. In our study, TA was activated to a similar amplitude, regardless of age. This may be related to the nature of the balance tasks, as in our study, the anterior movement of the COM puts the ankle joint in an unstable position (Brockett & Chapman, 2016), and thus both age groups required some TA activity to stabilize the joint.

There is a significant difference in the number of correct responses obtained during the Stroop test between young and older adults, such that older adults demonstrated a lower percentage of correct responses. Overall, however, the limited effect of the cognitive task on motor performance in both groups may be explained by the familiarity of the initial postural position. In this study, participants were instructed to stand in a comfortable position, with feet shoulder-width apart. This well-learned

position most likely required limited attention prior to the perturbation, and therefore participants were able allocate more resources to the successful completion of the cognitive task. For example, the difficulty of a postural stance alone (i.e. tandem stance on a see-saw), without any external perturbations, has been shown to be effective in decreasing stability (Dault, Geurts, Mulder, Duysens, 2001). Based on Pashler's capacity sharing theory (1994), it is possible that by allocating more attentional resources to an initial stance position, the cognitive task performance would decline.

### Limitations

One limitation of this study is that the perturbations were set relative to each participant. This makes direct comparison more difficult, as each participant was perturbed at a different intensity. For this study, however, relative perturbations were necessary to ensure balance could be maintained without taking a step. Additionally, the increased EMG activity prior to a perturbation in older adults may increase latency, as with a greater amount of pre-activation, the time it takes for the EMG amplitude to exceed 1.5 times is longer with elevated baseline values. Pre-activation has previously been demonstrated in older adults during functional task performance (Hsu, Wei, Yu, & Chang, 2007). Further, in older adults, any joint replacements as well as visual acuity and proprioceptive deficits were not measured which may influence the participant's ability to respond to support surface translations.

## **5.2 Muscle Power Outcomes**

It was hypothesized that an increase in muscle power would be correlated with an increase in functional outcomes (CB&M score), as well as an improvement in postural performance (i.e. increase in RMS amplitude) only in older adults, as the effect of ankle muscle power would be limited in young adults. In accordance with our hypotheses, older adults demonstrated a positive relationship between ankle muscle power and function and postural performance. Older adults demonstrated a significant correlation between ankle plantarflexor power and CB&M score, similar to previous literature, which has reported the beneficial effects of ankle power on functional outcomes (Reid & Fielding, 2011). While not significant, there was also a positive correlation between dorsiflexor muscle power and CB&M score in older adults. As a previous study has reported a significant correlation between the dorsiflexor power and functional performance (Suzuki et al., 2001), the addition of more participants may be required to achieve statistical significance. A lack of influence of muscle power on postural control in young adults has been reported in previous

studies, in which no correlation between dynamic balance and peak power of the lower limb muscles was found during chair jumping (Zemkova et al., 2017).

There was a significant correlation between ankle plantarflexor power and Gastrocs EMG activity during bilateral accelerations. Power is especially important during bilateral perturbations, as the action of both limbs being perturbed requires a shorter latency of muscle activation (i.e. an increased ability to produce force rapidly). As Gastrocs activity is crucial to the backward acceleration of the COM (Graham et al., 2017), the increase in plantarflexor power allows for a more forceful and rapid onset of muscle activity to return to a position of equilibrium. Plantarflexor power may only be crucial during bilateral perturbations, as during unilateral perturbations the stance limb minimizes the COM displacement (Duclos et al., 2014) and therefore limits the response required by the plantarflexor muscles. The lack of effect plantarflexor power has on Sol activity may be related to the functional roles in the Sol and Gastrocs, as Gastrocs activity has been shown to play a larger role following vestibular balance-corrections as well as in the maintenance of standing balance (Dakin, Heroux, Luu, Inglis, & Blouin, 2016; Giulio, Maganaris, Baltzopoulos, & Loram, 2009).

Further, there was a significant correlation between ankle plantarflexor power and unilateral acceleration intensity. That is, participants with a higher level of muscle power were able to maintain balance in response to larger unilateral perturbations. The correlation between plantarflexor power and unilateral, but not bilateral, perturbations may be explained by the reduction in functional ankle mobility associated with aging (Vandervoort et al., 1992). Bilateral perturbations may require greater movement at the ankle joint, as there is no stance limb to limit the loss of equilibrium. As older adults demonstrate a decrease in ankle range of motion (ROM), bilateral perturbations may be limited by the decreased ability to move through the appropriate range and regain stability (Mecagni, Smith, Robert, O'Sullivan, 2000), and therefore an increase in power alone may not be sufficient to control balance.

As participants experience a forward loss of balance, it is expected that the dorsal muscles would be primarily activated to regain balance (Kanekar & Aruin, 2014). This may explain the lack of effect dorsiflexor power and TA activity had on postural control. Overall, maintaining muscle power during the aging process is critical in the maintenance of not only functional performance, but also postural performance.

