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Mechanisms of Slowed Foot Tap Speed in Older Adults

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A Thesis Presented

by

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ABSTRACT

MECHANISMS OF SLOWED FOOT TAP SPEED IN OLDER ADULTS

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Rapid repetitive tapping, like the Foot Tap Test (FTT), slows with age, but the underlying mechanisms are unknown. **Purpose:** 1. Test the hypotheses that greater performance variability, increased muscle coactivation, and slowed muscle contractile speeds are related to lower foot tap count (FTC) in older adults; 2. Examine the relationship between FTC and physical function in older adults, using the advanced Short Physical Performance Battery (SPPB-A), usual and 400m brisk walking speed. **Methods:** 18 young (25.0±3.1years, 9F, mean±SD), and 28 older (73.4±4.9, 14F) healthy adults were recruited. The older adults were divided into Higher (HFO) and Lower (LFO) Functioning based on the median SPPB-A score. Participants performed 10s of rapid tapping (FTT) while seated with their foot on a force plate. A MATLAB program was used to calculate FTC and variability of the intertap-interval (COV-ITI). Contractile speed (rates of force development and relaxation, RFD and RFR) of the dorsiflexor muscles of the slower leg were determined using voluntary, rapid submaximal (ballistic) contractions. Electromyography (EMG) was recorded on the tibialis anterior (TA), soleus (Sol), medial and lateral gastrocnemius during the FTT on the slower foot. Coactivation was calculated using correlation analyses to determine agreement of TA and Sol activation during the FTT. **Results:** The LFO had a lower FTC than Young and HFO (45.9±7.0taps, 54.4±7.5, 53.1±5.7, respectively; p=0.003), and lower COV-ITI than

Young (12.3±5.9%, 20.5±8.1, respectively, p=0.009). No associations were found in the older adults between COV-ITI and FTC. The correlation-coefficient of the EMG signals was higher in Young than HFO (0.568±0.209, 0.321±0.129) and was negatively related to FTC in older adults (r^2=0.274, p=0.005). The LFO had a slower RFD than Young during ballistic contractions and FTC was positively related to maximal RFD (r^2=0.345, p=0.001) and RFR (r^2=0.162, p=0.038) during ballistic contractions in older adults. The FTC of the faster foot was related to SPPB-A (r^2=0.329, p=0.001), but not 400m or usual walking speed in older adults. **Conclusions:** Greater muscle coactivation during the FTT and slower force development in the dorsiflexor muscles may negatively affect FTC in older adults. In older adults, FTC is related to a composite measure of function.

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LIST OF ABBREVIATIONS

Act-R	Activation ratio
CAR	Central Activation Ratio
COV-ITI	Coefficient of Variation of the Intertap interval
DF	Dorsiflexion
EMG	Electromyography
FTC	Foot Tap count
FTT	Foot Tap Test
HFO	Higher Functioning Older
ITI	Intertap interval
LFO	Lower Functioning Older
LG	Lateral Gastrocnemius
MG	Medial Gastrocnemius
MVIC	Maximal Voluntary Isometric Contraction
PF	Plantar Flexion
RFD	Rate of Force Development
RFR	Rate of Force Relaxation
Sol	Soleus
SPPB-A	Short Physical Performance Battery – Advance
TA	Tibialis Anterior

CHAPTER 1

INTRODUCTION

During the 7th decade of life, there is usually a decline in physical function associated with aging. The decrease in physical function is due in part to a number of changes that occur within the neuromuscular system. In particular, older adults may have: reduced motor unit (MU) number and increased MU size, decreased muscle mass, decreased rate of force production and relaxation, decreased ability to fully activate their muscles, and increased muscle coactivation. Individuals with mobility impairments, such as those with multiple sclerosis (MS) and amyotrophic lateral sclerosis (ALS), have even greater neuromuscular changes than their healthy counterparts. Several tests have been validated for identifying individuals with declining physical function, including the 400m walk and the Short Physical Performance Battery (SPPB) (15, 80). While these tests are informative and commonly used, the Foot Tap Test (FTT), a 10-second test in which the participant is asked to tap their foot as quickly as possible, is a novel measure that is quicker and easier to administer than these other measures of function. The FTT is able to track changes in central motor control, or the ability to activate and coordinate muscle contractions, and upper motorneuron dysfunction in aging and diseased populations, along with having the potential to longitudinally track changes in functional ability (28). The FTT requires an individual to rapidly activate and deactivate their dorsiflexor muscles. It has been shown that slowed foot tap speed is a predictor for a decline in gait speed, particularly in populations with upper motor neuron diseases, such as ALS (27). Foot tap speed has also been shown to predict a decline in function with age, with older adults having a slower foot tap speed than younger adults, even when both populations

have comparable normalized muscle strength and rate of force development in the tibialis anterior (TA), and ability to activate their TA (29). It is postulated that slower foot tap speed indicates a decline in central function and that it can be used to identify the decline in central function earlier than other tests such as the central activation ratio (26, 28). The cause of the slower foot tap speed in older adults and those with mobility impairments is still unknown. The slowing of rapid movements in older adults could be due to a number or neuromuscular changes, such as a slowed rate of force development and relaxation, a higher prevalence of slow twitch muscle fibers, and a greater amount of muscle coactivation. While the first two likely contribute to the slowing of movement with age, they are due to changes in the muscle while greater muscle coactivation is due to changes in motor control, or the activation and coordination of muscle contractions. Since FTS has been shown to be slower in individuals with diseases affecting the central nervous system (CNS), it is possible that coactivation will play a larger role in the slowing of rapid repetitive movements than peripheral changes due to aging. Coactivation has been defined in two ways: 1) the quantity of antagonist muscle activation relative to the quantity of agonist muscle activation:

$$\mathrm{CoAct_M}\,(\%) = \frac{\%\ antagonist\ activation}{\%agonist\ activation} \qquad \text{Equation 1}$$

or, 2) the proportion of time that the antagonist is active during agonist activity ($\mathrm{CoAct_T}$, % of ms). An increase in coactivation with age is believed to be caused by poor motor control; for example, coactivations patterns during gait are not the same for affected vs. unaffected limbs in individuals who have had a stroke (35). Coactivation has been shown to be highest when performing small, rapid movements (48). However, coactivation is also an adaptation that could help increase stability around the joints (21). Joint stability

is important in older adults for a number of reasons, particularly fall prevention. Thus, an increase in coactivation in the leg muscles could slow the ability to perform rapid movements but improve joint stability in older adults, resulting in less falls. *The Specific Aims of this study are:*

Aim 1: Determine whether coactivation of antagonist muscles is a potential cause of the slowed foot tap speed in older adults

Hypothesis (H) 1.1. Foot tap speed will be faster in young adults than healthy older adults, and healthy older adults will have a faster foot tap speed than mobility-impaired older adults.

H 1.2. $CoAct_M$ will be longest in mobility impaired older adults, then healthy older adults, with young adults having the lowest $CoAct_M$.

H 1.3. $CoAct_T$ will be highest in mobility-impaired older adults, then healthy older adults, with young adults having the shortest amount of $CoAct_T$.

H 1.4. $CoAct_M$ will be indirectly related to foot tap speed in all older adults.

Aim 2: Explore the potential effect of coactivation on physical function in older adults.

H 2.1. $CoAct_M$ will be higher during gait in older adults than in young, and will be higher in mobility-impaired adults than healthy older adults.

H 2.2. $CoAct_M$ will be indirectly associated with gait speed in older adults.

Exploratory analyses of the associations between $CoAct_M$ and both gait speed variability during the 400m walk and Fall Efficacy Score-International score will also be performed.

Aim 3 (*exploratory*): To analyze the underlying movement patterns during 10-s FTTs in young, healthy older and impaired older adults and explore how movement patterns change during a task where the participant must match a specific speed.

3.1 Evaluate, for each group, dynamic variables such as Intertap-Interval (ITI), ground reaction force (GRF) and toe excursion for the 10-s FTT. Evaluate how these dynamic variables change throughout the 90-s FTT in each group.

3.2 Evaluate these variables under conditions of constrained (slow, moderate, fast) Foot Tap Speed (FTS). Slow will be established as 30% of max FTS from the 10-s FTT, moderate as 60% of max FTS, and fast as 100% of max FTS.

Significance: This study will further develop and validate the FTT, and will be the first to determine whether coactivation contributes to the decline in the ability to perform rapid movements with age. By examining the relationship between FTS and coactivation, along with other peripheral and central neuromuscular properties, the cause of slowed FTS in older adults may be identified. To begin to translate these findings to "real world" conditions, the relationship between coactivation during gait and concerns about falling will be explored in healthy and impaired older adults.

CHAPTER 2

LITERATURE REVIEW

Introduction

The number of individuals living past the age of 65 years has increased almost 20% in the past decade, along with an increase in life expectancy (77). A large percent of these older adults have functional limitations; particularly, 17% of 65-74 year olds and 28% of 75-84 year olds have difficulty walking (77). As individuals age, many physiological and behavioral changes occur that impact functional ability. Beyond the 7th decade of life, there are noticeable changes in gait, strength, concerns about falling, metabolic cost of activity, and physical activity (PA), among others, all of which can impact an older adult's functional ability, particularly their mobility (5, 16, 39, 68, 72). Maintenance of mobility is important for a good quality of life, as it allows for continued freedom and enables an individual to perform activities of daily living, such as dressing and grocery shopping, without assistance (65). It is therefore imperative that individuals with declining function be identified early so appropriate interventions can be implemented to slow the detrimental effects of aging. For our purpose, aging will be defined as the changes in cognitive and physical function that occur as we get older.

The SPPB and 400m walk time are commonly used tests which identify individuals with mobility impairments (15, 80). However, they are more difficult to perform in small spaces and have not been used to identify individuals with CNS dysfunction. The FTT is another informative test that is potentially an early predictor of a decline in function, such as gait speed, and can be used to identify changes within the CNS (28, 59). The FTT requires rapid activation and deactivation of the dorsiflexor

muscles, a task that becomes more difficult with age due to the slowing of rapid movements, which could be due to changes within the neuromuscular system that occur with aging. In particular, an increase in coactivation with aging may impact older adults' ability to rapidly activate and deactivate their muscles, including the muscles around the ankle joint. Maintenance of function in the dorsiflexor muscles is of particular importance in older adults due to the role of dorsiflexion in toe clearance during gait (55). Not only is the FTT an easy and informative marker of changes in the CNS with age, and it could potentially provide information about muscle recruitment patterns during a task requiring rapid repetitive activation and how these recruitment patterns are impacted by age, functional limitations, and movement speed.

This literature review will focus on the FTT, a potential test for predicting a decline in function with age and disease. It will also address the changes that occur in the neuromuscular system with aging, particularly the increase in coactivation. The relationship between coactivation and concerns about falling in older adults will also be addressed.

Neuromuscular changes with age

With aging, many neuromuscular changes occur that impact an individual's functional ability. These changes may include a: 1) decrease in motor unit (MU) number accompanied by an increase in MU size, 2) decrease in muscle mass, 3) increase in percentage of slow twitch muscle fibers, 4) decrease in ability to fully activate the muscle, 5) increase in muscle coactivation, and 6) decrease in rate of force production and relaxation. These neuromuscular changes are linked to a slowing in movement speed

(28, 72), a higher metabolic cost of activity (20), and lower power and strength (12) in older adults, all of which could impact older adults' ability to function independently. It is important to note that the decline in PA that usually occurs with age may also play a role in many of these changes; this problem will be discussed later.

The neuromuscular changes that occur with aging are due to changes both within the nervous system and the muscle itself. One of the main causes of the neuromuscular changes with aging is motor neuron death, which impacts the arrangement of MUs in the muscle (43). A MU is composed of a motor neuron and the muscle fibers it innervates. After the death of a motor neuron, some of its muscle fibers are reinnervated by another motor neuron, resulting in increased size of the remaining MU (43, 44). A larger MU means that an individual motor neuron is responsible for the innervation of more muscle fibers. Older adults recruit larger MUs when performing tasks, which could impact their ability to modulate their movements, resulting in increased difficulty of fine motor tasks (44).

There is also a loss in the number of muscle fibers with aging, suggesting that complete reinnervation by motor neurons does not occur (42). Both Type I and Type II muscle fibers are affected by motor neuron death, with a greater prevalence of loss of Type II fibers, thereby increasing the percentage of slow twitch fibers in older adults (39, 41). The reduction in the size and number of muscle fibers results in a loss of muscle mass, or sarcopenia, and a loss in strength, but not necessarily a loss in specific strength, which is strength relative to muscle mass (29).

Changes in the CNS with age can result in poor regulation and incomplete muscle activation. An impairment of voluntary muscle activation means that an individual is not

able to fully activate all MUs and potentially has a reduction in maximal discharge rate of the motorneuron when performing a maximal voluntary contraction (MVC; (26). The central activation ratio (CAR), or ratio of force produced during an isometric contraction relative to a stimulated contraction (isometric MVC/(MVC+superimposed tetanic stimulation)), is a measure that can indicate if there is an impairment in an individual's ability to fully activate the muscle (CAR<1; (26, 29). A lower CAR score is seen in individuals who have an impairment of the CNS, and thus, decreased motor control (26), but is rarely seen in healthy older adults (29, 79). A decline in motor control can also results in greater coactivation during movement (20, 21, 33, 53, 66), which will be discussed in detail later. Motor unit discharge rate has been shown to decrease with age; for instance, older adults have been shown to have a lower MU discharge rate than younger adults during maximal and submaximal (50% of MVC) isometric contractions, with a greater difference at higher forces (24, 61).

The maximal rate of force development and half relaxation time ($T_{1/2}$) are usually slower in older muscles than younger ones (6, 31, 49). A reduced rate of force development during a submaximal voluntary contraction relative to a stimulated contraction can be indicative of changes in upper motor neuron function, and has been shown to be correlated with slower foot tapping (26). Both of these muscle properties can be determined by stimulating the nerve of interest, which removes the voluntary component of the contraction (26). Together, the rate of force development and $T_{1/2}$ contribute to contraction duration (time to peak tension + ½ relaxation time), which tends to be longer in older adults for the tibialis anterior (TA) and plantar flexor muscles, which could impact older adults' ability to perform rapid contractions (57, 79). However, aging

has less of an impact on contraction duration in the thigh muscles, highlighting the fact that muscles are impacted by aging differently (31, 78).

Muscle groups do not change equally with age, partially because some muscles are essential for performing activities of daily living, such as walking, while others are used less frequently. For the purpose of this paper, the focus will be on the ankle dorsiflexor muscles, specifically the TA. It has been shown that there are significantly fewer MU in the TA in old (mean age 66 yrs) and very old (mean age 82 yrs) men than in young (mean age 27) men. Additionally, older men had fewer MUs than very old men, indicating an aging effect on MU number in the TA (49).

Studies have shown that there is a decrease in muscle mass with age in the dorsiflexors (29, 79), along with a decrease in strength (6, 49, 79), though not necessarily specific strength (29, 79). Age also does not have an impact on voluntary activation of the dorsiflexors, meaning older adults can fully activate their TA and they do not have a reduced CAR (6, 29, 32). In the TA, it is unclear whether the rate of force development changes with age, with some studies finding a significant difference (6, 32, 49) and others not (29), though this difference could be due to varying definitions for rate of force development. Contraction and relaxation durations in the TA have also been reported to last longer in older adults (6, 32, 49).

Some studies have reported a higher amount of muscle coactivation in the antagonist muscles during dorsiflexion in older adults during gait (10, 22, 53, 66) and postural control tasks (53), while others have found no difference in lower leg coactivation during gait with age (32, 64) and during isometric, concentric and eccentric contractions (32). Changes in the TA with age can impact toe clearance in gait, which is

a significant risk factor for falls in the elderly (55). It is therefore important to identify changes in the TA's function, such as the ability to rapidly activate and deactivate it, which could be important for catching onself after a lose of balance.

Foot Tap Speed

The ability to perform rapid movements, such as finger and foot tapping, decreases with changes in the neuromuscular system that are associated with aging and disease (51, 59). Rapid finger tapping is used by neurologists to track the progression of diseases impacting the upper motor neurons (UMN) by comparing finger tapping speed longitudinally, and against a normal population (51). A rapid FTT is indicative of changes in motor control that occur in diseases that affect the CNS (14, 27, 51, 58, 59), and with aging (29, 59). Foot tapping likely requires the rapid recruitment and derecruitment of MU (9), and the modulation of the number of MU recruited because it is a fine, submaximal, movement. For the FTT, participants are asked to tap their foot as rapidly as possible for 10s, a task which is more difficult for individuals with mobility and motor impairments.

The results of recent studies suggest that the FTT is potentially an informative measure of changes within the central motor system. Foot Tap Speed is lower in individuals who have diseases that affect the central motor system such as cervical myelopathy (59), multiple sclerosis (58), Parkinsons'(14), and amyotrophic lateral sclerosis (ALS) (27, 50, 51). The FTT is a measure that can be implemented in the clinical setting since it requires only a chair and a tap counter, and has already been shown to be correlated with results from current clinical tests (27, 50). In a study by

Miller et al., physicians were asked to identify the affected leg of individuals who had mild weakness in their leg brought on by an UMN disease using the Babinski sign, a commonly used neurological test for identifying an abnormality in the plantar reflex which is indicative of CNS dysfunction, and the FTT (50). This study found that the physicians were able to identify the affected limb with more accuracy and confidence using the FTT than the Babinski sign (50). In a study of neuromuscular differences in individuals with ALS, Kent-Braun et al., found that individuals with an impaired UMN function due to ALS, had a reduced ability to perform fine, rapid movements, measured using maximal rate of voluntary force rise and FTS (27). Foot Tap Speed was correlated with the Ashworth spasticity score ($P=0.02$) in the ALS participants, and a 6-month follow up showed a significant reduction in FTS in this population (27). The FTT is already in use by neurologists for assessment of the above mentioned diseases, but its clinical use in aging populations is still being developed.

Foot Tap Speed also decreases with age, is strongly correlated with functional measures and other predictors of mobility impairment, such as gait speed, and can identify individuals at risk for future mobility impairments (28, 59). Numasawa et al. examined FTS in 792 healthy adults ranging in age from 20-83 years old and found that FTS and age were moderately negatively correlated ($R= -0.369$, $P<0.0001$; (59). This study also found that FTS was strongly correlated with lower extremity motor function, as quantified by the modified Japanese Orthopedic Association (59). Submitted data from Kent-Braun et al. examined FTS and walking speed in 9,698 women over the age of 65 years old, and found that a slower FTS was directly associated with a lower gait speed and effectively predicts slower gait speed at a 2 year follow up (28). Additionally, this

study found a correlation between faster FTS and higher physical function, quantified as greater PA, greater grip strength, faster completion of 5-chair rises, and balancing longer in a tandem stand (28). While the use of FTT to track changes in aging is relatively new, the results of the above studies highlight the potential possibilities of the FTT.

The cause of the decrease in FTS with age is unknown. In a study by Kent-Braun et al. the properties of the TA were studied extensively in young (25-44 years) and older (65-83 years) men and women with comparable PA levels (29). The groups were compared on specific strength, normalized maximal rate of force development (RFD), CAR, and FTS. Normalized maximal RFD, CAR and FTS are all measures that are believed to indicate central deficit but only FTS was statistically different between the young (47 ±1 tap/10s) and older (34±1 tap/10s) group (29). This study found that the older group had an impaired ability to perform these rapid dynamic contractions, but did not have a difference in other properties in the TA (29). Additionally, it suggests that the FTS may be a more sensitive indicator of changes within the CNS than normalized maximal RFD and CAR, potentially causing FTS to be an early detection mechanism for changes in the CNS. The above-mentioned study called into question why FTS decreases with age, and highlighted the need for additional studies to determine which changes in the neuromuscular system with age are the source of this slowing.

Control of rapid movements

The ability to rapidly tap one's foot can be impacted by central or peripheral changes in the neuromuscular system. Centrally, MU discharge (i.e., firing) rate and rapid modulation of MUs control how quickly the motor neurons can be activated and

deactivated (9). In young adults, MU firing rate is higher and force required to active a MU is lower during rapid isometric contractions than when performing ramp isometric protocols, with the firing rate of the TA reaching 60-120 Hz during ballistic contractions (9). In a study by Klass et al., the firing rate of MUs in the TA during rapid isometric contractions was found to be higher in young adults than older adults (31). The change in firing rate between the MU's first, second and third discharge was also examined in young and older adults, and older adults were found to have a greater decrease in firing rate during the successive firings when compared with young adults (31). Additionally, it has been found that older adults have a lower MU force threshold in the TA than younger adults while performing isometric contractions (6). These studies suggest that MU firing rate is higher and the force threshold is lower during rapid contractions, and that young adults have higher MU firing rates and a higher force threshold than older adults (6, 9, 31). While these studies were isometric and the rapid contractions were not isolated vs successive, they provide insight into how MU recruitment might change during rapid, repetitive contractions in young and older adults.

Peripherally, the rate of activation and deactivation of the TA is controlled by RFD and relaxation time. In a study by Klass et al., older adults had lower maximal RFD and had longer time to peak torque during fast contractions of the TA when compared with young adults (31). Kent-Braun et al. did not find a difference in rate of force development during rapid isometric contractions with aging; however this is likely due a difference in methodology (29). This study expressed voluntary rate of force development relative to maximal stimulated rate of torque development in order to account for peripheral changes in the muscles, thus using rate of force development as a

central, not peripheral, measure (29). If the muscle has a reduced rate of force relaxation, it will take longer before the muscle can be activated again.

In addition to the changes in central and peripheral factors discussed above, changes in motor control, such as regulation of antagonist activity (48), could impact the ability to perform rapid movements in older adult.

Coactivation

Some studies have shown that older adults use greater coactivation than younger adults while performing a range of activities. Coactivation is defined here in two ways: 1) the quantity of antagonist activation relative to the quantity of agonist activation, or $CoAct_M$ (Equation 1); and 2) the amount of time in which the antagonist is active during the agonist activity, ($CoAct_T$, ms). Antagonist activity is not consistent across all muscle groups and actions. Coactivation tends to be higher in individuals with decreased postural stability, decreased motor control, and/or greater mobility impairment.