## **Chapter 6 – Conclusion**

Postural responses to external platform perturbations differed between young and older adults. Young adults adopted a distal to proximal recruitment strategy, and modulated the postural response between unilateral and bilateral perturbations. In contrast, older adults demonstrated early activation of the quadriceps muscles and responded to unilateral and bilateral perturbations in a similar manner. The addition of a cognitive task had minimal influence on the postural activity in the older adults suggesting that older adults prioritized their balance over their cognitive performance. A higher level of muscle power had a positive association with postural muscle activation and functional performance in older adults, but had minimal effect in young adults. Further research is needed to examine the mechanisms responsible for the lack of modulation of postural responses in older adults when responding to different types of perturbations.



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**APPENDIX I**

Ethics Approval Form

Letter of Information & Consent Form



**Date:** 19 March 2018

**To:** Dr. Jayne Garland

**Project ID:** 110471

**Study Title:** Regional Activation of Plantarflexor Muscles during Standing Balance

**Application Type:** HSREB Initial Application

**Review Type:** Delegated

**Meeting Date / Full Board Reporting Date:** 17/Apr/2018

**Date Approval Issued:** 19/Mar/2018

**REB Approval Expiry Date:** 19/Mar/2019

Dear Dr. Jayne Garland

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above mentioned study as described in the WREM application form, as of the HSREB Initial Approval Date noted above. This research study is to be conducted by the investigator noted above. All other required institutional approvals must also be obtained prior to the conduct of the study.

**Documents Approved:**

Document Name	Document Type	Document Date	Document Version
CB&M	Other Data Collection Instruments	15/Dec/2017	1
Comments about E-mail	Email Script	07/Feb/2018	1
Poster	Recruitment Materials	26/Feb/2018	2
Regional Activation Protocol	Protocol	02/Mar/2018	2
Regional Muscle Activation in Balance Tasks Information Letter and Consent Form	Written Consent/Assent	02/Mar/2018	2
Self Evaluation of Breathing Questionnaire V2	Paper Survey	13/Nov/2017	

**Documents Acknowledged:**

Document Name	Document Type	Document Date	Document Version
References - Ethics	References	26/Feb/2018	2

No deviations from, or changes to, the protocol or WREM application should be initiated without prior written approval of an appropriate amendment from Western HSREB, except when necessary to eliminate immediate hazard(s) to study participants or when the change(s) involves only administrative or logistical aspects of the trial.

REB members involved in the research project do not participate in the review, discussion or decision.

The Western University HSREB operates in compliance with, and is constituted in accordance with, the requirements of the TriCouncil Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2); the International Conference on Harmonisation Good Clinical Practice Consolidated Guideline (ICH GCP); Part C, Division 5 of the Food and Drug Regulations; Part 4 of the Natural Health Products Regulations; Part 3 of the Medical Devices Regulations and the provisions of the Ontario Personal Health Information Protection Act (PHIPA 2004) and its applicable regulations. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Please do not hesitate to contact us if you have any questions.

Sincerely,







Study Title: Regional Activation of Plantarflexor Muscles during Standing Balance

Principal Investigator: Dr. Jayne Garland, PhD, Faculty of Health Sciences, Western University  
 [REDACTED]

Research Team: Tanya Ivanova, PhD, Faculty of Health Sciences [REDACTED], Patrick Siedlecki, MSc, School of Kinesiology [REDACTED], Dominique Arsenault, BSc. (Hons) Kin, School of Physical Therapy [REDACTED], Joshua Cohen, School of Kinesiology  
 [REDACTED]

### Letter of Information

Dear Potential Participant,

You are being invited to participate in the following research project entitled “Regional Activation of Plantarflexor Muscles during Standing Balance”. The study will take place within the Wolf Orthopaedic Biomechanics Laboratory inside Western University’s 3M Building. The study is being conducted by Patrick Siedlecki, a PhD. student in the School of Kinesiology at Western University, Dominique Arsenault, an MSc. student in the School of Physical Therapy, Joshua Cohen, a BSc. undergraduate student in the School of Kinesiology at Western University, and Dr. Jayne Garland, Professor and Dean of the Faculty of Health Sciences at Western University in London, Ontario. The purpose of this study is to evaluate the activity of the calf muscles (ankle plantarflexors) in response to balance disruptions. A total of 20 participants in each age group are being recruited for this study.

#### Study Criteria:

To participate in this study, you must be between the ages of 18-30 years or 70+ years and be able to understand oral and written instructions in English. You will not be able to participate in the study if you have sustained a physical injury (e.g. leg fracture) within the last 6 months or have been diagnosed with a respiratory and/or neurological disorder.

#### Procedures:

You are being asked to attend a single session that will take approximately 60-90 minutes to complete. You will be asked to fill out The Self Evaluation of Breathing Questionnaire regarding any symptoms you may be experiencing.

After completing the questionnaire, you will be asked to complete the Community Balance and Mobility (CB&M) Assessment under the supervision of one of the student researchers. The CB&M requires you to perform various balancing activities (i.e. one legged stance, crouch walk, run, etc.). You will be scored on how well you complete each of the 13 tasks.

After the CB&M, your ankle muscle power (force per unit time) will be evaluated using the BIODEX strength testing system. You will be positioned in a reclined chair with your ankle strapped onto an immovable cushion. You will be asked to plantarflex (point toes down) and dorsiflex (pull toes up)

your ankle three times as hard as you can. The position of your ankle will then be held in neutral and you will be asked to push down with your foot as hard as you can without your ankle moving. You will also be asked to push your foot down slowly until you reach half of your maximal force, hold it for 5 seconds and then slowly relax.

Electrodes will be applied to muscles of the legs and trunk, and a pad of electrodes will be placed over one of your calf muscles to evaluate muscle activity. You will have 26 reflective markers placed on various places around your body and a strap will be placed around your chest to detect your breathing. You will be fitted in a safety harness that is connected to the ceiling above the treadmill. Your resting breathing and heart rate will be measured for 2 minutes while you are standing. Balance disruption tests will take place when the treadmill is not moving (0 km/h), and while walking (3.6 km/h). These balance disruptions involve moving one or both treadmill belts, on which you are standing, in a variety of directions. During some of these balance tests, you will also be completing a cognitive task. The cognitive task is the Stroop Test, in which the name of a colour will appear in a colour that is different than the name. You will have to say the colour the word appears in. The Stroop test will randomly appear on the left, middle or right projector screen.

#### Possible Risks and Harms:

There are minimal known risks for participating in this study. By collecting personal information, there is the risk of a breach of privacy; this is minimized by using initials and age as opposed to full name and date of birth. During the CB&M and treadmill sections, it is possible for you to lose your balance and sustain an injury (sprain or bruise). A fall will be minimized by the presence of a student researcher who will stay beside the participant to act as a spotter. You will also be wearing a safety harness that will prevent you from falling off of the treadmill. The treadmill is also equipped with an emergency stop button which will bring the treadmill to a stop if pressed.

#### Benefits:

You will not receive any direct benefits from participating in this study. The results of this study may provide further information to clinicians and researchers and help in identifying new appropriate treatments for clinical populations in the future.

#### Compensation:

You will not receive any compensation for participating. A parking token will be provided if you need one.

#### Confidentiality:

Participation in this study is voluntary; you have the right to withdraw at any time. If you are a student, withdrawal from the study will have no effect on your academic success. All information that is provided and collected will be kept strictly confidential and you have the right to decline providing any personal information or answering any questions that you do not want to answer. The personal information required includes initials, age and gender. Email address and phone number will also be collected for scheduling purposes. You will be assigned a unique identification number to prevent identification from third parties and only the research team will have access to the recorded data and personal information.

All of the information collected will be securely stored in a locked cabinet in the Wolf Orthopaedic Biomechanics Laboratory at Western University for a period of 7 years. Any data or information that is sent electronically between researchers will also be password protected. The results from this study will be presented in a paper and oral presentation as part of the requirement of completing a

thesis based undergraduate and graduate program. An abstract may also be submitted in the future to a scientific conference for consideration, with the possibility of a presentation. Confidentiality will be observed during the course of the research, in the final report, and in the presentation of the results. If you are interested in obtaining your results, a copy will be provided upon completion of this study.

Western Health Sciences Research Ethics Board (HSREB) may require access to the study records for quality assurance (to check that the information collected in the study is correct and follows proper guidelines).

Contact Information:

If you agree to participate in this study, please complete the attached consent form. If you have any other questions, please feel free to contact Patrick Siedlecki by email at [REDACTED] Dominique Arsenault by email at [REDACTED] or Joshua Cohen by email at [REDACTED]. If you have any questions related to the ethics of the research and would like to speak to someone outside of the research team, please contact The Office of Human Research Ethics at [REDACTED].

Sincerely,

Patrick Siedlecki, MSc

Doctor of Philosophy graduate student, School of Kinesiology,

Western University, London, Ontario

Dominique Arsenault, BSc

Master of Science graduate student, School of Physical Therapy,

Western University, London, Ontario

Joshua Cohen

Bachelor of Science undergraduate student, School of Kinesiology,

Western University, London, Ontario

Dr. Tanya Ivanova, PhD

Research Coordinator

Western University, London, Ontario

Dr. Jayne Garland, PhD

Professor and Dean, Faculty of Health Sciences

Western University, London, Ontario

This letter is yours to keep for future reference.



### Consent Form

Title: Regional Activation of Plantarflexor Muscles during Standing Balance

Principal Investigator: Dr. Jayne Garland, PhD.

Research Team: Patrick Siedlecki, MSc.

Dominique Arsenault, BSc.

Joshua Cohen

Tanya Ivanova, PhD

I, \_\_\_\_\_ have read the Letter of Information, have had the nature of the study explained to me and I agree to participate. All questions have been answered to my satisfaction.

\_\_\_\_\_  
Participant Name (please print)

\_\_\_\_\_  
Print Date

\_\_\_\_\_  
Signature of Participant

\_\_\_\_\_  
Print Date

\_\_\_\_\_  
Researcher Name (please print)

\_\_\_\_\_  
Print Date

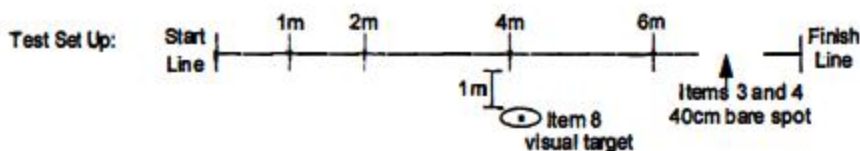
\_\_\_\_\_  
Signature of Researcher

\_\_\_\_\_  
Print Date

To receive a copy of your results after completion of the study, please provide an email address or telephone number below so you can be contacted:

\_\_\_\_\_

**APPENDIX II**  
CB&M Form

Participant  
ID Number Participant  
Initials    
F LDate      
DD MM YYYY**Community Balance & Mobility Scale (Page 1)****1. Unilateral Stance**

**Instructions to patient:** Stand on your right/left leg and hold for as long as you can up to 45 seconds. Look straight ahead.