Older adults tend to use greater coactivation in their legs than young adults. Thigh $CoAct_M$ has been shown to be higher in older adults while they are walking (64, 66), and climbing up and down stairs (21, 38). There are inconsistencies in the literature with regard to shank coactivation, with some studies finding that $CoAct_M$ does not differ between old and young while walking (10, 64), or when performing isometric, concentric or eccentric contractions (32), while others report a difference in $CoAct_M$ during gait (22, 53, 66) and static standing (40, 53). $CoAct_T$ of the TA and plantar flexors was found to be different between young and older adults in studies of gait and stair climbing (10, 22), with older adults having a greater overlap in timing of the activation of the TA and

gastrocnemius muscles, due to earlier onset and later offset of the gastrocnemius muscles (22). Coactivation could be impacted by gait changes that occur with aging, such as a change in muscle recruitment patterns and power during gait (45, 60, 66, 82). Older adults tend to walk slower, take shorter steps, have lower push-off power, and spend more time in double limb support (30, 45, 60, 82), with an even greater reduction of these parameters seen in older adults with reduced knee and ankle strength (36). Older adults also tend to have a decreased hip and ankle range of motion which could be related to a decline in maximal knee strength with age (34).

Coactivation during rapid movements is an area of research that has not been explored extensively. In a study on coactivation during elbow extension, Mardsen et al. found that coactivation was highest while performing small movements at high velocities in the elbow extensors (48). Conversely, Klass et al. found that $CoAct_M$ was not different when performing rapid movements, finding no difference in the amount of antagonist soleus activity relative to the TA's activity when performing fast, isometric dorsiflexion contractions in young and older adults (31). Coactivation has also been shown to increase with gait speed in both young and older adults, but this could be due to the difference in the tasks being performed (22). Additionally, a negative correlation has been shown between RFD and coactivation in the knee extensors and flexors in older adults, suggesting that greater coactivation could reduce the speed of force development (62). It is evident that additional research is needed to understand how coactivation may impact rapid movements in young and older adults.

It is unclear whether an increase in coactivation with age is a beneficial or harmful adaption, but more than likely it is both. Higher coactivation occurs because

more antagonist muscle fibers are recruited, which can decrease force output and increase the metabolic cost of movement. Higher antagonist activity might be an adaptation used to increase stiffness around the joint and thus an older adults' stability, or it could be due to poor motor control. A full understanding of the consequences of increased coactivation with aging remains to be determined.

With greater antagonist activity, it is likely that more MU are recruited in both the agonist and antagonist muscles. Greater antagonist activity could cause a reduction in force capability in older adults (46). To counter-act this increase in antagonist activity, it is possible that more MU in the agonist would be required. The increase in agonist and antagonist muscle activity likely leads to a higher metabolic cost of movement, which has been linked to the slowing of gait speed (67). Previous studies have shown a relationship between the increased coactivation in leg muscles in older adults and higher metabolic cost of walking (20, 47, 64).

In contrast to the negative effects of coactivation, increased antagonist activity helps to stiffen the joint, an adaptation that increases joint stability in older adults. Hortobagyi et al. found that when performing a downward step, $CoAct_M$ was 96% higher in older adults than younger adults, with the vastus lateralis and bicep femoris muscles having 140% greater activation, and the TA having 120% greater $CoAct_M$ than young adults (21). When the relationship between leg stiffness, defined as force production divided by leg displacement ($N \cdot m^{-1}$) and muscle activity was examined, the above study found that 50% of the variance in leg stiffness was accounted for by higher muscle activity in the older adults (21). The adaptation of increasing leg stiffness by coactivation has also been seen in studies on individuals who have a fear or history of falling, with

these individuals having greater muscle coactivation in the lower leg (7, 54). In a study by Marques et al., which compared gait in fallers and non-fallers, the $CoAct_M$ ratio for TA/Lateral Gastrocnemius (GL) was higher in fallers during all phases of gait (47). However, it is also possible that the higher coactivation seen in fallers is not an adaptation to increase joint stiffness, but rather because they have worse postural control. Older adults with who have less physical function during a functional reach task and greater sway area during static standing have been shown to have great coactivation in the shank than older adults with better postural control (40, 53).

Falls

Falling is a major concern for older individuals, with about a third of all persons over 65 experiencing a fall each year (5). Many of these falls lead to minor or major injuries. There are many different factors that can lead to a loss in stability in older adults. Fallers, frequently classified as individuals who had fallen, or nearly fallen, during the past year, tend to have a lower isometric strength in the ankle muscles (37) and rate of torque development in the dorsiflexor muscles (37, 63), It has been observed that fallers have a greater asymmetry in isometric dorsiflexor strength than nonfallers, along with during low velocity eccentric dorsiflexion and plantarflexion (63). Coactivation has been shown to be greater in fallers during gait (47) while it has not been shown to be different in the knee or ankle muscles during isometric contraction (37). In addition, a delay in ankle dorsiflexion at the beginning of the swing phase during gait has been correlated with higher prevalence of falls (25).

The Falls Efficacy Scale-International (FES-I) is a 16-question instrument designed to query individuals about their fear of falling during both basic and more demanding physical and social activities (83). The FES-I was developed from the Falls Efficacy Scale (FES). The FES has excellent reliability, is correlated with balance and gait, and is able to predict future falls and a decline in physical function (75, 83). The FES-I includes questions that are more relevant to individuals with higher functional ability, allowing it to discriminate between individuals with a wider range of functional abilities (83). The FES-I also addresses the impact of an individual's concern about falling on their participation in social activity, extending the questionnaire from the FES, which only focuses on physical situations and consequences. In a one-year follow up study, the FES-I showed good predictive validity and there was a general increase in FES-I score with time, indicating a greater concern of falling with age (8).

As discussed previously, coactivation is an adaptation that can help to stabilize joints. It has been found that older adults who have a fear or history of falling have greater coactivation than their peers who do not fear falling (40, 47, 54). Marques et al. found that older females who had fallen in the past year had a higher coactivation ratio for their TA and GL during gait than older females who had not fallen (47). A study by Laughton et al. examined postural sway and coactivation during quiet stance, and found that older adults had a higher rate of coactivation, but there was no difference in coactivation between fallers and nonfallers, which was possibly due to the already increased coactivation with age (40). It appears that if an individual is more concerned about falling, they will try to maintain stability in their joints, which would include stiffening the joints by increasing the activity of the muscles around the ankle and knee.

Physical activity and function

The decline in physical function with age greatly impacts the quality of life of older adults, because it results in greater disability and a decreased ability to perform activities of daily living (17, 65). A decline in physical function, specifically mobility, is also accompanied by an increased likelihood of falling, and the fear of falling can impact the individual's perceived mobility (2). Lower daily PA has been related to an increase in mobility impairments and a decrease in functional ability in older adults (52). Individuals who participate in a greater amount, and a higher intensity, of PA tend to have a higher gait speed and are less likely to develop sarcopenia (52, 68). Two common functional tests that have been strongly correlated with declining function in older adults are the SPPB and gait speed, specifically the 400 m walk.

The SPPB is a common functional test that scores individuals from 0-12 based on their ability to complete specific tasks (15, 16). The SPPB includes 3 tasks: time to complete a 4m walk at a casual walking speed, ability to balance for 10s in 3 positions (tandem, semi-tandem, side-by-side stance), and time to complete 5 chair rises (15, 16). The SPPB has been correlated with gait speed, and has proven reliable for testing functional ability in older adults (15). The SPPB has also been shown to predict morbidity in a 6 year follow up, with morbidity decreasing by 15% for each increase in SPPB point at baseline (80). An advanced version of the SPPB has also been developed and allows for the differentiation of individuals who score a 12 on the SPPB, along with more individualized scores for participants (70). The advanced SPPB (SPPB-A) expands

on the SPPB, making the tasks slightly longer and more difficult and minimizes the ceiling effect.

Gait speed has been shown to be a reliable indicator of changes in physical function and mobility limitations in older adults (16, 72). Preferred gait speed is correlated with survival rate, with individuals who have a lower gait speed having a lower survival rate (72). Preferred gait speed during a short walking task, specifically the 4m walk during the SPPB, has been shown to predict future mobility impairments (16). The 400m walk test is an endurance walk that is performed at a brisk pace. Time for completion has been related to current functional ability (13) and mobility limitations at a 5 year follow up (56). Time for completion of the 400m walk test is correlated with survival 6 years later, with individuals who were unable to complete the test or were in the group which took the longest time to complete the test having the highest rate of mortality 6 years out (56, 80). A study by Vestergaard et al. also found that a larger coefficient of variation in lap time, taken across 20 laps, was a predictor of morbidity at 6-year follow up (80). Additionally, greater stride time variability while walking has been correlated with an increased fall risk in older adults (19).

Foot tap speed has been correlated with gait speed and other functional measures, indicating that the FTT is a reliable way of predicting mobility impairments (28, 59). Individuals with mobility limitations have been found to have a lower FTS, gait speed and SPPB score. However, unlike the 400m walk test and the SPPB, the FTT does not require an individual to be mobile and could potentially be an early indicator of changes in the central nervous system (28). However, the FTT is currently limited because it is susceptible to recorder error. Currently, the FTT is performed by having an individual

tap their foot rapidly on the floor while someone counts their taps and tells them when to start and stop (27, 59). However, this method provides a single outcome variable, the number of taps. It is believed that using a force platform to record the force output of each tap and motion capture to track the motion of the foot during the task will increase counting accuracy and provide additional information about how the task is being performed. Variations on the traditional FTT, such as reducing the rate of tapping, could provide insight into how individuals approach the task of repetitive contractions and how speed might impact muscle activation.

Summary

Over the last 100 years, there has been a steady increase in the number of individuals living past the age of 65, along with an increase in life expectancy (77). A major concern for these older adults is a decrease in physical function, specifically mobility, and an increase in the prevalence of falls with aging (5, 65). A simple test, such as the FTT, could be beneficial for the identification of individuals who are at risk for mobility impairment due to aging and changes in the CNS. Slowing of FTS has been shown to be related to a decline in motor control with both disease and aging (28, 51, 58, 59). However, the cause of the decreased ability to rapidly activate and deactive the dorsiflexors is still unknown. Slowing of muscle properties with age, such as the rate of muscle activation and relaxation, could impact FTS. However, because FTS has been shown to be slower in individuals with varying diseases affecting the CNS, it is likely more strongly impacted by changes in central control (14, 27, 50, 51, 58, 59). Changes in central control, such as MU recruitment and muscle coactivation, could play a role in the

slowing of FTS (29, 31, 48, 62). Some studies have found that muscle coactivation in the lower leg is higher in older adults while walking, preforming postural control tasks, and standing still (22, 40, 53, 66). While the increase in muscle coactivation with age could be detrimental due to its correlation with a higher metabolic cost of movement (20, 47, 64), it has also been shown to increase joint stiffness (7, 21, 54). Increased joint stiffness is believed to be an adaptive mechanism to increase stability in fallers, which is of particular importance because about one in three older adults fall each year while walking (5). Further exploration into the cause of slowed FTS with aging could provide new insight into the relationship between coactivation and the ability to perform rapid repetitive movements. Additionally, further analysis of the relationship between lower leg coactivation and concerns about falling could yield new insight into identifying individuals at risk of falls.

CHAPTER 3

METHODS

Study Participants

This study will include three groups: young, older and older impaired adults. Sixteen individuals between the ages of 21 and 35 years will be recruited for the young group, and 32 individuals between 65 and 85 years will be recruited for the older groups. Males and females will be recruited equally. Half of the older participants will have a mild-to-moderate mobility impairment, as defined by a SPPB score of 8-10 (15), and will be categorized as "older impaired". The other half of the older adults will have no mobility impairments, as defined by a SPPB score of 12. Individuals with an SPPB score of 11 will still be tested and analyzed post-hoc. All experimental procedures and consent documents were approved by the University of Massachusetts Amherst Institutional Review Board.

The participants will be relatively sedentary, participating in no more than 1 structured exercise session $\geq$ 30 minutes' duration per week. Individuals will be excluded if they are currently taking medicine that may affect their physical function. Those who smoke or have stopped smoking within the previous year will be excluded. Individuals will be excluded if they have: significant arthritis in the lower extremities, a pacemaker, a history of muscle cramps or pain, a history of neurological or neuromuscular disease (including peripheral neuropathy), a history of symptoms upon exertion (including dyspnea, cramping, and light-headedness), or had a stroke within the past year. Anyone who has peripheral vascular, cardiac, or pulmonary disease will be excluded. Individuals with controlled hypertension or hypercholesterolemia will be

allowed to participate, as will those taking statins, sleep aids or antihypertensive medications other than beta-blockers. Individuals must score between an 8-12 on the SPPB in order to participate.

Procedures

Potential participants will be screened by telephone before the visits are scheduled. Participants will make 2 visits to the Muscle Physiology and Biomechanics Labs at the University of Massachusetts (Totman Bldg, Rm 22 and 23). Visits will be scheduled at least 1 but no more than 3 weeks apart. The first visit will be a Habituation Session lasting 80 minutes (Table 9). The second visit will be the Testing Session, which will last approximately 90 minutes (Table 10). The participant will be asked to wear shorts. Standard neutral running shoes (New Balance) will be provided for the participant to wear on both visits. If the participant wears orthotics, they will be allowed to put the orthotics in these shoes.

Visit 1: Habituation Session

When participants arrive, they will be led from the foyer of the Totman Building to the Muscle Physiology Laboratory. The study will be explained in detail and a researcher will review the Informed Consent document with the participant. If they choose to participate, the participant will read and sign the Informed Consent document, which satisfies the requirements of the University of Massachusetts Amherst Institutional Review Board. They will then fill out a Medical History Form, a Physical Activity Readiness Questionnaire (74), the FES-I questionnaire (83), and the SF-36 (81); Appendix).

The Medical History Form asks about relevant diseases and medical diagnoses. This questionnaire is designed to verify that the participant meets all of the inclusion criteria and does not meet any of the exclusion criteria. The Physical Activity Readiness Questionnaire is designed to verify that the participant does not have any restrictions during PA, such as light headedness or pain, and that it is safe for them to engage in PA. The FES-I asks a series of questions about how concerned an individual is about falling in a variety of scenarios including during basic and more demanding activities that are both physical and social. The SF-36 asks about physical and emotional health, and has questions designed to address if the individual experiences pain in general.

After completing the questionnaires, the participant's resting blood pressure will be taken. At this point they will have been seated quietly for at least 10 min. Next, the participant's height and weight will be taken using a Detecto-Medic scale (Detecto Scales Inc, Brooklyn NY). The participant's body mass index (BMI) will be calculated as mass/height^2 (kg·m^{-2}).

Physical Activity Assessment

Each participant will be given a uniaxial accelerometer (model GT1M, Actigraph, LLC Pensacola, FL., USA) to objectively record their PA. They will wear the accelerometer on a belt at their waist for 7 consecutive days, which will provide data about their activity during the week and weekend. They will be instructed to wear the accelerometer during all waking hours, except when they are in water. An activity log will be used by the participant to record their daily activities, sleep schedule, PA bouts, and any illness and activities outside of their normal activity. They will be instructed to maintain as normal a PA pattern as possible. This accelerometer is unable to record PA

from cycling and swimming; therefore participants will be encouraged to record these activities in their log carefully and avoid them if they are not part of their normal routine. Data will be collected in 60s epochs and used to determine total activity counts and count intensity for each day (11). The PA data will be separated into time spent in low-intensity PA (1-1951 counts·min^{-1}, ≤3 METS) and moderate-to-vigorous (≥1952 counts·min^{-1}, >3 METS) based on cutpoints established by Freedson et al. (11).

Physical Function Measures

The participant's functional ability will then be measured using the normal and advanced SPPB. The normal SPPB scores the participant from 0-12 based on their ability to complete specific tasks and will be used to separate individuals into groups (15, 16). The Advanced SPPB (SPPB-A) is an extended version of the test that allows for more precise scoring and distinguishes between individual who receive a 12, reducing the ceiling effect of the SPPB (70). A scoring chart for each test can be found in the Appendix. The chair rise and balance tests will occur in the Biomechanics Lab, and the walking test will occur in the hallway outside the Muscle Physiology Lab.

First, walking speed will be tested with a 6m walk between 2 lines 6 inches apart on the floor. The participant will be instructed to walk at a casual walking speed, as if they were walking down the street, with no criterion of staying between the lines. This will be done twice and the faster of the 2 walks will be used for analysis. Next, they will perform the Balance Gait test where they will be instructed to walk between the lines at a casual speed. This will be performed twice and the fastest time will be used. If they step outside the lines twice, they will be given a zero on the SPPB-A.

Next, the participant will perform the chair rise test. They will be led into the Biomechanics lab where a chair will be set up just off the force platforms so that when they stand up, their feet are on the force platform (AMTI, Advanced Mechanical Technology Inc, Watertown MA). The participant will perform 10 chair rises, which involves standing up from a standardized chair 10 times, as quickly as possible. A split time will be taken after 5 chair rises. Their arms will be crossed over their chest to prevent them from being used during the task.

Balance will then be tested on the force platform for 3 foot positions: tandem, semi-tandem, and side-by-side stance. The participant will be allowed to hold the researcher's arm as they are getting into each position. Once they are ready, they will release their grip and try to hold the foot position for as long as possible, for up to 30s. The time will be stopped if they move their foot from the position or grasp onto the researcher's arm. Testing will begin with the side-by-side stance, where the feet are next to each other. Next the participant will perform the semi-tandem stance, where the heel of one foot is placed next to the big toe of the other foot. They will then be tested using the full tandem stance, one foot directly in front of the other, for up to 30s. The participant will then stand on one leg for up to 30s, and they will be able to pick which leg they prefer.

Familiarization

Next, the participant will be introduced to the equipment that will be used during the Testing Session. In the Biomechanics Lab they will be familiarized with the Humac Norm dynamometer (CSMi, Stoughton MA). They will lay on the Humac with their leg fully extended and their thigh and torso strapped to the chair to prevent movement. The

foot that will be tested will be strapped to the force transducer plate, and their free leg will rest comfortably on a bar. The participant will practice plantar and dorsiflexion isometric MVCs. Once they have been familiarized with the MVC protocol, the participant will then be taken to the foot-tapping station, where they will sit comfortably in a chair with the ball of one foot resting on an AMTI force platform. The participant will be instructed on how to tap their foot (lifting the ball of the foot off the ground and putting it back down as fast as possible). The participant will practice rapidly tapping each foot for several seconds; this will be done 3-4 times for each foot. They will then perform 2 10-s FTT on each foot, alternating between legs, during which time the force platform will record the GRF. The slower leg, as defined by a slower FTS by manual analysis of the force data, will be used for further analysis.

Stimulated Force Production

In the Muscle Physiology Lab, a stimulating electrode will be placed on the peroneal nerve, which is about 1 cm distal to the fibular head, of the leg being tested in order to stimulate the TA. Surface electromyography (EMG) electrodes will be used to measure muscle activation. A gold-plated disk electrodes (10 mm) for recording EMG will be placed on the muscle belly of the TA, while another is placed on the distal tendon of the TA and will be used as a ground. A copper ground plate (6x6 cm) will be placed half way between the stimulating and EMG electrode to reduce stimulation artifact. The participant will be seated with their hip at ~180°, knee at ~120° of knee extension, and ankle at 10° of plantar flexion. Their foot will be securely strapped to a custom designed platform attached to a force transducer which is used to measure dorsiflexion and plantar flexion force. The stimulating electrode will be attached to a stimulator (model DS7,

Digitimer Stimulator, Hertfordshire, UK). All stimuli and EMG recordings will be obtained using LabView software (National Instruments, Austin TX). The stimulation intensity will be determined through single twitch stimuli with increasing current until additional current yield no increase in compound muscle action potential (CMAP). A current set at 115% of the current needed to elicit a maximal CMAP will be used for testing. The participant will be told to relax their muscle and three baseline twitches will be administered with at least 30s in between each of them. The participant will then be asked to perform 3 isometric dorsiflexion MVCs lasting 3-5s, with a minute rest in between. During the last MVC, a tetanic train (50 Hz, 0.50s) will be administer when force is at a plateau in order to calculate CAR. Next, the participant will perform a rapid contraction with the instruction to reach 40% of peak MVC torque as quickly as possible, then to relax. A light diode will inform the participant of the percent of their MVC. They will practice this test until they can reach 40% reliably then perform the test 3 times, with a 30s break in between. A twitch stimulation and a train stimulation (50 Hz, 0.5s) will then be applied while they are relaxed.

Visit 2: Testing Session

At the start of Visit 2, we will collect the activity log and accelerometer and the participant will then be taken into the Biomechanics Lab where testing will occur. The protocol will be reviewed with the participant. The participant will warm up by pedaling lightly on a recumbent cycle ergometer (Schwinn, Nautilus, Inc., Vancouver, Washington) for 5 minutes, followed by light stretching of the lower extremity muscles, focusing on the calf and TA.

EMG Electrode Application

Wireless surface electromyography (EMG) electrodes (Trigno, Delsys Inc, Natick MA, USA) will then be placed on the belly of the tibilias anterior (TA), medial gastrocnemius (GM), lateral gastrocnemius (GL), and soleus (SO) muscles of the chosen leg, using the "Surface Electromyography for Non-Invasive Assessment of Muscles" guidelines for EMG sensor placement (73). The locations for the GM, GL and SO electrodes will be identified by asking the participant to stand on their toes, while using a table to support their weight. The location for the TA will be identified by asking the participant to dorsiflex against manual resistance. Once the electrode locations have been determined and marked with a sharpie, a 5x3 cm rectangle will be shaved over each muscle belly. An alcohol swab will be used to clean the skin and the EMG electrodes will be adhered to the skin. After the EMG electrodes have been placed on the muscle, the electrode signal quality will be tested by asking the participant to again stand on their toes and then to dorsiflex. If necessary, the electrodes will be moved to achieve a better signal-to-noise ratio, which will be determined by visual inspection, using the Delsys display, of the difference between the amplitude at the baseline and when the muscle is contracting. Once a clear signal is achieved, pre-tape wrap will be wrapped around the leg and electrodes to further secure the electrodes in place.

Muscle Strength Tests

After placement of the EMG electrodes, the participant will be positioned on the Humac Norm dynamometer to test muscle strength and record EMG activity during MVCs. The participant will lie on the flat Humac chair as described previously, with the testing leg fully extended. The leg not being tested will rest comfortably on a bar

extending from the chair. The participant's foot will be strapped onto the force transducer plate, which will be at 10° of plantar flexion. The thigh and torso will be strapped securely to the Humac to prevent movement, and pads will be placed under the knee for support.

After the participant is positioned on the Humac, the plantar and dorsiflexion protocols will be reviewed. The participant will be instructed not to use their knee or hip to perform the contractions. They will have 2 practice trials of plantar flexion, during which their torque profile will be visible on the computer. The participant will be instructed to contract as fast and hard as possible and hold the MVC for 3-5s, with the goal of having the torque rise quickly and remain level during the MVC. After these 2 practice trials, the participant will perform 3 plantar flexion MVCs. Verbal encouragement will be provided during the 3 MVCs, and the participant will be instructed to push the ball of their foot down as hard as possible, as if they were hitting the gas pedal of a car. Each MVC will last for 3-5s, and the participant will be given 90s of rest between each trial, to prevent fatigue. Following the plantar flexion protocol, the procedure will be repeated for dorsiflexion, with the participant having 2 practice trials followed by 3 test trials. The participant will be instructed to pull their foot up, as if lifting their foot off the gas, as fast and as hard as possible.

Foot Tap Tests

The participant will rest for 3 min after the MVCs, during which time motion capture makers will be placed on the leg being studied. The motion capture markers are retro-reflective spheres of 2 cm diameter that will be placed on anatomical landmarks (5^{th} metatarsal, medial and lateral malleolus, tibial tuberosity, 1^{st} toe), along with a cluster of

markers on the heel. The markers will be used to track the motion of the foot during the FTT. Next, the participant will stand in the anatomical position in the center of the motion capture collection area on the middle force platform and a 5s static calibration will be taken. The collection area has 11 Qualysis motion capture cameras (Qualisys, Gothenburg, Sweden), which will collect data at a sampling rate of 200 Hz.

For the foot tap tests, the participant will sit in a standard chair centered in the calibrated volume of the motion capture area, about 15 cm behind the force platform, which is a 60 cm by 120 cm rectangle (Figure 10). The participant will be instructed to sit comfortably with the middle and ball of their foot on the force platform, but the heel resting off the platform. When the participant lifts the ball of their foot during the tapping task, no part of their shoe should be in contact with the force platform. The participant will be seated with their knee, ankle and hip each at approximately 90° of flexion. Tape will put on the platform along the edge or top of the participant's foot as a visual guideline for the foot's position. The participant will be instructed to tap their foot as quickly as possible by lifting the ball of their foot off the platform and placing it back down. They will be told that in order for a tap to count, their foot must clear the platform when lifting and make contact with the platform when descending. There will be no further instructions as to how they should tap their foot, and the participant will be encouraged to tap in a way that they feel will allow them to produce the fastest speed. The participant will be instructed to keep their foot resting calmly on the force platform before and after the collection period in order to obtain a baseline EMG. The participant will be allowed several brief practice trials of the tapping task before testing begins.

For all FTTs, force platform data will be collected at a sampling rate of 2,000 Hz and synchronized with the motion capture data, which will be collected at 200 Hz using Qualisys Oqus. EMG data will also be synchronized with the force and motion capture data and collected at 2,000 Hz using Trigno's recording system. Foot tap speed will be evaluated 3 ways: 1) research assistant manually counting the number of times, based on observation and sound, that the foot makes contact with the ground, 2) force platform recording of GRF, and 3) motion capture cameras tracking the foot markers' movements.

10-s FTT: The first test will be the 10-s FTT, for which the participant will be instructed to tap their foot as quickly as possible for 10s. The researcher who is running the computer will indicate when to begin and end tapping. This FTT will be performed 3 times, with a 60s break between each trial. The average number of taps from the 3 trails of the 10-s test, as determined by the researcher through visual inspection of the GRF data, will be used to determine each person's target speed for the 30%, 60%, and 100% trials that will follow.

Next, the participant will perform three 10-s trials; 1 at 30%, 1 at 60%, and 1 at 100% of maximal tapping speed. These trials will be used to examine whether muscle recruitment patterns change at submaximal tapping speeds and if individuals' ability to match a speed is impacted by age. To achieve the desired pace, a metronome will be set at the appropriate cadence and the participant will be given 3, 4 s long trials at the speed being tested to practice. Once the participant feels comfortable with the task, they will be given 30s to rest before the trials begin. The participant will perform each 10-s trial while trying to match the metronome's cadence. The order of the 30, 60, and 100% trials

will be randomized between participants and blocked by group. Sixty seconds of rest will be given between trials. Each speed will be tested once.

Preferred Gait Speed

Participants will walk around 100m around a 20m loop at their preferred walking speed and data will be collected 3 times as they pass through the collection zone. Additional trials where the participant walk 10m, starting from a stop, will be given if the trial speeds are greater than 0.2 m/s different. Both the preferred gait speed walk and the 400m walk will occur in the same space which will consist of 2 cones located 20m apart on a 22m long raised runway. The runway is 1.2m wide where the participant will be turning and a research assistant will be positioned to ensure the participant's safety at all times. The runway has a collection zone with 11 Qualysis motion capture cameras, and infrared timing gates which are 6m apart and are used to determine speed. Motion capture, EMG, and time to complete 6m will be collected each time the participant is walking to the right through the collection zone.

400m Walk

After completion of the foot tap tests, the participant will have a 5 minute rest period. An EMG electrode will be taped to the posterior heel of the shoe to determine timing of heel contact. For the 400m walk test, the participant will be instructed to walk at a brisk pace that they believe they can maintain the entire time, or to walk as if they were walking to catch the bus. The 400m walk will consist of 20 laps between two cones positioned 20m apart. Before the 400m walk, the research assistant will explain the modified Borg Scale to the participant, which will be used to rate their perceived exertion before, every 100m during, and immediately after the 400m walk (3). For this scale, a

“0” indicates an effort level of ‘nothing at all’ and “10” indicates an effort level of ‘extremely strong’ or absolutely maximal.

Following completion of all tests, the markers and electrodes will be removed from the participant and they will be given a $20 Visa gift card and the option to take booklets on PA for the aging adult. Any remaining questions will be addressed, and they will be escorted to their car.

The researchers will call the participants 3 and 6 months after their testing to ask if they have fallen, or had an unexpected contact with the ground, in the past 3 months, and if so, how many times.

Data Analysis

Physical function will be determined using the SPPB score and SPPB-A score. To determine the SPPB score (out of 12), each test (chair rise, walk time, and balance) will be scored from 0 to 4, with a 4 indicating no impairment for that task (Appendix). Not all of the tasks described will be used to determine the SPPB score. All of the described physical function tasks will be used to determine the SPPB-A score, and a more comprehensive score will be given (Appendix). Individual components of the physical function measures may also be used for exploratory analyses. Force data collected during the side-by-side balance stand may be used to examine margin of stability. Force data collected during the chair rise task may be used to examine distribution of pressure while standing to see if one leg is providing more of the force than the other.

The voluntary and stimulated measures during Visit 1 will provide information on central and peripheral muscle properties, such as peak torque, RFD, $T_{1/2}$, CAR. Peak torque will be determined for the MVC, twitch and tetanus. The maximal RFD ($Nm \cdot s^{-1}$) will be defined as the peak dF/dt while the torque is rising and will be determined for the MVC, 40% of MVC contractions, twitch and tetanus (50Hz, 0.5ms) contraction. Half relaxation time ($T_{1/2}$, ms) will be determined from the tetanus and will be defined as the time it takes for the torque to fall 50% after the last stimulation. The CAR will be determined from the superimposed tetanus during the MVC, with an increase in force during stimulation indicating a deficit in central activation. A twitch will be administered at the end of the collection to determine if there was any potentiation from the trials.

Data collected during the muscle strength tests on the Humac Norm will be: isometric plantar and dorsiflexion torque, and EMG activity during maximal contractions. The highest torque for plantar and dorsiflexion, identified using a MatLab program, from each set of 3 trials will be used to determine the participant's MVC for each task. The average rectified and integrated EMG signal for a 1-s window during maximal torque production from the highest MVC will be used as peak EMG (mV), which will be used for $CoAct_M$ normalization.

The FTTs will be analyzed using a Matlab program which will be written to analyze the force platform data and determine how many times the foot made contact with the platform based on a deviation of force from the baseline, and through this method, count the number of taps. This Matlab program will also be used to quantify several dynamic variables that will capture tapping patterns. These will include the ITI

(ms), as well as the average, standard deviation and coefficient of variation of the ITI, and the average, standard deviation, and coefficient of variation of the GRF.

Visual 3D (C-Motion) will be used to track the motion of the markers during all FTTs, and each time the participant is walking to the right during the preferred gait and 400m walk. The heel accelerometer will be used to identify foot contact during both walking trials. 6Motion capture data collected during the FTTs and gait trials will be analyzed by a Matlab program that will use the angle of the ankle and the foot's velocity to separate the motion into dorsiflexion and plantar flexion time segments. With this information, the EMG data will be separated into dorsiflexion and plantar flexion time segments, and the agonist and antagonist activity for each period will be quantified to determine $CoAct_M$, while the onset and offset time of the muscles will be used to determine $CoAct_T$.

The EMG data for visit 2 will be collected at a sampling rate of 2,000 Hz during the MVCs, foot tap tests, preferred gait, and 400m walk. Data will be rectified and filtered with a Butterworth filter, then integrated to determine the amount of muscle activity. The EMG data from the FTT, preferred gait, and 400m walk will be normalized to the maximal activity recorded when the muscle was acting as an agonist muscle during the MVC tests on the Humac Norm. The normalized antagonist and agonist activity for each task will be used to determine CoActM based on Equation 1.

Preferred and brisk gait speed (400m walk) will be determined using the timing gates 6m apart ($m \cdot s^{-1}$). Walking speed will be quantified at each lap, or 10 times, during the 400m walk, to examine how the participant's speed changes during the endurance walk. The total time required to complete the 400m walk is will also be recorded. If the

participant needs to rest during the study, which they will be encouraged not to do, the duration of time they rest will be recorded and added to the total walk time but will not be used in the calculation of 400m walk speed.

Statistical Analyses

Statistical Analysis Software, version 9.3 (SAS Institute Inc., Cary, NC) will be used for all statistical analyses (Table 11). A p value of 0.05 will be used to establish significance for all analyses. Differences between descriptive variables (age, height, body mass, BMI, BP, SPPB and SPPB-A score, PA counts and count intensity, 400m walk time, preferred and brisk gait speed, plantar and dorsiflexion MVC torque, maximal rate of torque development, $T_{1/2}$, CAR, FES-I, fall occurrence at follow up) of the groups will be evaluated using Analysis of Variance (ANOVA). These variables may be used as covariates in the primary analyses if statistical difference is found. To address the first aim, ANOVA tests will be used to determine whether there is a difference in FTS, $CoAct_M$, and $CoAct_T$ during the 10s-FTT between the young, older, and older impaired groups. A regression analysis will be applied to the $CoAct_M$ and FTS data for all of the older adults, combined. The second aim will be addressed through an ANOVA of $CoAct_M$ during the first three laps of 400m walk in all 3 groups, and a linear correlation between $CoAct_M$ and gait speed will be performed using the data for all older adults, combined. The second aim also includes exploratory regression analyses of $CoAct_M$ and gait speed variability during the 400m walk and FES-I score for all older adults, combined. The final, exploratory aim will be addressed by analyses of the dynamic variables, such as ITI, GRF, toe excursion and number of foot taps during a 10s period, to examine foot tapping patterns during the 10s and 90s FTT. This aim will also be

addressed by analyses of the dynamic variables during the constrained (30, 60 and 100% of maximal FTS) conditions.

Revisions from original proposal

The aims of the study have been adjusted slightly based on the methods that were analyzed. A subset of the data collected were analyzed and presented here in order to address a more cohesive question.

Coactivation during the 400m walk and at preferred walking speed are not presented in this paper, but will be analyzed later. The relationship between coactivation during gait and fear of falling are also not presented. Additionally, data were collected while participants tapped to a metronome which was set at 30, 60 and 100% of the participant's foot tap speed to address exploratory Aim 3.2. These data are not included in this thesis but will be analyzed in the future to look at variability while tapping to a rhythm.

The purpose of this study was to investigate the potential causes of slowed foot tap speed in older adults, determine whether mobility function is related to slowed tapping, and explore the relationship between foot tap speed and physical function in older adults. The following hypotheses were tested (Figure 1A):

Hypothesis 1. Greater performance variability during the FTT is related to slower foot tap speed

1.1 Performance variability (COV-ITI) during the FTT will be greater in higher and lower functioning older adults than young adults

1.2 COV-ITI will be negatively associated with FT count in older adults

Hypothesis 2. Greater muscle coactivation during the FTT is related to slower foot tap speed

2.1 Muscle coactivation during the FTT will be greater in higher and lower functioning older adults than young adults

2.2 Coactivation will be negatively associated with FTC in older adults

Hypothesis 3. Slower contractile properties of the dorsiflexor muscles is related to slower foot tap speed.

3.1 Young adults will have faster rates of force development and relaxation in the dorsiflexor muscles during the stimulated and voluntary submaximal contractions than both older groups

3.2 The rate of force development in the dorsiflexor muscles will be positively correlated with FTC in both young and older adults

3.3 The rate of force relaxation in the dorsiflexor muscles will be negatively correlated with FTC in both young and older adults

Hypothesis 4. Foot tap speed will be related to usual walk speed, 400m walk speed, and SPPB-A, in older adults

4.1 FTC will be positively associated with physical function in older adults

4.2 COV-ITI will be negatively associated with physical function in older adults

CHAPTER 4

EXPANDED MANUSCRIPT

Introduction

Beginning around the 7th decade of life, there are changes that occur within the neuromuscular system that can lead to a decline in physical function. Among other things, alteration in the neuromuscular system include changes in overall control of movement, muscle activation patterns, and muscle contractile speed.

Rapid repetitive tapping tests, such as a 10s foot tapping test (FTT), have been used by neurologists to track changes in central nervous system (CNS) disease as individuals with diseases affecting the CNS are unable to perform rapid foot tapping as quickly as healthy individuals (14, 27, 51, 58, 59, 76). The FTT has also been used in the study of neuromuscular function in aging (29, 59, 76). Studies have shown that older adults are unable to perform rapid foot tapping as quickly as young adults (29, 59). This slowing of foot tap speed holds true even when young and older adults have comparable muscle strength per unit mass (i.e specific strength), central control of rate of force development, and voluntary activation of their ankle dorsiflexor (DF) muscles (29). The cause of slower foot tap speeds in older adults is still not known.

Rapid tapping requires the rapid recruitment and relaxation of the muscles involved in the action. Therefore, the speed of muscle activation can impact how quickly the task is performed. Muscle contractile properties, such as the rates of force development and relaxation, can limit the overall speed of a movement during repetitive tasks. Kent-Braun et al. found that older adults did not have a deficit in

voluntary:stimulated RFD, indicating no impairment in central conduction speed of the DF muscles during submaximal, rapid contractions; however, the older adults still had a slower foot tapping speed, a potential indicator of slowing within the CNS (29). Older adults have been shown to have slower RFD and RFR in the DF muscles than younger adults when elicited by a stimulated contraction (57). The slowing of voluntary RFD and RFR of the DF have not been studied in conjunction with changes in rapid tapping performance. Thus, it is unknown whether slowing of the DF muscle during voluntary contractions impairs foot tap speed.

Poor control of repeated muscle activations could also limit the speed of rapid tapping, by means of increased coactivation and greater motor variability. Coactivation is defined as activation of the antagonist muscle during agonist activation. Greater muscle coactivation has been observed at faster movement speeds (23, 48). Muscle coactivation of the lower extremities has been found to be greater in older than young adults but there are inconsistencies in the literature specifically regarding shank coactivation (22, 38, 53, 64, 66). Some investigators have found that shank coactivation does not differ between old and young adults while walking (10, 64), or when performing isometric, concentric, or eccentric contractions (32), while others report greater shank coactivation during gait (22, 53, 66) and static standing (40, 53). It remains unclear whether coactivation could be a cause of slowed repetitive tapping in older adults.

A change in central motor drive could result in more variability in performance, and potentially contribute to the slowing of foot tapping speed. One way to determine tapping variability is the coefficient of variation of the timing between taps (COV-ITI). Older adults have been shown to have greater COV-ITI during rapid finger tapping, and

in both young and older adults, variability in tapping increased when tapping frequency increased (71). However, a study by Tomita et al., examined performance variability while foot tapping at a fixed speed and found that COV-ITI was not correlated with foot tapping speed in healthy older adults, but was correlated in individuals who had had a stroke (76). While the FTT and variability were not tested simultaneously, the variability seen in stroke patients but not healthy individuals might suggest that greater variability in tapping performance could be indicative of poor motor control.

Several functional tests have been validated for identifying older adults with declining physical function, including gait speed, 400m walk time, the Short Physical Performance Battery (SPPB), and the SPPB-A (15, 70, 72, 80). Speed of rapid, repetitive foot-tapping has been linked to physical function in individuals with cervical myelopathy (59), but few studies have examined its relationship to function in older adults. A longitudinal study of older women by Kent and colleagues (unpublished results) found that slower tapping speed at baseline predicted a decline in gait speed, and thus mobility, at a two year follow-up. These results suggests that the slowing of foot tap speed may precede changes in physical function.

The purpose of this study was to investigate the potential causes of slowed foot tap speed in older adults, determine whether mobility function exaggerates the causes of slowed tapping, and explore the relationship between foot tap speed and physical function in older adults. The following hypotheses were tested (Figure 1A):

Hypothesis 1. Greater performance variability during the FTT is related to slower foot tap speed

1.1 Performance variability (COV-ITI) during the FTT will be greater in higher and lower functioning older adults than young adults

1.2 COV-ITI will be negatively associated with FT count in older adults

Hypothesis 2. Greater muscle coactivation during the FTT is related to slower foot tap speed

2.1 Muscle coactivation during the FTT will be greater in higher and lower functioning older adults than young adults

2.2 Coactivation will be negatively associated with FTC in older adults

Hypothesis 3. Slower contractile properties of the dorsiflexor muscles is related to slower foot tap speed.

3.1 Both older adults will have a slower rate of force development and relaxation in the dorsiflexor muscles during the stimulated and voluntary submaximal contractions than Young adults

3.2 The rate of force development in the dorsiflexor muscles will be positively correlated with FTC in both young and older adults

3.3 The rate of force relaxation in the dorsiflexor muscles will be negatively correlated with FTC in both young and older adults

Hypothesis 4. Foot tap speed will be related to usual walk speed, 400m walk speed, and SPPB-A, in older adults

4.1 FTC will be positively associated with physical function in older adults

4.2 COV-ITI will be negatively associated with physical function in older adults

Methods

Study Design

Participants were tested at two visits, with approximately one week between each visit. The first visit included informed consent, anthropometrics, questionnaires, the SPPB and SPPB-A, usual walk tests, familiarization protocols, foot tapping tests on both legs, and stimulated and voluntary contractions to measure contractile properties of the DF of the slower leg. The second visit consisted of electromyography (EMG) measurements of the tibialis anterior, medial and lateral gastrocnemius, and soleus muscles of the slower leg during: DF and plantar flexion (PF) maximal voluntary isometric contractions (MVICs), foot tapping, and the 400m brisk walk; motion capture was record during the latter two tests. A physical activity monitor was worn between the first and second visit to assess habitual activity behavior.

Participant Characteristics

Eighteen young (9F) and 28 older (14 F) healthy adults were recruited. All participants were healthy, and self-reported as being free of any diseases that affected the central nervous system or blood flow. All participates were nonsmokers and were not taking any medication that impacted muscle function. Participants were sedentary to recreationally active. Informed consent, approved by the Institutional Review Board at the University of Massachusetts Amherst, was obtained for all participants.

Participants completed the Short Form-36 (SF-36), a short questionnaire which asks about physical and emotional health, and assesses whether the individual experiences general pain (81). Participants also completed the Falls Efficacy Scale-

International (FES-I), which asks a series of questions about how concerned an individual is about falling in a variety of scenarios (83).

Physical Activity (PA)

Participants wore a uniaxial accelerometer (model GT1M, Actigraph, LLC Pensacola, FL., USA) on their right hip during all waking hours for 7 days. Participants kept a log of their activity to enable detailed manual inspection of the accelerometry data. They were instructed to maintain as normal a PA pattern as possible. A minimum of 5 days with at least 10 hours of wear time each was needed for analysis, with one of the 5 days being a weekend day. Data was collected in 60s epochs and separated into time spent in low-intensity (1-1951 counts·min^{-1}, ≤3 METS) and moderate-to-vigorous (≥1952 counts·min^{-1}, >3 METS) PA based on cutpoints established by Freedson et al. (11). Counts, minutes of moderate to vigorous physical activity (MVPA) per week, and percent of wear time in activity (minutes of light + MVPA divided by minutes of wear time, %) were determined.

Physical Function

Physical function was determined using the SPPB, SPPB-A, usual walking speed, and 400m brisk walking speed (15, 70). The SPPB is a common functional test that scores individuals from 0-12 based on their ability to complete 3 tasks: time to complete a 4m walk at a preferred walking speed, ability to balance for 10s in 3 positions (tandem, semi-tandem, side-by-side stance), and time to complete 5 chair rises (15, 16). The SPPB-A (appendix) is an expanded version of the SPPB, scored continuously from 0-4,

which allows for more precise scoring and distinguishes among relatively high functioning individuals who receive a 12, thus reducing the ceiling effect inherent to the SPPB (70). The older adults were separated into higher (HFO) and lower (LFO) functioning groups based on their performance on the SPPB-A (70). The median value for women, 2.47, and the median value for men, 2.59, were used to divide the older adults, by gender, into 2 groups. Each group had 14 participants, 7 of which were women.