**Instructions to therapist:** Begin timing as soon as the patient's foot leaves the ground. Do not allow for the patient to brace the elevated leg against the supporting leg. Stop timing if stance foot moves from starting position or opposite foot touches ground.

**Right limb**

- <sub>0</sub> Unable to sustain
- <sub>1</sub> 2 to 4.49 seconds
- <sub>2</sub> 4.5 to 9.99 seconds
- <sub>3</sub> 10 to 20 seconds
- <sub>4</sub>  $\geq 20$  seconds
- <sub>5</sub> 45 seconds, steady and coordinated

**Left limb**

- <sub>0</sub> Unable to sustain
- <sub>1</sub> 2 to 4.49 seconds
- <sub>2</sub> 4.5 to 9.99 seconds
- <sub>3</sub> 10 to 20 seconds
- <sub>4</sub>  $\geq 20$  seconds
- <sub>5</sub> 45 seconds, steady and coordinated

**2. Tandem Walking**

**Instructions to patient:** Walk forward on the line, heel touching toes. Keep your feet pointing straight ahead. Look ahead down the track, not at your feet. I will tell you when to stop.

**Instructions to therapist:** Position the patient with one foot positioned on the 8m track. If able, allow the patient to take a maximum of 7 steps for which the heel is on the line and the heel-toe distance is  $\leq 8$  cm (3 inches).

- <sub>0</sub> Unable to complete 1 step on the line independently, i.e. requires assistance, upper extremity support, or takes a protective step
- <sub>1</sub> Able to complete 1 step independently, acceptable to toe out
- <sub>2</sub> Able to complete 2 to 3 consecutive steps on the line, acceptable to toe out
- <sub>3</sub> Able to complete > 3 consecutive steps, acceptable to toe out
- <sub>4</sub> Able to complete > 3 consecutive steps, in good alignment (heel-toe contact, feet straight on the line, no toeing out), but demonstrates excessive use of equilibrium reactions
- <sub>5</sub> Able to complete 7 consecutive steps, in good alignment (heel-toe contact, feet straight on the line, no toeing out), and in a steady & coordinated manner. Excessive use of equilibrium reactions or looking at feet is not
- } heel-to-toe distance < 3 inches

Participant Initials    
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## Community Balance & Mobility Scale (Page 2)

### 3. 180 degree Tandem Pivot

**Starting position:** Tandem stance on bare spot in track - aligned heel to toe, no toeing out, arms at sides, head in neutral position and eyes forward. Patient allowed to choose either foot in front and may use assistance or upper extremity support to achieve, but not sustain, tandem stance.

**Instructions to patient:** Lifting your heels just a little, pivot all the way around to face the opposite direction without stopping and maintain your balance in this position.

**Instructions to therapist:** When right foot is in front in tandem position, patient to turn towards left. When left foot is in front in tandem position, patient to turn towards right. Therapist may assist patient to assume starting position. Test is over when patient puts heels down or steps out of position.

- <sub>0</sub> Unable to sustain tandem stance independently i.e. requires assistance or upper extremity support
- <sub>1</sub> Sustains tandem stance but unable to unweight heels and/or initiate pivot
- <sub>2</sub> Initiates pivot but unable to complete 180 degree turn
- <sub>3</sub> Completes 180 degree turn but discontinues pivot (e.g. pauses on toes)
- <sub>4</sub> Completes 180 degree turn in a continuous motion but unable sustain reversed position (**Not acceptable:** heel -toe distance > 8 cm (3 inches))

Completes 180 degree turn in a continuous motion and sustains reversed position (acceptable to have feet slightly angled out in reversed position). **Not acceptable:** heel-toe distance > 8cm (3 inches); excessive use of equilibrium reactions.

### 4. Lateral Foot Scooting

**Starting position:** Patient to stand on the line beside the bare spot in the track in unilateral stance on right/left foot, arms at sides. Foot is perpendicular to the track.

**Instructions to patient:** Stand on your right/left leg and move sideways by alternately pivoting on your heel and toe. Keep pivoting straight across until you touch the line and maintain your balance in this position.

**Instructions to therapist:** The patient moves laterally along the length of the bare spot (40 cm). For the grading, one lateral pivot is defined as either pivoting on heel, moving toes laterally OR pivoting on toes, moving heel laterally.