Usual gait speed was determined during two 6m walks in the hallway, with the average speed during these 2 trials used for subsequent analysis. For the 400m walk, 2 cones were set up 20m apart in the Biomechanics Lab. Motion capture, force data, EMG and time were recorded in a 6m space approximately half way between the cones. The 400m walk consisted of 10 laps around the 2 cones, during which participants were instructed to walk at a brisk walking speed, and the verbal cue of "walk quickly as if you were trying to watch a bus" was given each lap. Total time to complete the 400m walk was determined.

Foot Tap Test

For the FTT, the participants were seated in a standard chair about 15 cm behind a 60 x 120 cm force platform (AMTI, Advanced Mechanical Technology Inc, Watertown MA, sampling rate 2,000 Hz). The participants were seated comfortably with their hip and knee at approximately 90° of flexion, the middle and ball of their foot on the force platform, and their heel resting off the platform (Figure 2A and 1B). Participants were positioned so that their shoe was not in contact with the force platform when the ball of

their foot was lifted. This placement produced distinct peaks for each tap during the FTT, as shown in Figure 2C. The participants were allowed several brief practice trials before testing began. For each trial, the participants were instructed to tap their foot as quickly as possible for 10s.

During the first visit, each participant performed the FTT on each leg at least two times, in a randomized, alternating order, and only force data was recorded. The foot tap count (FTC) from the fastest trial of each leg was determined. The leg with the lower FTC, or rather the slower leg, was subsequently tested for contractile speed and EMG.

During the second visit, the FTT was performed again on the slower leg and motion capture and EMG data were collected in addition to force data. Retro-reflective markers were placed on the 1st and 5th metatarsal, medial and lateral malleolus, tibial tuberosity, 1st toe, along with a heel cluster (Figure 2A and B). The collection area had 11 Qualysis motion capture cameras (Qualisys, Gothenburg, Sweden) set to collect data at a sampling rate of 200 Hz.

Force platform data from the FTT was analyzed with a MATLAB program that identified a tap as a local force maxima, calculated FTC as the sum of local maxima during the 10s trial, determined the timing between taps (intertap-interval, ITI) and calculated the variability of tap timing (COV-ITI) during the 10s trial (Figure 2C and Figure 3).

EMG

Wireless surface EMG electrodes (Trigno, Delsys Inc, Natick MA, USA) were placed on the belly of the tibilias anterior (TA), soleus (Sol), medial gastrocnemius (MG),

and lateral gastrocnemius (LG) muscles of the slower leg during the second visit following established guidelines (73). Before being placed, the skin was shaved with a razor and cleaned with alcohol swabs.

Maximal muscle activity for EMG normalization was achieved during DF and PF MVICs on a Humac Norm dynamometer. Participants were positioned with their foot at 10° of PF, their knee at approximately 160°, and their hip at approximately 170°. Participants completed three, 3-5s MVICs of PF with 90s of rest between trials. Verbal encouragement was provided during each MVIC. If two of the MVICs differed by more than 10%, the participant preformed a 4th MVIC. The same protocol was used for the DF MVICs. Electromyography was recorded for each muscle group during the MVICs, and the MVIC trial with the greatest peak torque was used for EMG normalization.

The EMG signal was rectified, bandpass filtered between 20 Hz and 500 Hz, and normalized to the average EMG signal collected for 0.5 seconds during peak torque of the DF and PF MVICs. The muscle activation ratio (Act-R) during the FTT was calculated to examine the overall activation of the TA, or agonist, relative to the plantar flexor, or antagonist, muscles and is defined as:

$$Act - R = \frac{Integrated\ TA\ Norm\ EMG\ (\%\ of\ \max)}{Average\ Integrated\ Norm\ EMG\ (\%\ of\ \max)\ of\ Sol, MG, LG} * \frac{1}{FTC}$$

For the FTT, the normalized EMG signal for each muscle was integrated over the 10s of tapping, and normalized to the length of the test (10s) and the number of taps. This yielded an integrated, normalized EMG value per tap for each muscle group which was used to calculate Act-R. An Act-R value greater than one indicates greater relative activation of the tibialis anterior than the plantar flexor muscles.

Coactivation during the FTT was calculated by determining the correlation between the agonist and antagonist's EMG signals. Correlation during the 10s of the FTT was calculated based on the agreement in timing and shape of the EMG signals for the TA and Sol, which were first normalized to the EMG during the MVIC. The Sol was chosen for this analysis because it is the most active PF muscle when the knee is bent (69). A value of 1 indicates that the EMG signals are identical and a value of 0 indicates no agreement in the timing and shape of the TA and Sol signal; thus greater coactivation was indicated by a correlation coefficient closer to 1. Custom MATLAB codes were written to process and analyze the EMG data. Specifically, EMG data was rectified, band pass filtered between 20-500 Hz, then normalized to EMG during the MVIC. Data was then run through the Act-R algorithm and the EMG correlation analysis. A time lag value was not calculated for the EMG correlation analysis measure. The EMG data was corrupted for one HFO and they were excluded from EMG analysis.

Contractile Speed

Contractile speed of the TA muscle of the slower leg were examined using voluntary and stimulated contractions. A stimulating electrode, attached to a stimulator (model DS7, Digitimer Stimulator, Hertfordshire, UK), was placed on the peroneal nerve, about 1 cm distal to the fibular head to stimulate the TA. A gold-plated disk electrode (10 mm) was placed on the muscle belly of the TA, determined during maximal DF, to record the EMG, and another acted as a ground and was placed on the distal tendon of the TA. A copper ground plate (6x6 cm) was placed half way between the stimulating and EMG electrode to reduce stimulation artifact. The participant was supine with their hip

at ~120°, knee at ~40° of knee flexion, and ankle at 10° of plantar flexion. Their foot was securely strapped to a custom designed platform attached to a force transducer which is used to measure DF force, and the knee was strapped down to reduce movement artifact. All stimuli and EMG recordings were obtained using LabView software (National Instruments, Austin TX). The stimulation intensity was determined through single twitch stimuli with increasing current until additional increases in current yield no increase in the compound muscle action potential. A supramaximal current (115% of the current associated with the compound muscle action potential) was used for subsequent stimulations.

Three baseline twitches were administered while the participant was relaxed and at least 30s rest was given between each of them. The participant then performed 4 DF MVICs lasting 3-5s, with a one min rest between each trial. During the last MVIC, a tetanic train (50 Hz, 0.50s) was administered when force had plateaued in order to calculate central-activation ratio (CAR). Next, the participant performed voluntary rapid, submaximal isometric (ballistic) contractions as quickly as possible with the target of 30-60% of peak MVIC force; a light diode box was used for visual feedback and verbal encouragement was given. Participants performed 3 trials, each consisting of 3 rapid contractions, and trials with peak force outside of the range of 30-60% of peak MVIC force were excluded from analysis. Thirty seconds of rest was given between trials. After a 1 min break, a tetanic train (50 Hz, 0.5s) and twitch stimulation were applied in quick succession while the participant remained fully relaxed.

The CAR was calculated as a rise in force when a tetanus stimulus was applied during a maximal voluntary contraction. If force did not rise, the CAR was determined to be 1. If force increased, the amount of central failure was calculated as:

$$CAR = \frac{Peak\ superimposed\ stimulated\ force\ (Nm)}{Peak\ \ voluntary\ force\ (Nm)}$$

Voluntary slope and Maximal Rate of Force Development (Max RFD) and Relaxation (Max RFR) were calculated for the ballistic contractions, and Stimulated Max RFD and RFR were calculated for the twitch contractions. For all contraction types, Max RFD and RFR were calculated by first normalizing the force values to peak force of the contraction, then the greatest instantaneous rate of force development or relaxation was determined; in other words, Max RFD and RFR occurred when the second derivative crossed zero. Slope of force development and relaxation were calculated for the ballistic contractions as the change in force and time from the start of force development to the peak force, or from peak force to the return of force to baseline. Slope of force development and relaxation were not determined for the twitch contractions. Figure 4 illustrates the analysis of Slope and Max RFD from a ballistic contraction.

Twitch contractions were used to examine twitch force and M-wave characteristics, or the muscle response to a single electrical stimulation. In addition to Stimulated Max RFD and RFR, time to peak force and half relaxation time ($T_{1/2}$) were calculated from twitch force. The M-wave duration was calculated as the length of time the TA muscle took to transmit the action potential, or duration of the negative peak plus the positive peak. The M-wave amplitude was calculated from the difference in mV between the negative and positive peak, while the M-wave negative peak was the

difference in mV between baseline and the negative peak. Twitch and M-wave characteristics were calculated from the average of three twitch contractions.

Statistics

A one-way ANOVA was used to compare the three groups for Hypotheses 1.1, 2.1, and 3.1. When significant main effects were found, Tukey's post-hoc analysis was performed to identify differences between groups. Data that were not normally distributed were tested with a Kruskal-Wallis test. To address Hypotheses 1.2 and 2.2, regression analysis was performed between FTC and potential mediators of slowed foot tap speed in all of the older participants. To address Hypothesis 3.2, regression analysis was performed between contractile speed and FTC in the young and older participants separately. A regression analysis was performed in order to examine the relationship between FTC and COV-ITI and physical function in all of the older participants for Hypotheses 4.1 and 4.2. Multiple regression analyses were used to determine which measures physical functions had the largest influence on FTC for the older participants. An alpha value of 0.05 was used to establish significance.

Results

Participants

Physical function and physical activity measures are summarized in Table 1. The HFO group was younger than the LFO. The SPPB-A differed across groups such that Young>HFO>LFO. For the SPPB, all Young scored a 12, eleven HFO scored a 12, and three HFO scored an 11. The LFO had SPPB scores ranging from 8-12 with a median value of 11. The three groups differed in usual walk speed, and post-hoc analysis revealed that LFO was slower than HFO and Young. The 400m brisk walking speed differed across groups such that Young>HFO>LFO; one HFO was excluded from analysis because his 400m walk speed was greater than two standard deviations above the mean speed for the HFO. For the SF-36, physical function, energy and fatigue, pain, and total score were examined and significant main effects between groups were found. Post-hoc analysis revealed that LFO scored worse than Young on the physical function questions. For their energy and fatigue score, the HFO>LFO>Young, with a lower value indicating greater fatigue. Post-hoc analysis of the pain scores indicated that LFO experienced greater pain, in general, than HFO. The overall composite score for the SF-36 was greater for HFO than LFO and Young. The groups did not differ in BMI or FES-I score.

On average, participants wore their physical activity monitors 14.3 hours per day (14.2±1.3 hrs for Young, 15.0± 1.1 for HFO, 13.8±1.0 for LFO), for 6.7 ±1.0 days. There was a significant main effect across groups for daily PA counts and MVPA; post hoc analyses indicated that LFO had fewer counts and both HFO and LFO had fewer minutes of MVPA than Young. All three groups spent a comparable percentage of wear

time in activity. One HFO woman was excluded from PA analysis because she was greater than two standard deviations about the HFO's mean for minutes of MVPA. She was not excluded from other calculations because she was not an outlier for any other metric.

Foot Tap Variability

Figure 3 shows examples of 10s of foot tap data from representative individuals in the Young (3A), HFO (3B) and LFO (3C) groups whose COV-ITI for the faster foot was close to the group mean. Group data for the FTT are presented in Table 2. For the faster foot, there were main effects for group for FTC and variability of tap timing (COV-ITI), with post hoc tests revealing slower tap speed in LFO compared with Young and HFO, and greater COV-ITI in Young than LFO ($p<0.05$). There were no differences between groups in FTT variables for the slower foot (second visit).

Muscle Activation

Figure 5 shows sample EMG data from the four muscles during the FTT. Muscle activation for each muscle during the FTT, relative to activation during the MVIC, showed a main effect between groups. Post-hoc analyses revealed that HFO and LFO had greater activation of their TA and MG than Young during the FTT, and HFO also had greater relative activation of the Sol and LG than Young ($p<0.05$, Table 3). The groups did not differ in average Act-R during the FTT, but Young had a higher correlation coefficient than HFO during the FTT, indicating greater coactivation ($p<0.05$). Figure 5,

panels B and C, show EMG data for a representative Young (5B) and HFO (5C) adults; participants whose correlation coefficients were close to the group means were selected.

Maximum EMG signals were recorded during MVIC performed on the Humac Norm dynamometer. There was a main effect for DF and PF force during the MVICs; post hoc analysis revealed that Young and HFO produced more force during DF trials than LFO, and Young produced greater PF force than LFO ($p<0.05$). Specifically, the Young adults produced an average PF force of 75.8 ± 22.8 Nm and DF force of 37.6 ± 10.3 Nm; HFO produced an average PF force of 56.4 ± 18.7 Nm and DF force of 36.7 ± 11.4 Nm; and LFO produced an average PF force of 56.9 ± 27.1 Nm and DF force of 26.8 ± 8.7 Nm. While MVIC force varied by group, the EMG amplitude during the MVICs, which were used for normalization, did not differ between the groups for any of the muscles ($p>0.05$).

No participants in Young or HFO showed central activation failure, thus they were able to fully activate their TA muscle; CAR values were 1.00 ± 0.00 for Young (n=14) and HFO (n=14). Two individuals in LFO had central activation failure, with CAR values of 0.90 and 0.92; the overall group average for LFO was 0.99±0.04 (n=12). Peak MVC torque recorded on the DF apparatus did not differ between groups and was 43.4 ± 11.7 (n=18), 35.8 ± 9.1 (n=13), and 35.2 ± 7.0 Nm (n=14) for Young, HFO, and LFO respectively.

Contractile Speed

For the voluntary ballistic contractions, the only measure that differed between groups was the slope of force development, with post-hoc analysis revealing that Young

had a faster slope of force development than LFO (Table 4). Force produced during these contractions did not differ across groups.

Twitch and M-wave characteristics are reported for a subset of participants due to difficulties during data collection, Table 5. Peak twitch force and time to peak force were the only twitch characteristics that differed between groups. Post-hoc analyses revealed that HFO had a lower peak twitch force than Young, and that LFO had a longer time to peak force than Young ($p<0.05$). There were significant differences between the groups for the M-wave properties. Post-hoc analyses revealed that Young had a greater M-wave amplitude than HFO and LFO, and a greater M-wave negative peak than HFO ($p<0.05$).

Twitch and M-wave data were excluded if stimulation was not done (n=2), or if twitch force was less than Nm (n =11). One HFO male was excluded from the calculations of voluntary and stimulated contractile speeds. The data from this participant were greater than 2 standard deviations above the mean DF force, slope of force development and relaxation for the HFO group. However, these data are included for all other analyses because the FTC for each leg and each of the functional measures were less than two standard deviations above the average for the HFO group. One possible explanation for the higher DF force and faster contractile speeds in this individual is that he is a drummer, an activity that trains the DF muscles.

Associations between Foot Tap Characteristics and Potential Moderators

Associations between FTC and variability of tapping (COV-ITI), coactivation, and muscle contractile speed were examined for the older participants and data are presented in Table 6. The FTC of the faster leg was not correlated with COV-ITI during

the same trial (p=0.517, r^2=0.016), nor was FTC of the slower leg correlated with COV-ITI in the older participants (Table 6).

Within the older participants, there was not an association between FTC and muscle activation, Act-R, for the same trial (Figure 6A). Foot tap count and the correlation coefficient during the same FTT were negatively associated (r^2=0.273, p=0.005) in the older participants (Figure 6B). The Act-R and correlation coefficient were not related in the older participants (r^2=0.061, p=0.214).

There was no significant relationship between FTC and slope of force development and relaxation during the ballistic contraction for the older participants (Figure 7 B and D). However, there was a relationship between FTC and Max RFD and RFR in the older participants (Figure 8 B and C). Foot Tap Count and MVIC force were not associated in the older participants (p=0.387). The Young adults' FTC was strongly associated with slopes of force development (r^2=0.523, p <0.001) and relaxation (r^2=0.394, p<0.005) during the ballistic contractions, as seen in Figure 7 A and C. The Young adults' FTC was also positively associated with Max RFD (r^2=0.245, p=0.037, Figure 8A) and with MVIC force (r^2=0.476, p=0.001).

Associations between Foot Tap Count and physical function in the older participants were examined and results are presented in Table 7. Foot tap count from the faster leg was positively correlated with SPPB-A score (r^2=0.329, p=0.001, Figure 9A), , and MVPA (r^2=0.182, p=0.023, Figure 9C) in the older participants. Foot tap count of the faster leg was not correlated with 400m brisk (p=0.176, Figure 9B) or usual walking speed (p=0.094). Foot tap count from the faster leg was negatively correlated with age for the older participants (r^2=0.277, p=0.004, Figure 9D). Foot tap count of the slower

leg from visit 2 was positively correlated with MVPA (r^2=0.158, p=0.036), but not with SPPB-A (p=0.084), usual walk speed (p=0.633), 400m walk speed (p=0.108), or age (p=0.441) in the older participants.

The COV-ITI of the faster foot was not associated with any measures of physical function or age (Table 8). The COV-ITI of the slower foot was positively associated with SPPB-A score (r^2=0.181, p=0.024) and usual walking speed (r^2=0.202, p=0.017), but not with 400m walk speed (p=0.212), MVPA (p=0.887) or age (0.248).

A step-wise multiple regression analysis of the impact of age + SPPB-A score on FTC of the faster foot was significant (r^2=0.413, p=0.0013), but only SPPB-A contributed significantly to this association (p=0.024). A multiple regression analysis was also run to examine the impact of age, SPPB-A score, MVPA, and 400m walk speed on FTC of the faster foot. The regression was significant (r^2=0.482, p=0.0034) with all four variables, but only SPPB-A contributed significantly (p=0.023).

Discussion

The main purpose of this study was to determine whether increased performance variability (COV-ITI), greater muscle coactivation, or slower muscle contractile properties are associated with slowed foot tap speed in older adults (Figure 1A). Overall, lower FTC in older adults was related to greater muscle coactivation, determined by correlation analysis of the EMG signals, and slower Max RFD and Max RFR. However, FTC was not related to COV-ITI in older adults (Figure 1B). Higher FTC was associated with faster voluntary contractile speeds in Young adults (Figure 1C). The secondary purpose was to determine if FTC and COV-ITI were related to physical function in older adults. The data showed that FTC of the faster foot was related to SPPB-A score, a composite measure of physical function, in older adults. Contrary to what was hypothesized, the COV-ITI of the FTT on the slower leg was positively associated with SPPB-A and usual walking speed, with a lower COV-ITI related to worse physical function.

Foot Tap Variability

Hypothesis 1.1 was not supported by the data, as Young adults had a greater COV-ITI than LFO, but COV-ITI did not differ between Young and HFO. The COV-ITI was not related to FTC in the fastest trial from either the faster or the slower foot in older adults. This result suggests that variability in performance of the FTT does not limit foot-tapping speed in older adults. This result is not in agreement with findings from other studies which found greater variability with age, but those studies were examining variability while tapping to a set metronome speed (71, 76). The FTT does not supply a

rhythm for participants to match but rather allows participants to employ whatever tapping method yields the best results, and greater tapping variability did not negatively affect performance for this metric.

A smaller COV-ITI score in the LFO group could indicate a more diseased state as a reduction in movement variability has been associated with diseased states (18). Findings from our study support the idea that there is reduced variability in a diseased state as COV-ITI of the slower foot was positively related to SPPB-A and usual walking speed. These data suggest that those with lower physical function tended to have less variability while tapping their slower foot. Thus a smaller COV-ITI during the FTT could indicate a movement impairment that is not seen in healthy older adults.

Muscle Activation

Muscle coactivation was hypothesized to be greater and to negatively affect foot tap speed in older adults. Overall, muscle activation was greater in HFO than Young for each muscle, and greater in LFO than Young for the TA and MG muscles. To calculate muscle activation, EMG data during the FTT were normalized to muscle activation during MVICs. The Act-R, a ratio indicating the relative magnitude of DF:PF muscle activation during the whole 10s trial, did not differ between the groups. The Act-R was normalized to the number of taps to remove the possibility of a bias based on FTC. The HFO had the closest Act-R value to one, indicating that their PF muscles were more active relative to their TA muscle; one possible explanation for the greater relative PF activity is that HFO had greater PF activation between each tap, potentially helping the foot return to the ground. Figure 5 helps to visually support this hypothesis, showing a

HFO individual with PF activity between each TA burst and an Act-R of 1.24 (5C). The EMG data in Figure 5B shows a Young adult who had smaller PF activity between taps and an Act-R of 2.21, indicating greater DF activation relative to PF activation. The Act-R per tap does not indicate how much the TA and PF muscle activity overlapped, but a correlation analysis does.

Here, EMG correlation analysis indicated how much the timing of the TA and Sol signals were in agreement during the FTT; a larger correlation coefficient indicates greater coactivation. Relative to EMG collected during an MVIC, the Sol was the most active PF muscle during the FTT (Table 3). Previous studies have also shown that the Sol is more active during rapid DF tasks than the MG and LG (23), and that the Sol is relatively more active when the knee is bent than straight (69). Because of this, the Sol's EMG activity was selected for the correlation analysis with the TA. A correlation coefficient of 1 indicates that the muscles were active at the same time with the same relative shape, while a value closer to 0 indicates that the EMG signals did not align. It was hypothesized that a smaller correlation coefficient would be more beneficial during the FTT because it would indicate that the muscle groups were not opposing each other, or rather, coactivation was less.

Young adults were hypothesized to have less coactivation than HFO and LFO, and in older adults, greater coactivation was hypothesized to be associated with a lower FTC. The data do not fully support this hypothesis. Young had a greater correlation coefficient than HFO, but there was no difference in the correlation coefficient between Young and LFO. In the older adults, there was a negative association between the correlation coefficient and FTC (Figure 6B). It appears that it is more advantageous in

older adults to have a smaller amount of coactivation, or overlap in TA and Sol activity during the FTT, consistent with the original hypothesis. However, in Young adults, greater coactivation was not associated with a lower FTC. It is possible that the Young adults had compensatory mechanisms to deal with the greater coactivation, such as producing a greater amount of DF force on each tap. In Young adults, coactivation appears to play a minimal role in determining FTC, while muscle properties like strength and speed have a stronger association with FTC.

Notably, there was PF activity between the foot taps in some individuals, suggesting that some individuals are employing a tapping strategy where the foot is being actively returned to the ground (Figure 5C). It is possible that those with a lower correlation coefficient are activating the PF muscles to return the foot to the ground during the FTT, and those with a higher correlation coefficient are activating their PF throughout the FTT to stabilize their foot. Interestingly, there was not a relationship between Act-R and the correlation coefficient in a given trial in older adults, suggesting that the older adults are employing varying muscle activation patterns to tap as fast as possible. Overall, the negative association between FTC and the correlation coefficient supports the hypothesis that greater coactivation limits FTC in older adults.

Contractile Speed

The third hypothesis addressed the relationship between contractile speed of the DF muscles and FTC in the slower leg in young and older adults during voluntary ballistic contractions and stimulated twitch contractions. Ballistic contractions with the target of ~40% MVIC force have been used previously in the literature to quantify the

maximum voluntary RFD (29). Ballistic contractions of the DF were chosen for this study because they mimic the contractions necessary for the FTT; both are submaximal tasks that require rapid activation and deactivation of the DF muscles and modulation of motor unit recruitment. However, one major difference is that the ballistic contractions are singular and isometric while the FTT employs dynamic, repeated contractions through a limited range of motion.

During the voluntary ballistic contractions, the only difference between the groups was that Young adults had a greater slope of force development than the LFO. For the stimulated twitch contractions presented on a subset of participants, Young adults had a faster time to peak force than LFO, and Max RFD was approaching significance between the groups (Table 5). Time to peak twitch force is dependent on peak force and is not necessarily indicative of contraction speed. However, Young and LFO had similar peak twitch forces and LFO had a slower time to peak; therefore, slower time to peak does indicate slowing of stimulated force development in LFO.

The LFO had slower rates of force development during both their voluntary and stimulated contractions when compared with the Young adults, indicating slowing of force development in their DF muscles. The LFO also had a lower FTC than Young. These relationships were not seen in HFO, suggesting that greater mobility impairments may be related to slowed DF force development speed and FTC. Kent-Braun et al. did not see an impairment in central rate of force development during ballistic contractions in older adults but did see a difference in FTC (29). One possible reason for the difference between the results of this thesis and Kent-Braun's study is that they were expressing RFD as a measure of central function and normalized the voluntary RFD to the

stimulated RFD, which was not done here. It has been suggested that the FTT can be used as a measure of central function (29, 59), partially because slowing is seen in diseases affecting the CNS; however, this thesis did not compare FTC to other measures of central function, like central RFD.

In the older adults, FTC of the slower leg was correlated with the Max RFD and Max RFR during the ballistic contractions, but not with the slopes of force development and relaxation. This suggests that the maximum, instantaneous rate at which the muscle is able to contract and relax is related to foot tap speed in older adults, but not the speed of the overall movement. It is possible that the FTT, a dynamic repetitive task, and the ballistic contractions, a single isometric contraction, were eliciting different responses in the DF muscles of the older adults. This difference in contraction type could potentially explain why Max RFD and RFR were related to FTC in older adults but the slope of the full ballistic contraction was not.

Moderate correlations between FTC and slope of force development and relaxation were observed in Young adults. The Max RFD was also positively correlated with FTC in the Young adults. These relationships suggest that contractile speed during voluntary contractions controls how quickly young adults can perform the FTT. Differences in muscle contractile speed appear to explain a large amount of the variations in FTC in the younger adults.

The Young adults produced greater force during maximal DF and PF than LFO. Peak torque production was correlated with performance on the FTT in the young adults but not the older adults, indicating that strength impacts FTT performance in young adults but not older adults. Tomita et al. suggested that one of the advantages of the FTT

is that participants are not instructed to go through their full range of motion while tapping and are only instructed to go as fast as possible (76). By removing the restriction of using the full range of motion, the FTT may be able to reduce the impact strength has on performance in older adults. This hypothesis is supported by the observation that FTC and strength were not associated in the older participants. Future studies should examine the foot's excursion during the FTT to determine what percent of the range of motion is employed and whether this impacts FTC. Toe excursion was measured for the FTT, though the data are not presented.

The M-wave characteristics of the muscle were also determined during the twitch stimulation, however, it is hard to draw conclusions about the muscle properties from this data. The M-wave is the EMG response to a single stimulation and generally indicates the excitability of the muscle (57). However, M-wave amplitude and duration will vary based on adiposity and distance between electrodes, making it difficult to compare between individuals (57, 79). Our results suggest that HFO had reduced excitability of the TA muscle compared to Young, but this could be due, in part, to the smaller twitch force response in HFO than Young.

Foot Tap Test and Physical Function

The Young and HFO had a faster FTC than LFO, indicating an impairment in foot tapping speed with age and mobility function. In the older adults, the FTC of the faster foot was positively associated with SPPB-A score, providing support to hypothesis 4. Based on the finding that FTC of the slower foot was only related to MVPA, it appears that FTC of the faster foot is a better predictor of physical function in older adults. It is possible that the older adults in this study were healthy enough that any reductions in

function of the slower leg, such as reduced DF during swing phase, could be compensated for by the faster leg during measures of physical function.

The COV-ITI of the slower foot during the FTT was positively correlated with SPPB-A and usual walking speed in the older adults, but the COV-ITI of the faster foot was not. It was hypothesized that greater variability would be indicative of worse function, but the data does not support this hypothesis. Rather, our results suggested that a lower COV-ITI could be indicative of a diseased state (18).

Notably, FTC of the faster foot was related to physical function while COV-ITI of the slower foot was related to physical function in the other adults. This study measured the FTC on both legs because FTC of the faster, dominate foot is typically reported in the literature but mobility could be restricted by the more impaired limb (29, 59, 76). This study was not aimed at comparing the two legs but rather was aimed at understanding why a slowing of foot tapping speed might occur. Future studies may address the differences in the faster and slower leg and explore the relationship between function and asymmetry during the FTT.

Physical Function

The older adults in this study were healthy with minimal limitations to their physical function. All of the older participants had a usual walking speed above 0.8 $m \cdot s^{-1}$, which has been proposed as a threshold for identifying individuals with mobility impairments (72). Another common measure of physical function is the SPPB. The older adults in this study scored between an 8-12 on the SPPB. A score of 12 on the SPPB indicates no functional impairment, and a score between 8-10 indicates mild to

moderate impairment in older adults (15). The SPPB-A was used to separate the older adults because it reduces the ceiling effect of the SPPB and is a more sensitive measure of function (70). To the best of our knowledge, there are no set criteria for dividing older adults based on the SPPB-A. The original paper by Simonsick et al. reported a mode range of 2.33- 2.66 on the SPPB-A for women and a mode range of 2.66-3 for men (70). The median value for the older women in our study, 2.47, was within the range reported by Simonsick, and the median value for the older men in our study, 2.59, was slightly below the range reported by Simonsick (70). The FTC was sensitive enough to distinguish between Young and LFO and was related to a composite measure of physical function in the healthy older cohort. One advantage of the FTT over usual walking speed and SPPB is that individuals with limited mobility can perform it. However, in a study of healthy older adults, by itself, the FTT is not indicative of current mobility function.

The participants in this study were moderately active. The HFO and Young group did not differ in counts, but Young had a greater amount of MVPA than HFO and LFO. The percent wear time spent in activity was comparable across groups, suggesting that the older adults remained active but at a lower intensity than the young adults. On average, the older adults in both groups were meeting PA guidelines of 150 minutes of MVPA a week (1). The FTC and MVPA were related in the older adults, suggesting speed of rapid repetitive activation is maintained with physical activity. Although the older adults in this study were active, their physical function was still reduced compared to the young adults and reduced function was correlated with foot tapping speed.

According to the SF-36, Young adults scored the lowest in the energy/fatigue category, contributing to their lower SF-36 score than HFO. When compared to

normative values for the SF-36, Young scored slightly below their age's mean for energy, LFO scored slightly above their age's mean, and HFO were considerably above the mean for their age (4). All three groups scored higher than their age's mean for pain and physical function, contributing to the idea that this is a healthy group of individuals. The HFO had a higher overall composite score of the SF-36 than LFO, due in part to the HFO's higher scores on energy/fatigue, pain, and physical function. Overall, the quality of life in HFO was higher than LFO based on the results of the SF-36. Notably, there was no difference in FES-I score between groups, indicating that the groups had comparable fears of falling.

The relationship between FTC and physical function in young adults was not examined in this study, primarily because the Young adults were not expected to have any functional impairments. The FTT can indicate changes in function, but it is unlikely that it is related to function in young adults who have a greater number of compensatory mechanisms than older adults. Likewise, the associations between FTC and potential moderators of speed were not studied in Young and old combined.

Limitations

A limitation of this study was that the participants were relatively active and healthy. Participants were, on average, meeting physical activity guidelines of >150 min of MVPA a week. The Young adults were also more active than LFO and HFO, making it harder to remove the impact of aging on function. The older adults in this study were relatively healthy, with all participants having a gait speed greater than 0.8 $m \cdot s^{-1}$ and an SPPB ≥8. Having older adults who were frailer have led to different results, such as a

larger range in function. This study was also a cross-sectional, making it impossible to test if the FTT can predict future mobility impairments in older adults. This also limits the exploration of causal relationships between FTC and potential moderators of slow speed.

Conclusion

Overall, greater muscle coactivation during the FTT and slowed force development in the DF muscles negatively affects the speed with which older adults can perform rapid repetitive foot tapping. Foot tap speed, particularly of the faster foot, and foot tap variability, particularly of the slower foot, is related to physical function in healthy to mildly mobility-impaired older adults. In young adults, the largest limiting factors for rapid repetitive foot tapping is the contractile speed and strength of the DF muscles.

CHAPTER 5

SUMMARY

With age, many changes occur within the neuromuscular system which can negatively affect muscle and mobility function. Among other things, with age there is slowed activation and deactivation of the dorsiflexor muscle. However, the dorsiflexor muscles typically are less affected by declines in physical activity associated with aging compared with other muscle groups, such as the knee extensors and plantar flexors. Slowed activation and deactivation of the dorsiflexor muscles with age is evident during rapid tapping tasks, such as the Foot Tap Test (FTT). The FTT is an easy, potentially useful tool for monitoring changes in dorsiflexion function in older adults. This study suggests that declines in foot tap speed with age could be caused by greater muscle coactivation during the FTT and reduced rate of force development of the dorsiflexor muscles. Declines in the speed of dorsiflexor activation becomes vitally important in individuals with large mobility impairments; specifically because impaired dorsiflexion during gait can increase the risk of falling. The FTT is potentially better at tracking functional changes in a population with mobility impairment and reduced dorsiflexor function. However, even among the healthy older adults in this study, slower foot tap speed was related to reduced physical function, which shows promise for predicting future changes in mobility function (28). Simple tests to measure mobility function, like the FTT and gait speed, may aid clinicians in tracking the mobility of their patients and identifying individuals at risk of future mobility impairments. The FTT could also aid in identifying individuals in need of training interventions to prevent or delay the onset of mobility impairment.

Table 1. Participant Characteristics

	Young (n=18)	HFO (n=14)	LFO (n=14)	p value, main effect
Age, years	25.0 (3.1)	70.9 (3.1) *	76.0 (5.0)* ‡	<0.001
BMI, kg / m^2	23.1 (2.6)	24.4 (3.8)	25.4 (2.6)	0.101
Physical Function				
SPPB-A	3.11 (0.35)	2.78 (0.15) *	2.24 (0.28) *‡	<0.001
Usual walk speed, 6m, m·s^{-1}	1.46 (0.28)	1.40 (0.16)	1.11 (0.14)* ‡	<0.001
400m brisk walk speed, m·s^{-1}	1.92 (0.16)	1.68 (0.15) *	1.53 (0.11) *‡	<0.001
FES-I	17.1 (1.8)	18.1 (3.1)	18.9 (2.2)	0.097
SF-36, sum	656.2 (81.8)	740.3 (48.2) *	667.1 (76.2) ‡	<0.001
SF-36, physical function score	98.9 (2.1)	95.4 (5.7)	89.6 (6.9) *	<0.001
SF-36, Energy/fatigue score	56.9 (13.2)	85.0 (8.8) *	67.9 (13.4) *‡	<0.001
SF-36, Pain score	90.6 (16.6)	94.3 (6.5)	82.5 (13.3) ‡	0.031
Physical Activity				
PA counts/1000·day^{-1}	295.8 (99.3)	241.9 (127.0)	187.5 (46.8)*	0.011
MVPA, min per week	301.4 (108.8)	173.4 (140.6)*	173.2 (84.8)*	0.002
% of wear time in activity	29.7 (7.3)	33.7 (8.2)	29.3 (7.5)	0.265

Participant characteristics for Young, Higher Functioning Older (HFO) and Lower Functioning Older (LFO) adults. Number of participants per group indicated as (n). Values are mean ±SD; * different than young, ‡ different than HFO. Body Mass Index (BMI) and Fall Efficacy Scale-International (FES-I) did not differ between groups. Physical Activity (PA) and minutes of Moderate to Vigorous Physical Activity (MVPA) were greater in Young than LFO. The Short Form-36 (SF-36) asked about overall health of the participants and included specific questions for fatigue and pain.

Table 2: Outcomes of the Foot Tap Test (FTT) of the Faster and Slower Foot

	Young (n=18)	HFO (n=14)	LFO (n=14)	p value, main effect
FTT faster foot				
Count	54.4 (7.5)	53.1 (5.7)	45.9 (7.0) *‡	0.003
ITI, ms	0.187 (0.022)	0.190 (0.022)	0.223 (0.035) *‡	<0.001
COV-ITI, %	20.5 (8.1)	18.7 (7.6)	12.3 (5.9) *	0.009
FTT slower foot				
Count	51.3 (8.0)	48.3 (7.3)	44.9 (6.8)	0.063
ITI, ms	0.200 (0.031)	0.212 (0.033)	0.229 (0.036)	0.060
COV-ITI, %	19.8 (8.6)	20.7 (7.6)	16.4 (6.6)	0.310

Data collected on Young, Higher Functioning Older (HFO) and Lower Functioning Older (LFO) adults during the FTT, including the intertap-interval (ITI) and coefficient of variability of the ITI (COV-ITI). Foot tap data from the slower foot were collected on the second visit, simultaneously with EMG and motion capture data. Number of participants per group indicated as (n). Values are mean ±SD; * different than young ‡ different than HFO.

Table 3. Electromyography (EMG) data during the Foot Tap Test from the Slower Foot

	Young (n=18)	HFO (n=13)	LFO (n=14)	p value, main effect
TA EMG, %·tap^{-1}	0.444 (0.186)	0.655 (0.173) *	0.700 (0.238) *	0.002
Sol EMG, %·tap^{-1}	0.380 (0.190)	0.856 (0.600) *	0.625 (0.376)	0.008
MG EMG, %·tap^{-1}	0.129 (0.096)	0.302 (0.165) *	0.307 (0.218) *	0.004
LG EMG, %·tap^{-1}	0.255 (0.144)	0.597 (0.350) *	0.449 (0.299)	0.004
Activation-ratio	1.92 (0.69)	1.45 (1.04)	1.94 (1.10)	0.307
Correlation coefficient	0.568 (0.209)	0.321 (0.129) *	0.437 (0.159)	0.001

Electromyography (EMG) collected during the Foot Tap Test for the tibialis anterior (TA), soleus (Sol), medial gastrocnemius (MG) and lateral gastrocnemius (LG) muscles in Young, Higher Functioning Older (HFO) and Lower Functioning Older (LFO) adults. The EMG data is normalized to EMG activity during a maximal voluntary contraction and to the number of foot taps. Number of participants per group indicated as (n). Values are means ±SD; * different than young ǂ different than HFO. Tukey's PostHoc run to test for significance.

Table 4. Voluntary Contractile Speed of the Slower Foot during Ballistic Contractions

	Young (n=18)	HFO (n=13)	LFO (n=14)	p value, main effect
Force, % MVIC	44.3 (6.0)	46.9 (6.26)	44.8 (5.8)	0.461
Slope of force development, Nm·ms^{-1}	0.137 (0.039)	0.117 (0.035)	0.098 (0.031) *	0.013
Slope of force relaxation, Nm·ms^{-1}	0.115 (0.040)	0.112 (0.039)	0.093 (0.043)	0.259
Max RFD, %peak force·s^{-1}	1.080 (0.190)	1.037 (0.174)	0.998 (0.139)	0.412
Max RFR, %peak force·s^{-1}	-1.004 (0.170)	-1.012 (0.188)	-0.961 (0.218)	0.753

Dorsiflexor contractile speed collected during voluntary ballistic contractions to ~45% of Maximal Voluntary Isometric Contractile (MVIC) force in Young, Higher Functioning Older (HFO) and Lower Functioning Older (LFO) adults. The dorsiflexor muscles were tested for contractile properties, including Slope of force development and relaxation, and Maximal Rate of Force Development (Max RFD) and Relaxation (Max RFR). Number of participants per group indicated as (n). Values are means ±SD; * different than young ǂ different than HFO. Tukey's PostHoc run to test for significance.

Table 5. Dorsiflexion Contractile Characteristics of Slower Leg during Stimulated Twitch Contractions

	Young (n=13)	HFO (n=12)	LFO (n=6)	p value, main effect
M-wave amp, peak to peak, mV	9.20 (1.43)	7.19 (2.21) *	6.90 (1.18) *	0.009
M-wave duration, ms	38.5 (3.2)	34.4 (5.2) *	38.4 (2.1) ǂ	0.046
M-wave negative peak, mV	5.31 (0.94)	3.97 (1.28) *	4.13 (0.69)	0.009
Peak Twitch force, Nm	2.76 (0.77)	1.95 (0.73) *	2.61 (0.39)	0.021
Max RFD, %peak·s^{-1}	2.26 (0.31)	2.33 (0.47)	1.88 (0.25)	0.056
Max RFR, %peak·s^{-1}	-1.11 (0.25)	-1.18 (0.53)	-0.85 (0.11)	0.225
Time to peak force, ms	93.5 (11.3)	99.7 (16.2)	111.8 (15.1) *	0.045
$T_{1/2}$, ms	71.9 (16.8)	84.0 (31.1)	95.2 (7.8)	0.115

Twitch and M-wave data from a subset of participants in the Young, Higher Functioning Older (HFO) and Lower Functioning Older (LFO) groups. Twitch contractile characteristics include maximal rate of force development (Max RFD) and relaxation (Max RFR), time to peak force, and time until half relaxation ($T_{1/2}$). Number of participants per group indicated as (n). Values are means ±SD; * different than young ǂ different than HFO. Tukey's PostHoc run to test for significance.

Table 6. Regression Analyses for Potential Moderators of Foot Tap Count (FTC) of the Slower Leg in Young and Older Adults

	FTC in older adults		FTC in young adults	
	r^2	p value	r^2	p value
Foot Tap Variability				
COV-ITI slower foot	0.001	0.855	0.024	0.541
Muscle coactivation				
Act-R	0.024	0.442		
Correlation coefficient	**0.274**	**0.005**	0.087	0.236
Ballistic contractions				
% MVIC force	0.090	0.128	0.024	0.540
Slope of force development	0.117	0.081	**0.523**	**0.001**
Slope of force relaxation	0.135	0.059	**0.394**	**0.005**
Max RFD	**0.345**	**0.001**	**0.245**	**0.037**
Max RFR	**0.162**	**0.038**	0.032	0.476
MVIC force, $N \cdot m^{-1}$	0.173	0.387	**0.476**	**0.002**

Foot Tap Count and COV-ITI for the same trial was compared for and slower foot in older adults. Coactivation was determine based on the correlation coefficient and relative muscle activation was determined by the activation ratio (Act-R). Foot Tap Count was also compared with force of ballistic contractions, which were ~ 45% of peak Maximal Voluntary Isometric Contraction (MVIC) force. Foot tap count was compared with dorsiflexor contractile properties, including Slope of force development and relaxation, and maximal rate of force development (Max RFD) and relaxation (Max RFR). Bolded lines indicate regressions with $p<0.05$.

Table 7. Regression Analyses for Foot Tap Count (FTC) and Measures of Physical Function in Older Adults

	FTC of faster foot vs function in older adults		FTC of slower foot vs function in older adults	
	r^2	p value	r^2	p value
SPPB-A	**0.329**	**0.001**	0.111	0.084
Usual walking speed	0.104	0.094	0.009	0.633
400m walking speed	0.072	0.176	0.096	0.108
MVPA	**0.158**	**0.040**	0.143	0.065
PA counts	**0.211**	**0.014**	0.117	0.075
age	**0.277**	**0.004**	0.023	0.441

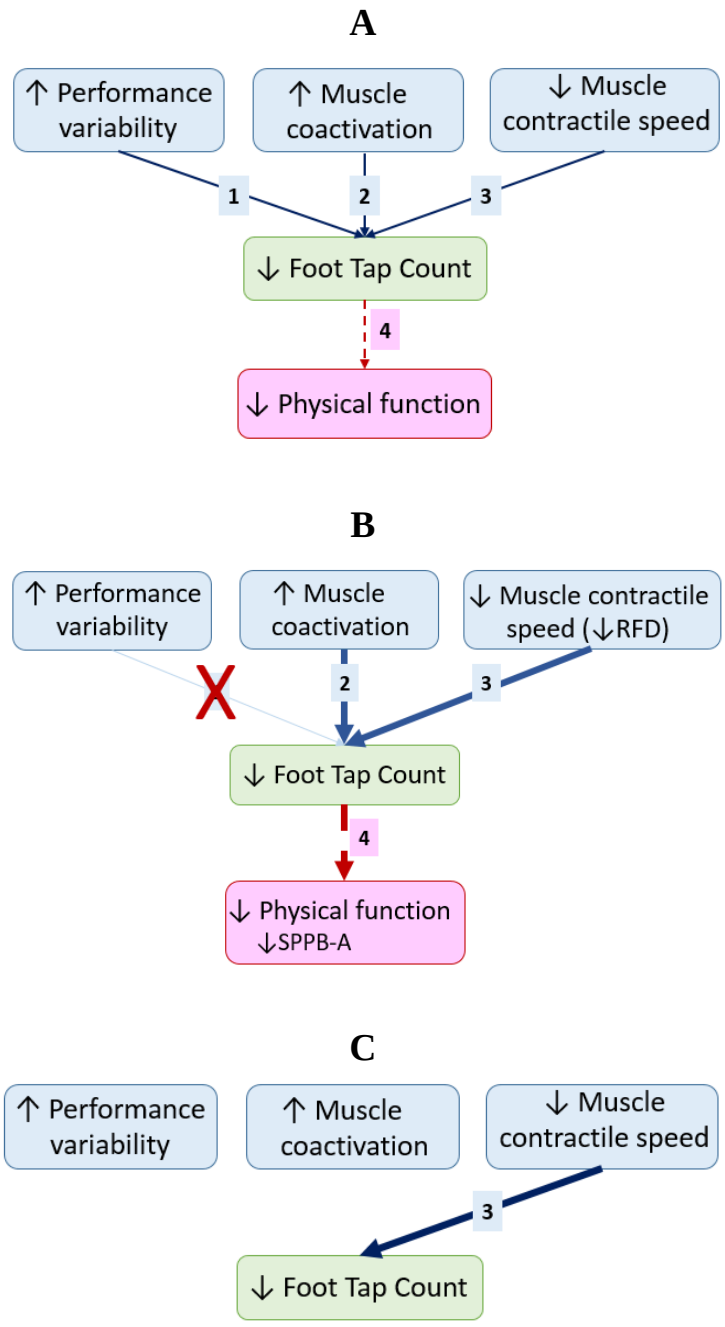
Foot Tap Count from the faster and slower feet (visit 2) in older adults compared with measures of physical function. Functional measures included the advance Short Physical Performance Battery (SPPB-A), usual walking speed, 400m walking speed, minutes of Moderate to Vigorous Physical Activity (MVPA) a week, and age. Bolded lines indicate regressions with $p<0.05$.