#### Right limb

- <sub>0</sub> Unable to sustain unilateral stance independently
- <sub>1</sub> Able to perform 1 lateral pivot in any fashion
- <sub>2</sub> Able to perform 2 lateral pivots in any fashion
- <sub>3</sub> Able to perform  $\geq 3$  pivots but < 40 cm
- <sub>4</sub> Able to complete 40 cm in any fashion acceptable to be unable to control final position

Able to complete 40 cm continuous, rhythmical motion demonstrating a controlled stop briefly maintaining unilateral stance. **Not acceptable** to pause while pivoting to regain balance, veer from a straight line, excessive use of equilibrium reactions, or excessive trunk rotation while pivoting

#### Left limb

- <sub>0</sub> Unable to sustain unilateral stance independently
- <sub>1</sub> Able to perform 1 lateral pivot in any fashion
- <sub>2</sub> Able to perform 2 lateral pivots in any fashion
- <sub>3</sub> Able to perform  $\geq 3$  pivots but < 40 cm
- <sub>4</sub> Able to complete 40 cm in any fashion acceptable to be unable to control final position

Able to complete 40 cm continuous, rhythmical motion demonstrating a controlled stop briefly maintaining unilateral stance. **Not acceptable** to pause while pivoting to regain balance, veer from a straight line, excessive use of equilibrium reactions, or excessive trunk rotation while pivoting



Participant Initials    
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### Community Balance & Mobility Scale (Page 3)

#### 5. Hopping Forward

**Starting position:** Unilateral stance on right/left with entire foot on the track. Heel placed on inside edge of starting line.

**Instructions to patient:** Stand on your right/left foot. Hop twice straight along this line to pass the 1 m mark with your heel. Maintain your balance on your right/left leg at the finish.

**Instructions to therapist:** It is recommended that the therapist assess safety prior to commencing task by having the patient hop in one spot. Patient is successful in completing 1 m when the heel of the foot is touching or beyond the 1 m line.

##### Right limb

- <sub>0</sub> Unable
- <sub>1</sub> 1 to 2 hops, uncontrolled
- <sub>2</sub> 2 hops, controlled but unable to complete 1 meter
- <sub>3</sub> 1 meter in 2 hops but unable to sustain landing
- <sub>4</sub> 1 meter in 2 hops but difficulty controlling landing (hops or pivots)
- <sub>5</sub> 1 meter in 2 hops, coordinated with stable landing

##### Left limb

- <sub>0</sub> Unable
- <sub>1</sub> 1 to 2 hops, uncontrolled
- <sub>2</sub> 2 hops, controlled but unable to complete 1 meter
- <sub>3</sub> 1 meter in 2 hops but unable to sustain landing
- <sub>4</sub> 1 meter in 2 hops but difficulty controlling landing (hops or pivots)
- <sub>5</sub> 1 meter in 2 hops, coordinated with stable landing

#### 6. Crouch and Walk

**Starting position:** Bean bag is placed to right or left side of 2m mark on the track according to which hand the patient will use to pick it up.

**Instructions to patient:** Walk forward and, without stopping, bend to pick up the bean bag and then continue walking down the line.

**Instructions to therapist:** This task is performed using only half of the track. Start timing when the patient's foot leaves the ground. Stop timing when both feet cross the 4m line.

- <sub>0</sub> Unable to crouch (descend) to pick up bean bag independently
- <sub>1</sub> Able to descend but unable to maintain crouch to pick up bean bag or rise to stand independently
- <sub>2</sub> Descends and rises but hesitates, unable to maintain forward momentum
- <sub>3</sub> Crouches and walks in continuous motion, time  $\leq 8$  seconds and demonstrates protective step at any time
- <sub>4</sub> Crouches and walks in continuous motion, time  $\leq 8$  seconds and/or uses excessive equilibrium reaction to maintain balance. **Not acceptable** to veer off course
- <sub>5</sub> Crouches and walks in continuous and rhythmical motion, time  $\leq 4$  seconds. **Not acceptable** to veer off course or to use excessive equilibrium reactions.



Participant Initials    
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## Community Balance & Mobility Scale (Page 4)

### 7. Lateral Dodging

**Starting position:** Starting at the 2m mark with feet perpendicular to the track. The toes of both feet should cover the track.

**Instructions to patient:** Move sideways along the line by repeatedly crossing one foot in front of and over the other. Place part of your foot on the line with every step. Reverse direction whenever I call "Change". Do this as fast as you can, yet at a speed that you feel safe.

**Instructions to therapist:** Patient moves laterally back and forth along the line, between the 2 m and 4 m marks by repeatedly crossing one foot over and in front of the other. It is acceptable for the patient to look at the line to monitor foot placement. Begin timing as soon as the patient's foot leaves the ground. To cue the patient to change direction, call out "change!" when one foot passes the 2 and 4 m marks. The patient should believe direction changes are random. One cross-over = crossing one leg over to land beside the other and returning the back leg to an uncrossed position. One cycle = the patient completes cross-overs for a 2 m distance and return. The test requires that the patient perform 2 of these cycles (a total of 8 m).

- <sub>0</sub> Unable to perform 1 cross-over in both directions without loss of balance or use of support
- <sub>1</sub> 1 cross-over in both directions without use of support, but unable to contact the line with part of the foot
- <sub>2</sub> 1 or more cycles to and from the 2m mark, but unable to contact line with every step
- <sub>3</sub> 2 cycles in any fashion (to the 2m line and back twice) and one part of the foot contacts line during every step
- <sub>4</sub> 2 cycles in any fashion as described in the response above (3) in 12 to 15 seconds
- <sub>5</sub> 2 cycles in <12 seconds in a continuous, rhythmical fashion with coordinated direction changes immediately after verbal cue

### 8. Walking & Looking

**Instructions to patient:** Walk at your usual pace to the end of the line. I will tell you when to look at the circle. Keep looking at the circle while you walk past it. I will then tell you when to look straight ahead again. Try not to veer off course while you walk.