Table 8: Regression Analyses for Variability of the Intertap Interval (COV-ITI) during the Foot Tap Test and Measures of Physical Function in Older Adults

	COV-ITI of faster foot vs function in older adults		COV-ITI of slower foot vs function in older adults	
	r^2	p value	r^2	p value
SPPB-A	0.077	0.153	**0.181**	**0.024**
Usual walking speed	0.110	0.084	**0.202**	**0.017**
400m walking speed	0.001	0.894	0.029	0.212
MVPA	**0.166**	**0.035**	0.001	0.861
PA counts	0.036	0.334	0.011	0.590
age	0.002	0.815	0.051	0.248

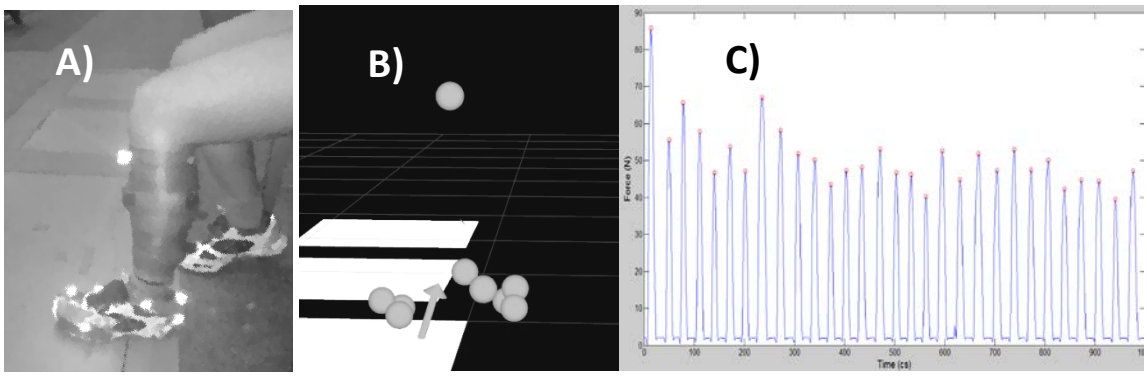
Variability of tapping (COV-ITI) during the Foot Tap Test from the faster and slower feet (visit 2) in older adults compared with measures of physical function. Functional measures included the advance Short Physical Performance Battery (SPPB-A), usual walking speed, 400m walking speed, minutes of Moderate to Vigorous Physical Activity (MVPA) a week, and age. Bolded lines indicate regressions with $p<0.05$.

Figure 1. Summary of Primary Hypotheses and Results



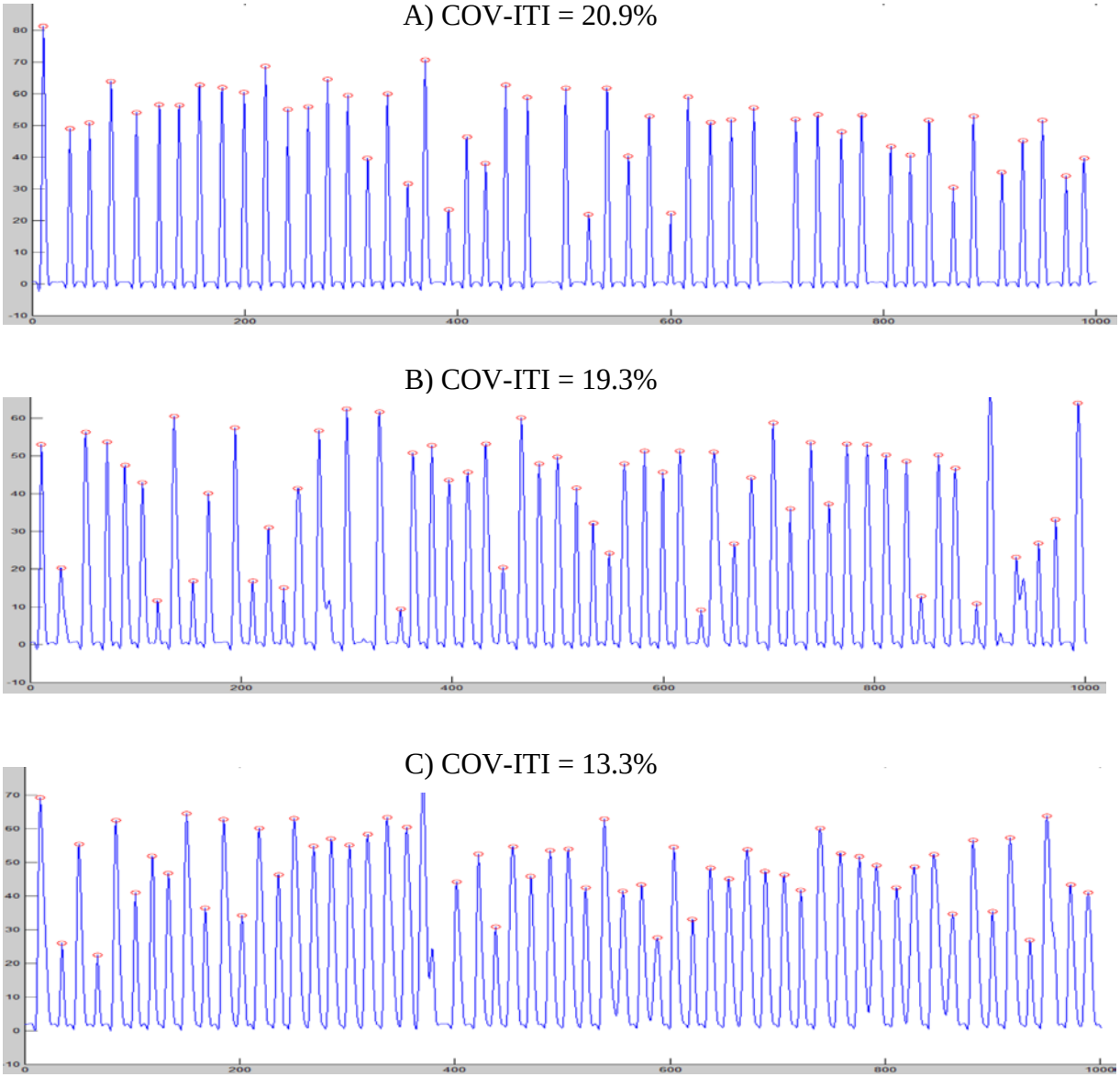
A) Summary schematic of the hypotheses for older adults. Solid arrows indicate a hypothesized moderator of Foot Tap Count (FTC) and the dotted arrow indicates a predictive relationship between FTC and function. The numbers in each figure indicate the corresponding hypothesis. ***B)*** Summary schematic of the results in older adults. ***C)*** Summary schematic of the results in young adults. Thicker lines in panels B and C indicate supported hypotheses. X indicates unsupported hypothesis.

Figure 2. Experimental Arrangement for the Foot Tap Test and Sample Force Output



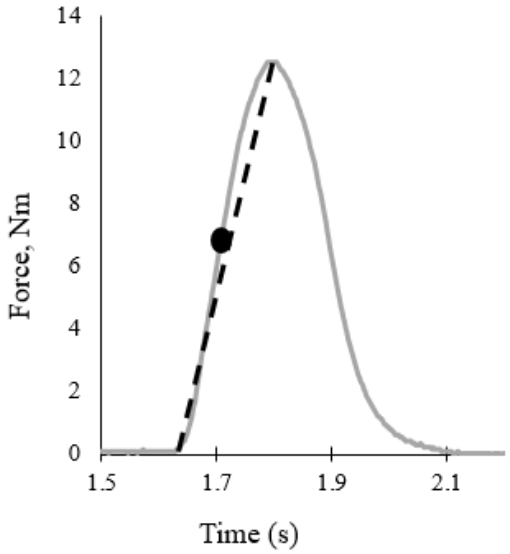
A) Placement of foot for the FTT. Participants were seated so the ball of the foot was on the force platform and the heel was off the force platform; retroreflective markers were place on specific anatomical locations to track foot movement; ***B)*** Retroreflective markers viewed in Qualysis; the arrow represents the net ground reaction force applied to the force platform; ***C)*** Sample force tracing from the FTT; local maxima are identified with a circle.

Figure 3. Examples of Force Platform Fata from the Foot Tap Test



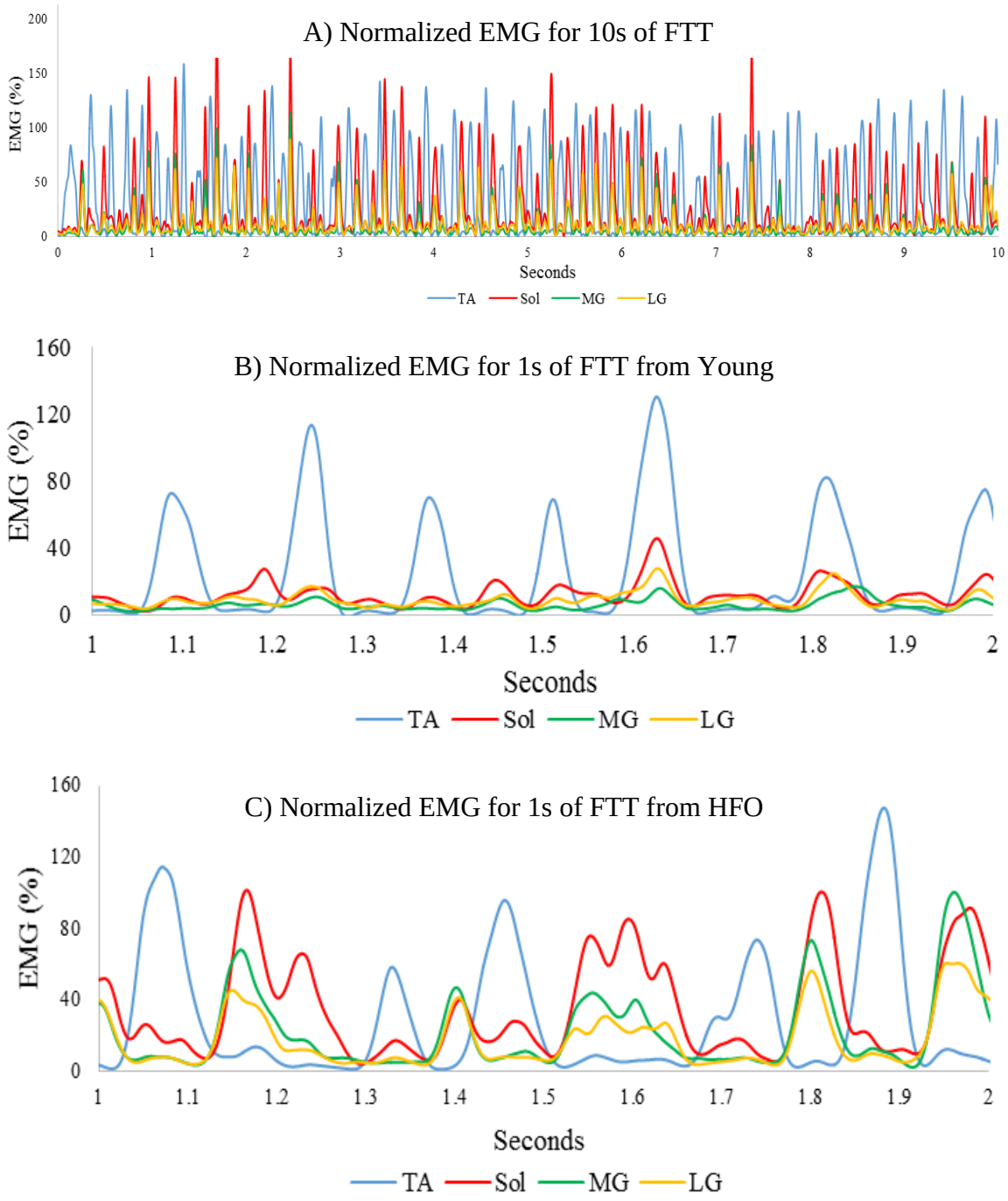
An example of foot tap data recorded on the force platform from ***A)*** Young, ***B)*** Higher functioning older, and ***C)*** Lower functioning older adults. A larger coefficient of variation of the intertap-interval (COV-ITI) indicates greater variability in foot tap timing. Examples were selected to be close to each group's average COV-ITI.

Figure 4: Example of Voluntary Ballistic Contraction and Calculation of Slope and Maximum Rate of Force Development (Max RFD)



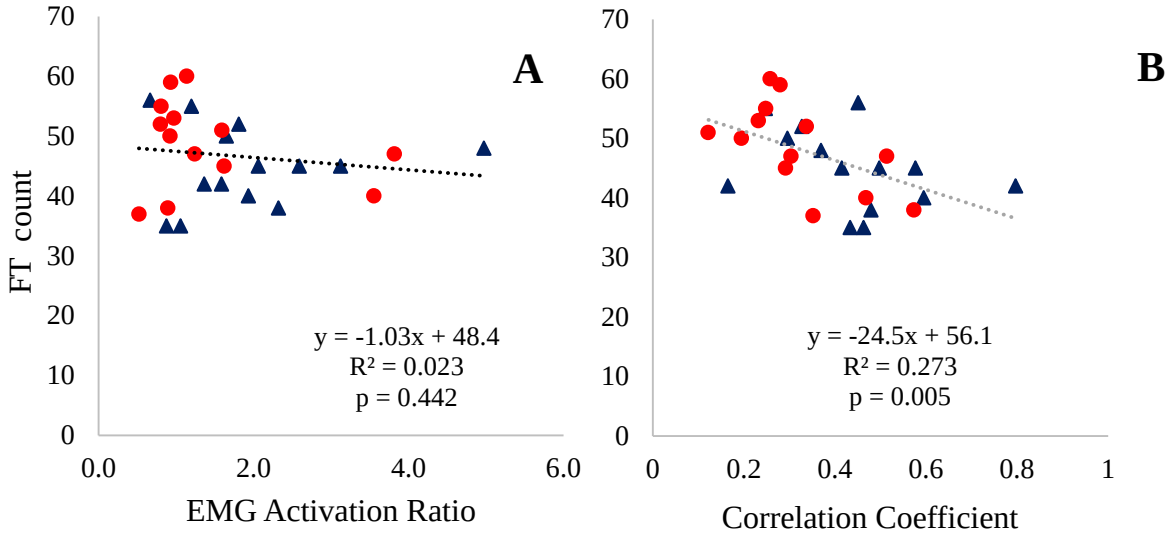
An example voluntary ballistic dorsiflexion contraction is shown in gray. The Max RFD, shown here by a black dot, is the greatest instantaneous change in force. The slope of force development, shown here as a dotted line, was calculated as the change in force from baseline divided by the change in time from the beginning of the force rise above baseline to peak force.

Figure 5: Examples of Normalized Electromyography (EMG) Signal during the Foot Tap Test (FTT)



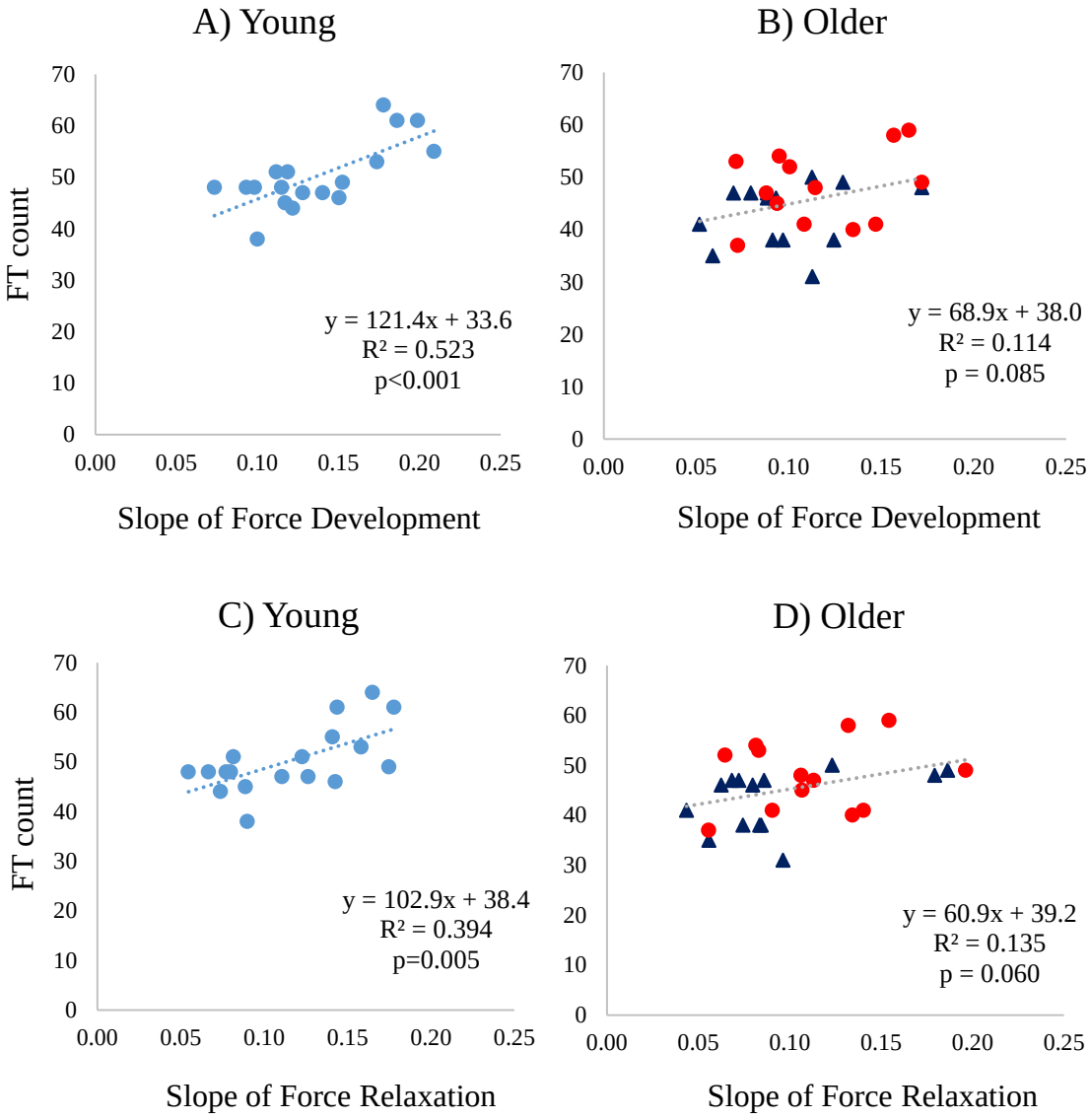
A) Example of normalized EMG for each muscle during 10s of rapid foot tapping. ***B)*** Example of normalized EMG for 1s of foot tapping in a Young adult; activation ratio (Act-R) = 2.21, correlation coefficient = 0.59. ***C)*** Example of normalized EMG for 1s of foot tapping in a HFO adult; Act-R = 1.24, correlation coefficient = 0.30. For each muscle, the EMG data during the FTT were normalized to EMG data during a maximal voluntary isometric contraction.

Figure 6. Activation, Coactivation and Foot Tap Count in Older Adults



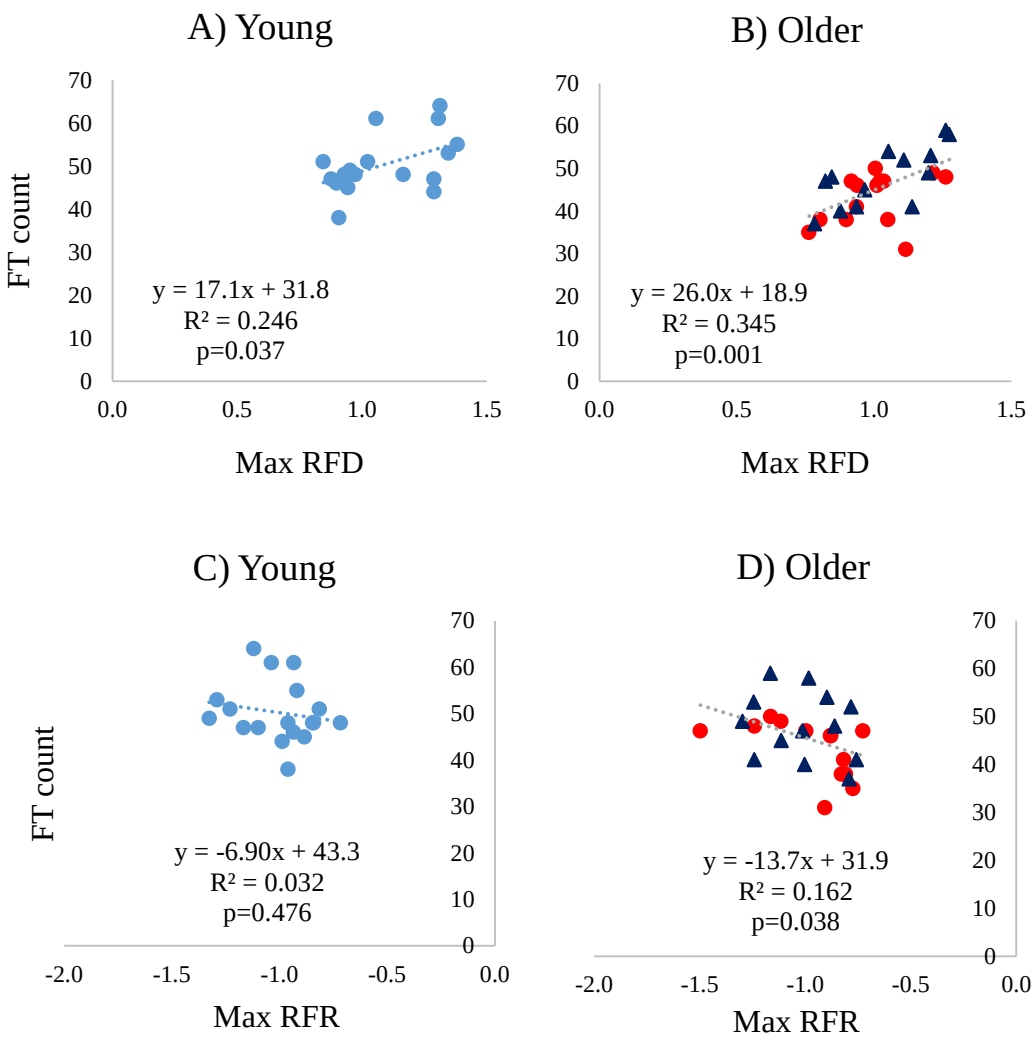
Electromyography (EMG) data were collected during the Foot Tap Test for the slower foot at Visit 2. Data are presented from the fastest trial on Visit 2. ***A)*** Foot Tap Count was not related to the Coact-R. ***B)*** Foot Tap Count was negatively related with the correlation coefficient (TA:Sol) in older adults. Higher functioning older adults are indicated by red circles and lower functioning older adults indicated by blue triangles.

Figure 7. Foot Tap Counts and Voluntary Slope of Force Development and Relaxation of the Dorsiflexor Muscles during Ballistic Contractions in Young and Older Adults



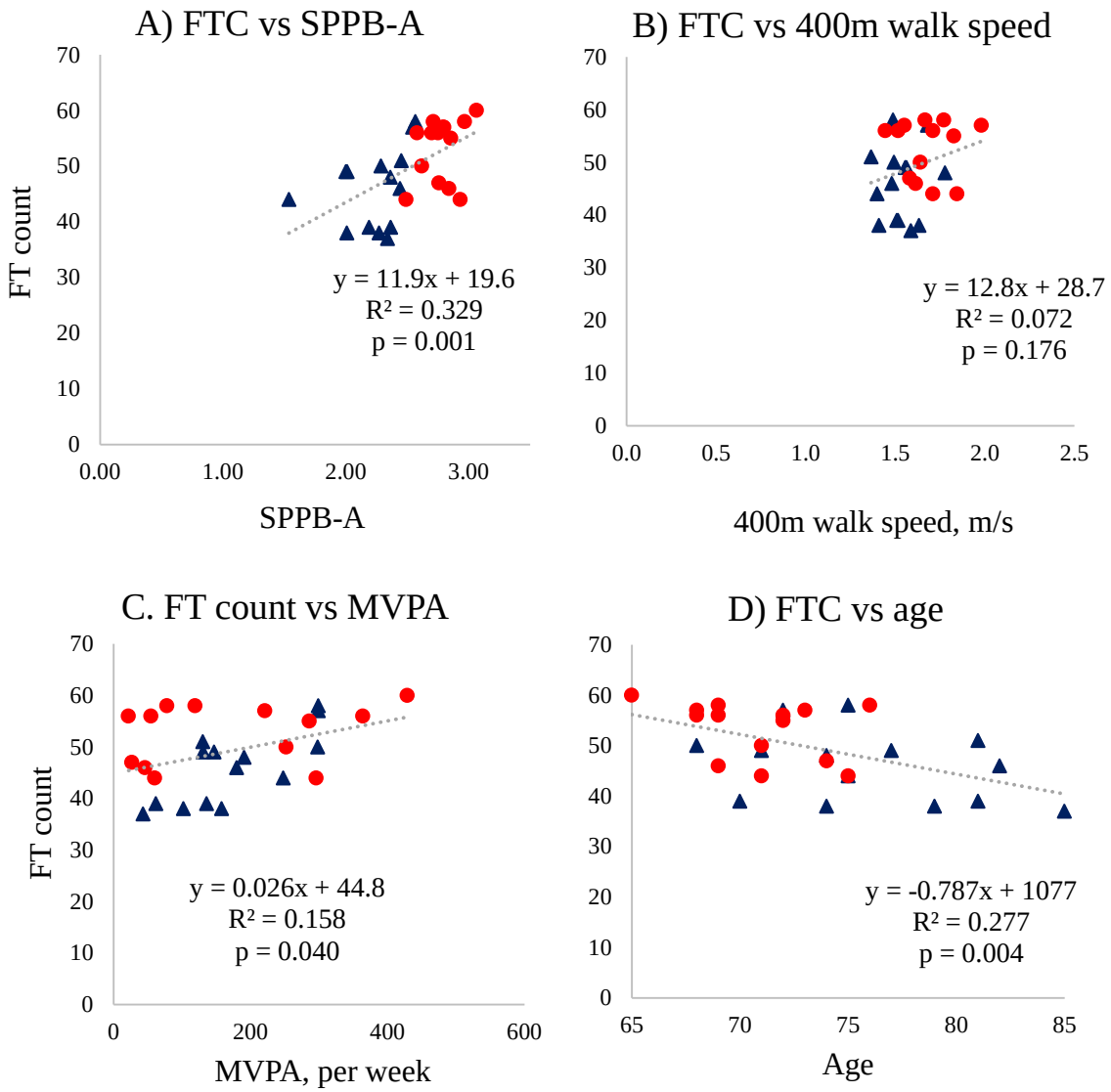
Foot Tap Count vs slope of force development during ballistic contractions of slower foot in ***A)*** young, and ***B)*** older adults. Foot Tap Count vs slope of force relaxation during ballistic contractions of slower foot in ***C)*** young, and ***D)*** older adults. Higher functioning older adults indicated by red circles and lower functioning older adults indicated by blue triangles.

Figure 8. Foot Tap Counts and Voluntary Maximum Rate of Force Development and Relaxation (Max RFD and RFR) of the Dorsiflexor Muscles during Ballistic Contractions in Young and Older Adults



Foot Tap Count vs maximum rate of force development (Max RFD) during ballistic contractions of slower foot in ***A)*** young, and ***B)*** older adults. Foot Tap Count vs maximum rate of force relaxation (Max RFR) during ballistic contractions of slower foot in ***C)*** young, and ***D)*** older adults. Higher functioning older adults indicated by red circles and lower functioning older adults indicated by blue triangles.

Figure 9: Correlations between Foot Tap Count (FTC) of the Faster Foot and Function in Older Adults



Associations in older adults between FTC and ***A)*** advanced Short Physical Performance Battery (SPPB-A), ***B)*** 400m brisk walk speed, ***C)*** minutes of Moderate-to-Vigorous Physical Activity a week (MVPA), ***D)*** age. Higher functioning older adults are indicated by red circles and lower functioning older adults indicated by blue triangles.

APPENDIX A

ADDITIONAL TABLES

Table 9: Habituation Session Schedule

Activity	Time (min)	Data collected
Informed consent, Medical history form, FES-I, Par-Q, SF-36	15	FES-I score
Resting BP, height and body mass	5	BP, height, body mass, BMI
PA monitor explanation	5	PA log, PA activity for 7 days
Physical Function measures	15	SPPB and SPPB-A score, force platform data from balance tests and chair rise
Familiarization: MVC, foot tap	20	FTS for each leg; testing leg determined
Stimulation	20	Torque (voluntary and stimulated),CAR, RFD, $T_{1/2}$
Total time	~80	

Table 10: Testing Session Schedule

Activity	Time (min)	Data collected
Warm up cycling and stretching	7	None
EMG electrode placement and signal check	10	None
MVCs: plantar and dorsiflexion	20	EMG for TA, GM, GL, SO; torque for MVCs
Motion capture markers placement and standing calibration, FTTs explained	7	Standing calibration
10 s foot tap test x3	10	# taps from the counter, GRF, motion capture, EMG
30, 60 and 100% trials	10	# taps from the counter, GRF, motion capture, EMG
100m walk- preferred gait speed	5	motion capture, EMG, speed (3 times each)
400 m walk- brisk walk	10	motion capture, EMG, speed (10 times each)
Total time	~80	

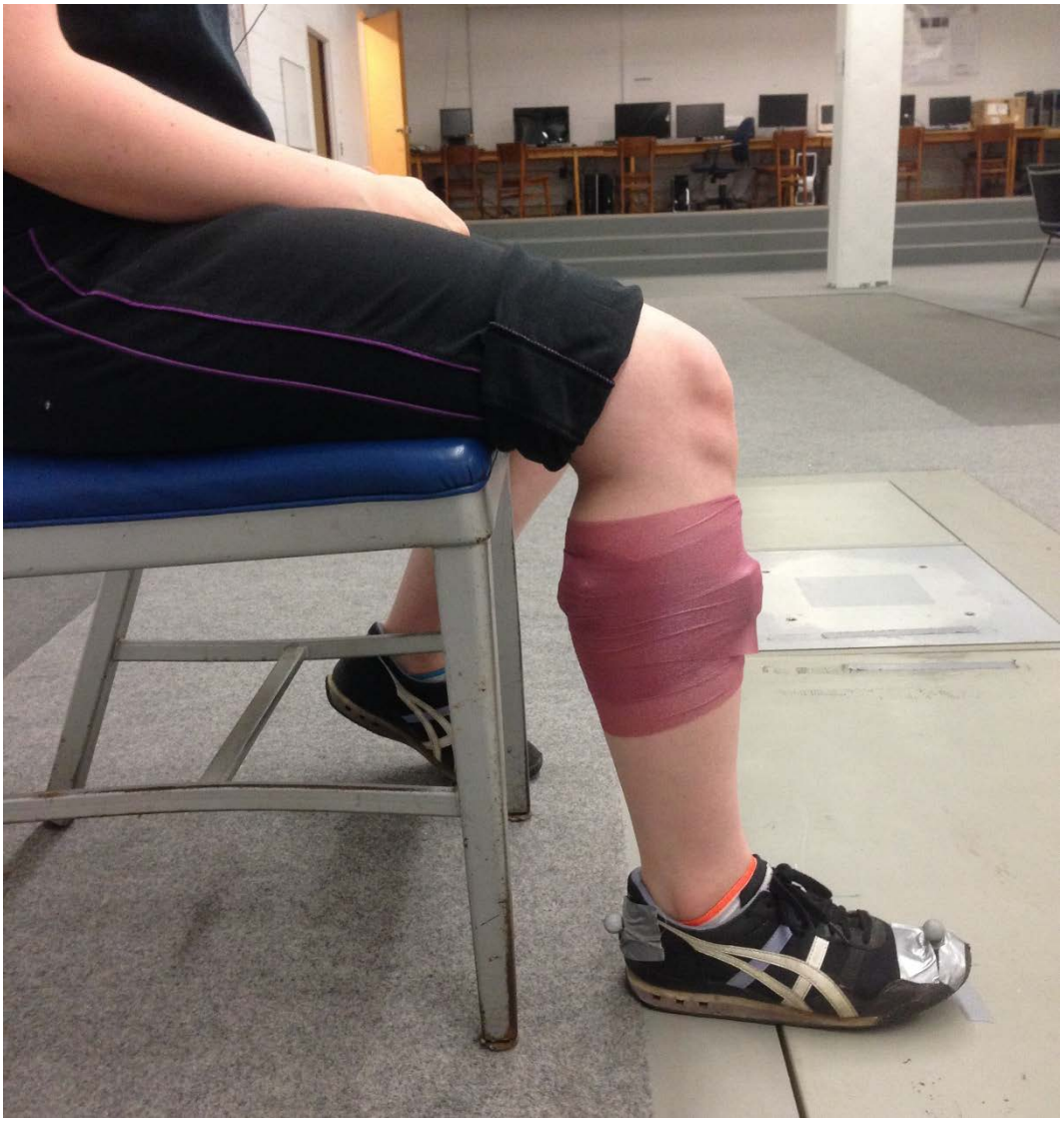
Table 11: Summary of statistical analyses and hypothesis testing

Hypothesis	Primary Variables	Groups	Statistic
1.1	FTS	Young, older, older impaired	ANOVA
1.2	$CoAct_M$ (FTT)	Young, older, older impaired	ANOVA
1.3	$CoAct_T$ (FTT)	Young, older, older impaired	ANOVA
1.4	$CoAct_M$ (FTT) FTS	All older	Linear regression
2.1	$CoAct_M$ (400m walk)	Young, older, older impaired	ANOVA
2.2	$CoAct_M$ (400m walk) Gait speed	All older	Linear correlation

APPENDIX B

ADDITIONAL FIGURE

Figure 10: Set up of Foot Tap Tests



APPENDIX C

SUPPLEMENTARY DOCUMENTS

Medical History Form

Please fill out and sign in ink. This record is confidential.

Medical History
Do you take any prescribed or over-the-counter medications? Please include vitamins, herbs, or other dietary supplements. If yes please list the dose, frequency and the duration of use.

_____
_____

Have you ever been told by a physician that you should not exercise?

Yes ____ No ____ If yes, please explain:

_____

_____

Do you have or have you EVER had any of the following problems? Check if YES and provide details below.

____ Heart disease/rheumatic fever	____ Thyroid disorder	____Asthma
____ High blood pressure	____ Claustrophobia	____Allergies
____ Elevated Cholesterol	____ Anemia	____Stroke
____ Epilepsy or seizure disorder	____Diabetes	____Dizziness

____ Blurred or double vision
____ Orthopedic or joint problems (e.g., arthritis)
____ Shortness of breath or difficulty in breathing
____ Phlebitis, blood-clots, varicose veins, peripheral vascular disease

Lifestyle

Do you smoke cigarettes?	Yes ____ No ____
Do you drink alcohol?	Yes ____ No ____
Do you get regular exercise?	Yes ____ No ____
	If yes, number of times per week _____
Have you had surgery?	Yes ____ No ____
	If yes, when was this? _____

Is there any other information or concerns you have that you feel we should know about before you participate in the study? If yes please explain.

_____
_____

Physical Activity Readiness Questionnaire

1. Has a doctor ever said you have a heart condition and recommended only medically supervised activity?

   YES_____ NO_____

2. Do you have chest pain brought on by physical activity?

   YES_____ NO_____

3. Have you developed chest pain in the last month?

   YES_____ NO_____

4. Do you tend to lose consciousness or fall over as a result of dizziness?

   YES_____ NO_____

5. Do you have a bone or joint that could be aggravated by the proposed physical activity?

   YES_____ NO_____

6. Has a doctor ever recommended medication for your blood pressure or a heart condition?

   YES_____ NO_____

7. Are you aware through your own experience, or a doctor's advice, of any other physical reason against your exercising without medical supervision?

   YES_____ NO_____

Note: If you have a temporary illness, such as a common cold, or are not feeling well at this time – POSTPONE.

Falls Efficacy Scale-International

FES-I

Now we would like to ask some questions about how concerned you are about the possibility of falling. Please reply thinking about how you usually do the activity. If you currently don't do the activity (e.g. if someone does your shopping for you), please answer to show whether you think you would be concerned about falling IF you did the activity. For each of the following activities, please tick the box which is closest to your own opinion to show how concerned you are that you might fall if you did this activity.

		Not at all concerned 1	*Somewhat concerned* 2	*Fairly concerned* 3	*Very concerned* 4
1	Cleaning the house (e.g. sweep, vacuum or dust)	*1* ☐	*2* ☐	*3* ☐	*4* ☐
2	Getting dressed or undressed	*1* ☐	*2* ☐	*3* ☐	*4* ☐
3	Preparing simple meals	*1* ☐	*2* ☐	*3* ☐	*4* ☐
4	Taking a bath or shower	*1* ☐	*2* ☐	*3* ☐	*4* ☐
5	Going to the shop	*1* ☐	*2* ☐	*3* ☐	*4* ☐
6	Getting in or out of a chair	*1* ☐	*2* ☐	*3* ☐	*4* ☐
7	Going up or down stairs	*1* ☐	*2* ☐	*3* ☐	*4* ☐
8	Walking around in the neighbourhood	*1* ☐	*2* ☐	*3* ☐	*4* ☐
9	Reaching for something above your head or on the ground	*1* ☐	*2* ☐	*3* ☐	*4* ☐
10	Going to answer the telephone before it stops ringing	*1* ☐	*2* ☐	*3* ☐	*4* ☐
11	Walking on a slippery surface (e.g. wet or icy)	*1* ☐	*2* ☐	*3* ☐	*4* ☐
12	Visiting a friend or relative	*1* ☐	*2* ☐	*3* ☐	*4* ☐
13	Walking in a place with crowds	*1* ☐	*2* ☐	*3* ☐	*4* ☐
14	Walking on an uneven surface (e.g. rocky ground, poorly maintained pavement)	*1* ☐	*2* ☐	*3* ☐	*4* ☐
15	Walking up or down a slope	*1* ☐	*2* ☐	*3* ☐	*4* ☐
16	Going out to a social event (e.g. religious service, family gathering or club meeting)	*1* ☐	*2* ☐	*3* ☐	*4* ☐

FES-I: Prof Lucy Yardley and Prof Chris Todd

Medical Outcomes Study: 36-Item Short Form Survey Instrument

RAND 36-Item Health Survey 1.0 Questionnaire Items

1. In general, would you say your health is:

Excellent	1
Very good	2
Good	3
Fair	4
Poor	5

2. Compared to one year ago, how would you rate your health in general now?

Much better now than one year ago	1
Somewhat better now than one year ago	2
About the same	3
Somewhat worse now than one year ago	4
Much worse now than one year ago	5

The following items are about activities you might do during a typical day. Does **your health now limit you** in these activities? If so, how much? **(Circle One Number on Each Line)**

	Yes, Limited a Lot	Yes, Limited a Little	No, Not limited at All
3. **Vigorous activities**, such as running, lifting heavy objects, participating in strenuous sports	[1]	[2]	[3]
4. **Moderate activities**, such as moving a table, pushing a vacuum cleaner, bowling, or playing golf	[1]	[2]	[3]
5. Lifting or carrying groceries	[1]	[2]	[3]
6. Climbing **several** flights of stairs	[1]	[2]	[3]
7. Climbing **one** flight of stairs	[1]	[2]	[3]
8. Bending, kneeling, or stooping	[1]	[2]	[3]
9. Walking **more than a mile**	[1]	[2]	[3]

	Yes, Limited a Lot	Yes, Limited a Little	No, Not limited at All
10. Walking **several blocks**	[1]	[2]	[3]
11. Walking **one block**	[1]	[2]	[3]
12. Bathing or dressing yourself	[1]	[2]	[3]

During the **past 4 weeks**, have you had any of the following problems with your work or other regular daily activities **as a result of your physical health**?
(Circle One Number on Each Line)

	Yes	No
13. Cut down the amount of time you spent on work or other activities	1	2
14. **Accomplished less** than you would like	1	2
15. Were limited in the **kind** of work or other activities	1	2
16. Had **difficulty** performing the work or other activities (for example, it took extra effort)	1	2

During the **past 4 weeks,** have you had any of the following problems with your work or other regular daily activities **as a result of any emotional problems** (such as feeling depressed or anxious)?
(Circle One Number on Each Line)

	Yes	No
17. Cut down the **amount of time** you spent on work or other activities		2
18. **Accomplished less** than you would like	1	2
19. Didn't do work or other activities as **carefully** as usual	1	2

20. During the **past 4 weeks,** to what extent has your physical health or emotional problems interfered with your normal social activities with family, friends, neighbors, or groups? **(Circle One Number)**

Not at all 1
Slightly 2
Moderately 3
Quite a bit 4
Extremely 5

21. How much **bodily** pain have you had during the **past 4 weeks**? **(Circle One Number)**

None 1
Very mild 2
Mild 3
Moderate 4
Severe 5
Very severe 6

22. During the **past 4 weeks,** how much did **pain** interfere with your normal work (including both work outside the home and housework)? **(Circle One Number)**

Not at all 1
A little bit 2
Moderately 3
Quite a bit 4
Extremely 5

These questions are about how you feel and how things have been with you **during the past 4 weeks**. For each question, please give the one answer that comes closest to the way you have been feeling.
How much of the time during the **past 4 weeks** . . .
(Circle One Number on Each Line)

	All of the Time	Most of the Time	A Good Bit of the Time	Some of the Time	A Little of the Time	None of the Time
23. Did you feel full of pep?	1	2	3	4	5	6
24. Have you been a very nervous person?	1	2	3	4	5	6
25. Have you felt so down in the dumps that nothing could cheer you up?	1	2	3	4	5	6
26. Have you felt calm and peaceful?	1	2	3	4	5	6
27. Did you have a lot of energy?	1	2	3	4	5	6
28. Have you felt downhearted and blue?	1	2	3	4	5	6

29. Did you feel worn out?	1	2	3	4	5	6
	All of the Time	Most of the Time	A Good Bit of the Time	Some of the Time	A Little of the Time	None of the Time
30. Have you been a happy person?	1	2	3	4	5	6
31. Did you feel tired?	1	2	3	4	5	6

32. During the **past 4 weeks,** how much of the time has your **physical health or emotional problems** interfered with your social activities (like visiting with friends, relatives, etc.)? **(Circle One Number)**

All of the time 1
Most of the time 2
Some of the time 3
A little of the time 4
None of the time 5

How TRUE or FALSE is <u>each</u> of the following statements for you.
(Circle One Number on Each Line)

	Definitely True	Mostly True	Don't Know	Mostly False	Definitely False
33. I seem to get sick a little easier than other people	1	2	3	4	5
34. I am as healthy as anybody I know	1	2	3	4	5
35. I expect my health to get worse	1	2	3	4	5
36. My health is excellent	1	2	3	4	5

Short Physical Performance Battery (SPPB) scoring chart

	4	3	2	1	0
Walk Time (s)	< 4.82	4.82-6.20	6.21-8.70	>8.70	Unable to complete
Chair Rise Time (s)	<11.1	11.2-13.6	13.7-16.6	>16.7	Unable to complete
Balance Tests:					
Side-by-side (s)	Not needed	Not needed	Not needed	10	0-9; tried but unable; not attempted
Semi-tandem (s)	10	10	10	0-9; tried but unable; not attempted	<10; Tried but unable; not attempted
Full Tandem (s)	10	3-9	0-2; tried but unable; not attempted	Not needed	Not needed

*For the balance test, if an individual is able to hold the semi-tandem pose for 10s they will not be tested in the side-by-side position, which is considered easier. If an individual is unable to hold the semi-tandem pose for 10s, they will not be tested in the full tandem position because it is considered more difficult.