**Instructions to therapist:** Start timing when the patient's foot leaves the ground. Stop timing when both feet cross the 8m finish line. At the 2m mark, ask the patient to "Look at the circle". Cue the patient to "Keep looking at the circle" as they look back over their shoulder until they reach the 6m mark. At the 6m mark, ask the patient to "Look straight ahead and continue walking until the end of the line". Stand beside the target so that you can assess the patient's ability to maintain fixation. It may be necessary to have another person present to walk along side the patient to ensure safety. It is acceptable to continue to remind the patient of where they should be looking at each segment. To score in the opposite direction, repeat the task starting from the opposite end of the line.

#### Target to the right

- <sub>0</sub> Unable to walk and look e.g. stops
- <sub>1</sub> Performs but loses visual fixation at or before 4 m mark
- <sub>2</sub> Performs but loses visual fixation after 4 m mark
- <sub>3</sub> Performs and maintains visual fixation between 2 to 6 m mark but protective step
- <sub>4</sub> Performs and maintains visual fixation between 2 to 6 m mark but veers
- <sub>5</sub> Performs, straight path, steady and coordinated  $\leq 7$  seconds

#### Target to the left

- <sub>0</sub> Unable to walk and look e.g. stops
- <sub>1</sub> Performs but loses visual fixation at or before 4 m mark
- <sub>2</sub> Performs but loses visual fixation after 4 m mark
- <sub>3</sub> Performs and maintains visual fixation between 2 to 6 m mark but protective step
- <sub>4</sub> Performs and maintains visual fixation between 2 to 6 m mark but veers
- <sub>5</sub> Performs, straight path, steady and coordinated  $\leq 7$  seconds

Participant Initials 

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## Community Balance & Mobility Scale (Page 5)

### 9. Running with Controlled Stop

**Instructions to patient:** Run as fast as you can to the end of the track. Stop abruptly with both feet on the finish line and hold this position.

**Instructions to therapist:** Begin timing when initial foot leaves ground. Stop timing when both feet reach the finish line. It does not matter whether the feet land consecutively or simultaneously on the finish line.

- <sub>0</sub> Unable to run (with both feet off ground for a brief instant), demonstrates fast walking or leaping from foot to foot
- <sub>1</sub> Runs in any fashion, time > 5 seconds
- <sub>2</sub> Runs in any fashion, time > 3 seconds, but  $\leq$  5 seconds, unable to control stop (uses protective step or excessive equilibrium reactions)
- <sub>3</sub> Runs, time > 3 seconds, but  $\leq$  5 seconds, with controlled stop, both feet on line. **Not acceptable** to use excessive equilibrium reactions
- <sub>4</sub> Runs in any fashion, time  $\leq$  3 seconds, unable to control stop with both feet on the line (uses protective step(s) or excessive equilibrium reactions)
- <sub>5</sub> Runs in a coordinated, rhythmical manner and performs a controlled stop with both feet on the line,  $\leq$  3 seconds **Not acceptable** to use excessive equilibrium reactions.

### 10. Forward to Backward Walking

**Instructions to patient:** Walk forward to the halfway mark, turn around and continue to walk backward until I say, "Stop". Try not to veer off course. Walk as quickly as you can, yet at a speed that you feel safe.

**Instructions to therapist:** Start timing when the patient's foot leaves the ground. Stop timing when both feet cross the 8m finish line. The patient is to turn at the 4m mark. It is acceptable for the patient to turn in any direction. Count the number of steps required to turn 180 degrees. **Note:** The first step in the turn is angled away from the forward trajectory. The last step in the turn completes the 180 degree turn and is oriented towards the starting line, initiating backwards walking. It is also acceptable to pivot on one foot rather than stepping around.

- <sub>0</sub> Unable to complete task (requires assistance or upper extremity support)
- <sub>1</sub> Performs but must stop to regain balance at any time during the task
- <sub>2</sub> Performs with reduced speed, time > 11 seconds and/or requires 4 or more steps to turn
- <sub>3</sub> Performs in  $\leq$  11 seconds and/or veers from straight path during backwards walking
- <sub>4</sub> Able to complete task in a continuous motion,  $\leq$  9 seconds and/or uses protective step(s) during or just after turn
- <sub>5</sub> Able to complete task in a continuous motion with brisk speed,  $\leq$  7 seconds, maintains straight path throughout

Participant Initials 

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## Community Balance & Mobility Scale (Page 6)

### 11. Walk, Look & Carry

**Starting Position:** Start patient at the end of the track carrying a plastic grocery bag in each hand by the handle, with a 7.5 pound (3.4 kg) weight inside each bag.

**Instructions to patient:** Walk at your usual pace to the end of the line carrying the grocery bags. I will tell you when to look at the circle. Keep looking at it while you walk past it. I will then tell you when to look straight ahead again. Try not to veer off course while you walk.

**Instructions to therapist:** Start timing when the patient's foot leaves the ground. Stop timing when both feet cross the 8m finish line. At the 2m mark, ask the patient to "Look at the circle". Cue the patient to "Keep looking at the circle" as they look back over their shoulder until they reach the 6m mark. At the 6m mark, ask the patient to "Look straight ahead and continue walking until the end of the line". Stand beside the target so that you can assess the patient's ability to maintain fixation. It may be necessary to have another person present to walk along side the patient to ensure safety. It is acceptable to continue to remind the patient of where they should be looking at each segment. To score in the opposite direction, repeat the task starting from the opposite end of the line.

**Note:** Patient to only carry one grocery bag if unable to perform bilaterally due to motor control problems of the upper extremity. Indicate that the patient was only able to carry one bag.

#### Target to the right

- 0 Unable to walk and look e.g. has to stop to look, or requires assistance or upper extremity support at any point during the test
- 1 Able to continuously walk and initiate looking, but loses visual fixation on circle at or before 4m mark
- 2 Able to continuously walk and look, but loses visual fixation on circle after 4 m mark i.e. while looking back over the shoulder
- 3 Able to continuously walk and fixate upon the circle between the 2m and 6m mark, but demonstrates a protective step. Acceptable for patient to demonstrate inconsistent or reduced speed.
- 4 Able to continuously walk and fixate upon the circle between the 2m and 6m mark but veers off course. Acceptable for patient to demonstrate inconsistent or reduced speed.
- 5 Able to continuously walk and fixate upon circle between 2m and 6m mark, maintains a straight path, in a steady & coordinated manner,  $\leq 7$  seconds Not acceptable to walk at an inconsistent or reduced speed or to be looking down at feet.

#### Target to the left

- 0 Unable to walk and look e.g. has to stop to look, or requires assistance or upper extremity support at any point during the test
- 1 Able to continuously walk and initiate looking, but loses visual fixation on circle at or before 4m mark
- 2 Able to continuously walk and look, but loses visual fixation on circle after 4 m mark i.e. while looking back over the shoulder
- 3 Able to continuously walk and fixate upon the circle between the 2m and 6m mark, but demonstrates a protective step. Acceptable for patient to demonstrate inconsistent or reduced speed.
- 4 Able to continuously walk and fixate upon the circle between the 2m and 6m mark but veers off course. Acceptable for patient to demonstrate inconsistent or reduced speed.
- 5 Able to continuously walk and fixate upon circle between 2m and 6m mark, maintains a straight path, in a steady & coordinated manner,  $\leq 7$  seconds Not acceptable to walk at an inconsistent or reduced speed or to be looking down at feet.

Participant Initials 

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## Community Balance & Mobility Scale (Page 7)

### 12. Descending Stairs

**Starting Position:** Quiet standing at top of staircase (minimum 8 steps). Depending on patient's skill on the stairs, may begin by descending from the first or third step at the bottom of the flight.

**Instructions to patients:** Walk down the stairs. Try not to use the railing.

**Instructions to therapist:** Depending on patient's skill on the stairs, may use a cane as in level 1 or level 2.

**\*Bonus:** If the patient achieves a score of 4 or 5, and if deemed safe by the rating therapist, the patient is asked to repeat the task and descend stairs while carrying a weighted basket (laundry basket with 2 pound weight in it). It is acceptable for the patient to intermittently look at the steps.

Add one bonus point to the score of 4 or 5 if the patient can descend the stairs safely while carrying the basket without the need for continuous monitoring of their foot placement. If the patient is unable to hold the basket with one or both arms, they are not eligible for the bonus point.

**Instructions to patient:** Hold this basket, keeping it in front of you at waist level. Walk down the stairs and try not to look at your feet. You may look at the steps once in a while for safety.

- <sub>0</sub> Unable to step down 1 step, or requires railing or assistance
- <sub>1</sub> Able to step down 1 step with/without cane
- <sub>2</sub> Able to step down 3 steps with/without cane, any pattern
- <sub>3</sub> 3 steps reciprocal or full flight in step-to pattern no railing
- <sub>4</sub> Full flight reciprocal, awkward, uncoordinated\* no cane
- <sub>5</sub> Full flight reciprocal, rhythmical and coordinated\*
- <sub>+1</sub> \*BONUS for carrying basket

Participant Initials 

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### Community Balance & Mobility Scale (Page 8)

#### 13. Step Ups X 1 Step

**Starting Position:** In front of step at bottom of stairs

**Instructions to patient:** i) Step up and down on this step as quickly as you can until I say "Stop". The pattern is right-left up and right-left down. Try not to look at your feet. ii) Step up and down on this step as quickly as you can until I say "Stop". The pattern is left-right up and left-right down. Try not to look at your feet.

**Instructions to therapist:** Start timing when the patient's foot leaves the ground. Stop timing after the completion of 5 cycles. A cycle is one complete step up and one complete step down.