Advanced Short Physical Performance Battery (SPPB-A) scoring chart

6m walk (casual speed; s): 1) _____ 2)_____

6m balance walk (casual speed, s): 1) _____ # times stepped outside _____

2) _____ # times stepped outside _____

Timed 5x Chair rise (s): _____ (split time) Force file name _____

Timed 10x Chair rise (s): _____

Balance	Side-by-Side	Semi-Tandem	Tandem	One-leg
Time (s)				
Force File				

Leg selected **R** **L**

Scoring for Advanced Short Physical Performance Battery	
1. Total Advanced Balance Test Score (0 – 1) (Semi-tandem+ tandem + one leg time)/90s)	☐. ☐☐ points
2. Normalized Gait Speed (4m/time)/(2 m/s)	☐. ☐☐ points
3. Normalized Balance Gait Speed (4m/time)/(2 m/s)	☐. ☐☐ points
3. Repeated chair stand ratio score (10 stands/ time to complete)	☐. ☐☐ points
4. Total Advanced SPPB Score	☐. ☐☐ points

APPENDIX D

ADDITIONAL MEASURES COLLECTED

Data were collected for the following measures but were not analyzed for this thesis

- Force platform data during 30s balance tests
    - Feet side-by-side, semi-tandem, tandem, single leg stance
    - No motion capture or EMG data
- Learning effect or repeatability of FTT from visit 1 to visit 2
- Asymettry of the two feet during the FTT on visit 1
- Speed, EMG, and motion capture of slower leg during preferred walking speed trials and during 400m walk
    - Analysis has been completed on the 400m walk but was not completed with enough time to add it to this paper
- Foot tap data for 30, 60, 100% of max FTT speed. Individuals were instructed to match the metronome speed while performing the task
    - Intertap-interval and coefficient of variation of the intertap-interval
- Toe excursion during the Foot Tap Test

BIBLIOGRAPHY

1. **American College of Sports Medicine.** *ACSM's guidelines for exercise testing and prescription.* Lippincott Williams & Wilkins, 2013.

2. **Blake AJ, Morgan K, Bendall MJ, Dallosso H, Ebrahim SB, Arie TH, Fentem PH and Bassey EJ.** Falls by elderly people at home: prevalence and associated factors. *Age Ageing* 17: 6: 365-372, 1988.

3. **Borg G.** A category scale with ratio properties for intermodal and interindividual comparisons. 25-34, 1982.

4. **Burholt V and Nash P.** Short Form 36 (SF-36) Health Survey Questionnaire: normative data for Wales. *J Public Health (Oxf)* 33: 4: 587-603, 2011.

5. **Centers for Disease Control and Prevention (CDC).** Self-reported falls and fall-related injuries among persons aged > or =65 years--United States, 2006. *MMWR Morb Mortal Wkly Rep* 57: 9: 225-229, 2008.

6. **Connelly DM, Rice CL, Roos MR and Vandervoort AA.** Motor unit firing rates and contractile properties in tibialis anterior of young and old men. *J Appl Physiol* 87: 2: 843-852, 1999.

7. **Crozara, Luciano Morcelli, Mary Marques, Nise Hallal, Camilla Spinoso, Deborah de Almeida Neto, Antônio Francisco Cardozo,Adalgiso Gonçalves, Mauro.** Motor readiness and joint torque production in lower limbs of older women fallers and non-fallers. *J Electromyogr Kinesiol.* 23: 5: 1131-1138, 2013.

8. **Delbaere K, Close JC, Mikolaizak AS, Sachdev PS, Brodaty H and Lord SR.** The Falls Efficacy Scale International (FES-I). A comprehensive longitudinal validation study. *Age Ageing* 39: 2: 210-216, 2010.

9. **Desmedt JE and Godaux E.** Ballistic contractions in man: characteristic recruitment pattern of single motor units of the tibialis anterior muscle. *J Physiol.* 264: 3: 673-693, 1977.

10. **Franz JK, Rodger.** How does age affect leg muscle activity/coactivity during uphill and downhill walking? *Gait Posture* 37: 3: 378-384, 2013.

11. **Freedson PS, Melanson E and Sirard J.** Calibration of the Computer Science and Applications, Inc. accelerometer. *Med.Sci.Sports Exerc.* 30: 5: 777-781, 1998.

12. **Frontera WR, Hughes VA, Fielding RA, Fiatarone MA, Evans WJ and Roubenoff R.** Aging of skeletal muscle: a 12-yr longitudinal study. *J Appl Physiol* 88: 4: 1321-1326, 2000.

13. **Gabriel KKP, Rankin RL, Lee C, Charlton ME, Swan PD and Ainsworth BE.** Test-Retest Reliability and Validity of the 400-Meter Walk Test in Healthy, Middle-Aged Women. *J Phys Act Health* 7: 649-657, 2010.

14. **Gunzler SA, Pavel M, Koudelka C, Carlson NE and Nutt JG.** Foot-tapping rate as an objective outcome measure for Parkinson disease clinical trials. *Clin.Neuropharmacol.* 32: 2: 97-102, 2009.

15. **Guralnik JM, Simonsick EM, Ferrucci L, Glynn RJ, Berkman LF, Blazer DG, Scherr PA and Wallace RB.** A short physical performance battery assessing lower extremity function: association with self-reported disability and prediction of mortality and nursing home admission. *J.Gerontol.* 49: 2: M85-M94, 1994.

16. **Guralnik JM, Ferrucci L, Pieper CF, Leveille SG, Markides KS, Ostir GV, Studenski S, Berkman LF and Wallace RB.** Lower extremity function and subsequent disability: consistency across studies, predictive models, and value of gait speed alone compared with the short physical performance battery. *J.Gerontol.A Biol.Sci.Med.Sci.* 55: 4: M221-31, 2000.

17. **Guralnik JM, Ferrucci L, Simonsick EM, Salive ME and Wallace RB.** Lower-Extremity Function in Persons over the Age of 70 Years as a Predictor of Subsequent Disability. *N.Engl.J.Med.* 332: 9: 556-562, 1995.

18. **Hamill J, Palmer C and Van Emmerik REA.** Coordinative variability and overuse injury. *Sports Med Arthrosc Rehabil Ther Technol* 4: 1: 45-45, 2012.

19. **Hausdorff JM, Rios DA and Edelberg HK.** Gait variability and fall risk in community-living older adults: a 1-year prospective study. *Arch.Phys.Med.Rehabil.* 82: 8: 1050-1056, 2001.

20. **Hortobágyi, Tibor Finch, Adria Solnik, Stanislaw Rider,Patrick DeVita, Paul.** Association between muscle activation and metabolic cost of walking in young and old adults. *J Gerontol A Biol Sci* 66: 5: 541-547, 2011.

21. **Hortobágyi T and DeVita P.** Muscle pre-and coactivity during downward stepping are associated with leg stiffness in aging. *J Electromyogr Kinesiol.* 10: 2: 117-126, 2000.

22. **Hortobágyi T, Solnik S, Gruber A, Rider P, Steinweg K, Helseth J and DeVita P.** Interaction between age and gait velocity in the amplitude and timing of antagonist muscle coactivation. *Gait Posture* 29: 4: 558-564, 2009.

23. **Hubley Kozey C and Earl EM.** Coactivation of the ankle musculature during maximal isokinetic dorsiflexion at different angular velocities. *Eur.J.Appl.Physiol.* 82: 4: 289-296, 2000.

24. **Kamen G and Knight CA.** Training-related adaptations in motor unit discharge rate in young and older adults. *J.Gerontol.A Biol.Sci.Med.Sci.* 59: 12: 1334-1338, 2004.

25. **Kemoun G, Thoumie P, Boisson D and Guieu JD.** Ankle dorsiflexion delay can predict falls in the elderly. *J.Rehabil.Med.* 34: 6: 278-283, 2002.

26. **Kent Braun JA and Le Blanc R.** Quantitation of central activation failure during maximal voluntary contractions in humans. *Muscle Nerve* 19: 7: 861-869, 1996.

27. **Kent-Braun JA, Walker CH, Weiner MW and Miller RG.** Functional significance of upper and lower motor neuron impairment in amyotrophic lateral sclerosis. *Muscle Nerve* 21: 6: 762-768, 1998.

28. **Kent J, Lui L, Cummings S, Ensrud K and Cauley J. Foot Tap Speed as a Prospective Marker for Mobility Impairment in Older Women**. Submitted.

29. **Kent-Braun JA and Ng AV.** Specific strength and voluntary muscle activation in young and elderly women and men. *J.Appl.Physiol.* 87: 1: 22-29, 1999.

30. **Kerrigan DC, Todd MK, Della Croce U, Lipsitz LA and Collins JJ.** Biomechanical gait alterations independent of speed in the healthy elderly: evidence for specific limiting impairments. *Arch.Phys.Med.Rehabil.* 79: 3: 317-22, 1998.

31. **Klass M, Baudry S and Duchateau J.** Age-related decline in rate of torque development is accompanied by lower maximal motor unit discharge frequency during fast contractions. *J.Appl.Physiol.(1985)* 104: 3: 739-746, 2008.

32. **Klass M, Baudry S and Duchateau J.** Aging does not affect voluntary activation of the ankle dorsiflexors during isometric, concentric, and eccentric contractions. *J.Appl.Physiol.(1985)* 99: 1: 31-38, 2005.

33. **Klein C, Rice C and Marsh G.** Normalized force, activation, and coactivation in the arm muscles of young and old men. *J.Appl.Physiol.* 91: 3: 1341-1349, 2001.

34. **Ko S, Stenholm S, Metter EJ and Ferrucci L.** Age-associated gait patterns and the role of lower extremity strength - results from the Baltimore Longitudinal Study of Aging. *Arch.Gerontol.Geriatr.* 55: 2: 474-479, 2012.

35. **Lamontagne A, Richards CL and Malouin F.** Coactivation during gait as an adaptive behavior after stroke. *J Electromyogr Kinesiol.* 10: 6: 407-415, 2000.

36. **LaRoche D, Millett E and Kralian R.** Low strength is related to diminished ground reaction forces and walking performance in older women. *Gait Posture* 33: 4: 668-672, 2011.

37. **LaRoche DP, Cremin KA, Greenleaf B and Croce RV.** Rapid torque development in older female fallers and nonfallers: A comparison across lower-extremity muscles. *J Electromyogr Kinesiol.* 20: 3: 482-488, 2010.

38. **Larsen AH, Puggaard L, Hämäläinen U and Aagaard P.** Comparison of ground reaction forces and antagonist muscle coactivation during stair walking with ageing. *J Electromyogr Kinesiol.* 18: 4: 568-580, 2008.

39. **Larsson L, Grimby G and Karlsson J.** Muscle strength and speed of movement in relation to age and muscle morphology. *J.Appl.Physiol.* 46: 3: 451-456, 1979.

40. **Laughton CA, Slavin M, Katdare K, Nolan L, Bean JF, Kerrigan DC, Phillips E, Lipsitz LA and Collins JJ.** Aging, muscle activity, and balance control: physiologic changes associated with balance impairment. *Gait Posture* 18: 2: 101-108, 2003.

41. **Lexell J, HENRIKSSON-LARSÉN K and SJÖSTRÖM M.** Distribution of different fibre types in human skeletal muscles 2. A study of cross-sections of whole m. vastus lateralis. *Acta Physiol.Scand.* 117: 1: 115-122, 1983.

42. **Lexell J, Taylor CC and Sjöström M.** What is the cause of the ageing atrophy?: Total number, size and proportion of different fiber types studied in whole vastus lateralis muscle from 15-to 83-year-old men. *J.Neurol.Sci.* 84: 2: 275-294, 1988.

43. **Lexell J.** Human aging, muscle mass, and fiber type composition. *J.Gerontol.A Biol.Sci.Med.Sci.* 50 Spec No: 11-16, 1995.

44. **Ling S, Conwit R, Ferrucci L and Metter EJ.** Age-associated changes in motor unit physiology: observations from the Baltimore Longitudinal Study of Aging. *Arch.Phys.Med.Rehabil.* 90: 7: 1237-1240, 2009.

45. **Lord SR, Lloyd DG and Li SK.** Sensori-motor function, gait patterns and falls in community-dwelling women. *Age Ageing* 25: 4: 292-299, 1996.

46. **Macaluso A, Nimmo MA, Foster JE, Cockburn M, McMillan NC and De Vito G.** Contractile muscle volume and agonist-antagonist coactivation account for differences in torque between young and older women. *Muscle Nerve* 25: 6: 858-863, 2002.

47. **Marques NR, LaRoche DP, Hallal CZ, Crozara LF, Morcelli MH, Karuka AH, Navega MT and Goncalves M.** Association between energy cost of walking, muscle activation, and biomechanical parameters in older female fallers and non-fallers. *Clin.Biomech.* 28: 3: 330-336, 2013.

48. **Marsden C, Obeso J and Rothwell J.** The function of the antagonist muscle during fast limb movements in man. *J.Physiol.(Lond.)* 335: 1: 1-13, 1983.

49. **McNeil CJ, Doherty TJ, Stashuk DW and Rice CL.** Motor unit number estimates in the tibialis anterior muscle of young, old, and very old men. *Muscle Nerve* 31: 4: 461-467, 2005.

50. **Miller TM and Johnston SC.** Should the Babinski sign be part of the routine neurologic examination? *Neurology* 65: 8: 1165-1168, 2005.

51. **Mitsumoto H, Uluğ A, Pullman S, Gooch C, Chan S, Tang M, Mao X, Hays A, Floyd A and Battista V.** Quantitative objective markers for upper and lower motor neuron dysfunction in ALS. *Neurology* 68: 17: 1402-1410, 2007.

52. **Morie M, Reid KF, Miciek R, Lajevardi N, Choong K, Krasnoff JB, Storer TW, Fielding RA, Bhasin S and LeBrasseur NK.** Habitual physical activity levels are associated with performance in measures of physical function and mobility in older men. *J.Am.Geriatr.Soc.* 58: 9: 1727-1733, 2010.

53. **Nagai K, Yamada M, Uemura K, Yamada Y, Ichihashi N and Tsuboyama T.** Differences in muscle coactivation during postural control between healthy older and young adults. *Arch.Gerontol.Geriatr.* 53: 3: 338-343, 2011.

54. **Nagai K, Yamada M, Uemura K, Tanaka B, Mori S, Yamada Y, Aoyama T, Ichihashi N and Tsuboyama T.** Effects of fear of falling on muscular coactivation during walking. *Aging Clin.Exp.Res.* 24: 2: 157-161, 2012.

55. **Nagano H, Begg R, Sparrow W and Taylor S.** Ageing and limb dominance effects on foot-ground clearance during treadmill and overground walking. *Clin.Biomech.* 26: 9: 962-968, 2011.

56. **Newman AB, Simonsick EM, Naydeck BL, Boudreau RM, Kritchevsky SB, Nevitt MC, Pahor M, Satterfield S, Brach JS and Studenski SA.** Association of long-distance corridor walk performance with mortality, cardiovascular disease, mobility limitation, and disability. *JAMA* 295: 17: 2018-2026, 2006.

57. **Ng AV and Kent-Braun JA.** Slowed muscle contractile properties are not associated with a decreased EMG/force relationship in older humans. *J Gerontol A Biol Sci Med Sci.* 54: 10: B452-B458, 1999.

58. **Ng A, Miller R, Gelinas D and Kent-Braun J.** Functional relationships of central and peripheral muscle alterations in multiple sclerosis. *Muscle Nerve* 29: 6: 843-852, 2004.

59. **Numasawa T, Ono A, Wada K, Yamasaki Y, Yokoyama T, Aburakawa S, Takeuchi K, Kumagai G, Kudo H and Umeda T.** Simple foot tapping test as a quantitative objective assessment of cervical myelopathy. *Spine* 37: 2: 108-113, 2012.

60. **Öberg T, Karsznia A and Öberg K.** Basic gait parameters: reference data for normal subjects, 10-79 years of age. *J Rehabil Res Dev* 30: 210-210, 1993.

61. **Patten C and Kamen G.** Adaptations in motor unit discharge activity with force control training in young and older human adults. *Eur.J.Appl.Physiol.* 83: 2-3: 128-143, 2000.

62. **Pereira M and Gonçalves M.** Muscular coactivation (CA) around the knee reduces power production in elderly women. *Arch.Gerontol.Geriatr.* 52: 3: 317-321, 2011.

63. **Perry MC, Carville SF, Smith ICH, Rutherford OM and Newham DJ.** Strength, power output and symmetry of leg muscles: effect of age and history of falling. *Eur.J.Appl.Physiol.* 100: 5: 553-561, 2007.

64. **Peterson DS and Martin PE.** Effects of age and walking speed on coactivation and cost of walking in healthy adults. *Gait Posture* 31: 3: 355-359, 2010.

65. **Sawada Y.** Maintenance of Physical Function and Related Factors for Community Dwelling Elderly: A Nine-Year Follow-up Study. *J Phys Ther Sci* 21: 3: 245-251, 2009.

66. **Schmitz A, Silder A, Heiderscheit B, Mahoney J and Thelen DG.** Differences in lower-extremity muscular activation during walking between healthy older and young adults. *J Electromyogr Kinesiol.* 19: 6: 1085-1091, 2009.

67. **Schrack JA, Simonsick EM, Chaves PH and Ferrucci L.** The Role of Energetic Cost in the Age-Related Slowing of Gait Speed. *J.Am.Geriatr.Soc.* 60: 10: 1811-1816, 2012.

68. **Shephard, Roy Park, Hyuntae Park,Sungjin Aoyagi, Yukitoshi.** Objectively measured physical activity and progressive loss of lean tissue in older Japanese adults: longitudinal data from the nakanojo study. *J.Am.Geriatr.Soc.* 61: 11: 1887-1893, 2013.

69. **Signorile JF, Applegate B, Duque M, Cole N and Zink A.** Selective recruitment of the triceps surae muscles with changes in knee angle. *J.Strength Cond Res.* 16: 3: 433-439, 2002.

70. **Simonsick EM, Newman AB, Nevitt MC, Kritchevsky SB, Ferrucci L, Guralnik JM, Harris T and Health ABC Study Group.** Measuring higher level physical function in well-functioning older adults: expanding familiar approaches in the Health ABC study. *J.Gerontol.A Biol.Sci.Med.Sci.* 56: 10: M644-9, 2001.

71. **Sommervoll Y, Ettema G and Vereijken B.** Effects of age, task, and frequency on variability of finger tapping. *Percept.Mot.Skills* 113: 2: 647-61, 2011.

72. **Studenski S, Perera S, Patel K, Rosano C, Faulkner K, Inzitari M, Brach J, Chandler J, Cawthon P and Connor EB.** Gait speed and survival in older adults. *JAMA* 305: 1: 50-58, 2011.

73. **Surface Electromyography for Non-Invasive Assessment of Muscles.** http://seniam.org/sensor_location.htm 2014].

74. **Thomas S, Reading J and Shephard RJ.** Revision of the physical activity readiness questionnaire (PAR-Q). *Can J Sport Sci.* 17: 4: 338-45, 1992.

75. **Tinetti ME, Richman D and Powell L.** Falls efficacy as a measure of fear of falling. *J.Gerontol.* 45: 6: P239-43, 1990.

76. **Tomita Y and Usuda S.** Temporal motor coordination in the ankle joint following upper motor neuron lesions. *J Phys Ther Sci* 25: 5: 539-44, 2013.

77. **US Department of Health and Human Services.** A profile of older Americans: 2011. 2011.

78. **Vandervoort AA.** Aging of the human neuromuscular system. *Muscle Nerve* 25: 1: 17-25, 2002.

79. **Vandervoort AA and McCOMAS AJ.** Contractile changes in opposing muscles of the human ankle joint with aging. *J.Appl.Physiol.* 61: 1: 361-367, 1986.

80. **Vestergaard S, Patel KV, Bandinelli S, Ferrucci L and Guralnik JM.** Characteristics of 400-meter walk test performance and subsequent mortality in older adults. *Rejuvenation Res* 12: 3: 177-184, 2009.

81. **Ware Jr JE and Sherbourne CD.** The MOS 36-item short-form health survey (SF-36): I. Conceptual framework and item selection. *Med.Care* 473-483, 1992.

82. **Winter DA, Patla AE, Frank JS and Walt SE.** Biomechanical walking pattern changes in the fit and healthy elderly. *Phys.Ther.* 70: 6: 340-347, 1990.

83. **Yardley L, Beyer N, Hauer K, Kempen G, Piot-Ziegler C and Todd C.** Development and initial validation of the Falls Efficacy Scale-International (FES-I). *Age Ageing* 34: 6: 614-619, 2005.