##### Right

- <sub>0</sub> Unable to step up, requires assistance or railing
- <sub>1</sub> Steps up, requires assistance or railing to descend
- <sub>2</sub> Steps up and down (1 cycle)
- <sub>3</sub> Completes 5 cycles, acceptable to demonstrate incoordination or inconsistent speed/rhythm
- <sub>4</sub> Completes 5 cycles in > 6 seconds but < 10 seconds, acceptable to demonstrate incoordination or inconsistent speed/rhythm
- <sub>5</sub> Completes 5 cycles in ≤ 6 seconds, rhythmical and coordinated manner
- | unacceptable to look at feet

##### Left

- <sub>0</sub> Unable to step up, requires assistance or railing
- <sub>1</sub> Steps up, requires assistance or railing to descend
- <sub>2</sub> Steps up and down (1 cycle)
- <sub>3</sub> Completes 5 cycles
- <sub>4</sub> Completes 5 cycles in > 6 seconds but < 10 seconds
- <sub>5</sub> Completes 5 cycles in ≤ 6 seconds, rhythmical
- | unacceptable to look at feet

**APPENDIX III**

Post-hoc comparison results tables

Table 6. EMG Latency, denoted by mean (SD), of combined cognitive load types describing the interaction between perturbation type and age.

Muscle	Perturbation type	Age group	Latency (ms)
Quads	Unilateral acceleration	Young	128.3 (38.0) <sup>a,c</sup>
		Older	78.6 (19.7)
	Bilateral acceleration	Young	99.5 (25.5) <sup>b</sup>
		Older	76.6 (22.4)
Gastrocs	Unilateral acceleration	Young	85.8 (16.8) <sup>c</sup>
		Older	83.0 (11.9)
	Bilateral acceleration	Young	64.9(8.1) <sup>b</sup>
		Older	79.0 (9.6)
Sol	Unilateral acceleration	Young	71.7 (11.0) <sup>c</sup>
		Older	71.6 (8.8)
	Bilateral acceleration	Young	58.8 (8.5) <sup>b</sup>
		Older	70.1 (8.1)
TA	Unilateral acceleration	Young	84.8 (12.0) <sup>c</sup>
		Older	89.0 (19.5)
	Bilateral acceleration	Young	72.5 (15.9) <sup>b</sup>
		Older	88.6 (22.7)

<sup>a</sup> denotes a significant difference from older adults during unilateral accelerations; <sup>b</sup> denotes a significant difference from older adults during bilateral accelerations; <sup>c</sup> denotes a significant difference between unilateral and bilateral accelerations in young adults



Table 7. EMG Latency in Quads, denoted by mean (SD), of combined perturbation types describing the interaction between cognitive load type and age.

Muscle	Cognitive load type	Age group	Latency (ms)
Quads	No Stroop	Young	105.0 (27.2) <sup>a,c</sup>
		Older	78.3 (22.0)
	Stroop	Young	122.9 (40.1) <sup>b</sup>
		Older	76.8 (20.2)

<sup>a</sup> denotes a significant difference from older adults during No Stroop; <sup>b</sup> denotes a significant difference from older adults during Stroop; <sup>c</sup> denotes a significant difference between No Stroop and Stroop in young adults

Table 8. EMG Amplitude, denoted by mean (SD), of combined cognitive load types describing the interaction between perturbation type and age.

Muscle	Perturbation type	Age group	RMS (a.u)
Quads	Unilateral acceleration	Young	2.79 (0.84) <sup>a,c</sup>
		Older	1.47 (0.54) <sup>c</sup>
	Bilateral acceleration	Young	3.67 (1.17) <sup>b</sup>
		Older	1.67 (0.74)
Gastrocs	Unilateral acceleration	Young	4.68 (1.83) <sup>a,c</sup>
		Older	2.70 (1.15) <sup>c</sup>
	Bilateral acceleration	Young	7.45 (2.58) <sup>b</sup>
		Older	4.06 (2.06)
Sol	Unilateral acceleration	Young	2.21 (0.87) <sup>a,c</sup>
		Older	1.46 (0.44) <sup>c</sup>
	Bilateral acceleration	Young	4.27 (1.63) <sup>b</sup>
		Older	1.81 (0.44)

<sup>a</sup> denotes a significant difference from older adults during unilateral accelerations; <sup>b</sup> denotes a significant difference from older adults during bilateral accelerations; <sup>c</sup> denotes a significant difference between unilateral and bilateral accelerations in young adults; <sup>d</sup> denotes a significant difference between unilateral and bilateral accelerations in older adults



Table 9. EMG Amplitude, denoted by mean (SD), of combined perturbation types describing the interaction between cognitive load type and age.

Muscle	Cognitive load type	Age group	RMS (a.u)
Quads	No Stroop	Young	2.96 (0.95) <sup>a,c</sup>
		Older	1.61 (0.76)
	Stroop	Young	3.50 (1.19) <sup>b</sup>
		Older	1.52 (0.52)
TA	No Stroop	Young	6.15 (2.41) <sup>a,c</sup>
		Older	4.01 (3.19)
	Stroop	Young	7.16 (3.01) <sup>b</sup>
		Older	3.83 (3.19)

. <sup>a</sup> denotes a significant difference from older adults during No Stroop; <sup>b</sup> denotes a significant difference from older adults during Stroop; <sup>c</sup> denotes a significant difference between No Stroop and Stroop in young adults

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