The Influence of Muscular Fatigue on Human Multi-Joint Movement: Determinants of Sit-to-Stand Capacity with Aging

MEGAN BRYANTON

Thesis submitted to the
Faculty of Graduate and Postdoctoral Studies
in partial fulfillment of the requirements
for the Doctorate of Philosophy degree in Human Kinetics

School of Human Kinetics
Faculty of Health Sciences
University of Ottawa

ABSTRACT

The sit-to-stand (STS) is a multi-articular movement of daily living that requires significantly higher knee extensor (KE) efforts compared to ankle and hip musculature, which approach near maximal levels in older adults populations. As well, fatigue may develop more readily with repetitive actions. Consequently, it is understandable how KE strength reserves have been previously correlated with both functional independence and STS strategy characteristics in older persons, and why STS capacity is a significant predictor of disability. However, it is still unclear why compensatory movement strategies manifest when rising from a seated position, and how this may be influenced by aging. The purpose of this thesis compilation was to evaluate alterations in muscular contributions at the ankle, knee, and hip, in relation to STS performance strategies in young and older adults either: a) with repetitive multi-joint STS exercise or b) before and after isolated fatigue of KE musculature. Results showed that aging caused a redistribution of joint torques when ascending from a seated position, and was associated with significantly higher quadriceps muscular efforts in older persons in comparison to their younger counterparts. In contrast, young and older adults exhibited similar compensatory movement and loading strategies during repetitive STS exercise, which appeared to be limited by the ability to sustain KE force output. In turn, lower KE strength reserves of older persons were responsible for their disproportionately higher quadriceps efforts and reduced STS capacities. Young and older persons also appeared to employ motor strategies to compensate for reduced KE force output via increased contribution of the biarticular rectus femoris within the quadriceps KE synergy, as well as through increases in the initially less active ankle plantar flexor and hip extensor musculature. Older adults may benefit from strengthening of thigh extensor musculature to maintain or improve their strength reserves to promote independent living.

ACKNOWLEDGMENTS

I would first like to thank my respective committee members Dr. Martin Bilodeau, Dr. Heidi Sveistrup and Dr. Yves Lajoie for their help and guidance during this process and broadening my experience in the field of human kinetics and rehabilitative sciences. Your contribution has further prepared me for my future career aspirations in academics. Also, thanks to Dr. Gordon Robertson for his additional contributions to perfecting my motion data, and Dr. Loren Chiu for continuing to be a strong mentor of mine despite continuing my education elsewhere.

A special thanks to the young and older adult men and women who participated in my research studies presented in this thesis compilation, and to my colleagues Dan McEwen, Anthony Remaud, Dylan Crake, and Paulo Nascimento; their comradery and generous support I will never forget. Also, I would like to thank the Bruyere Research Institute for providing me with a unique, multi-disciplinary working environment and valuable research experience that I would not have been able to receive elsewhere.

To my friends, thank you for your continued encouragement during my long career as a "professional student", regardless of how far we are apart. Lastly, to my family; thank you for your loving support and patience, for all of those long drives back and forth between PEI and Ottawa, and lastly for all of the "grand-dog" sitting. I am so fortunate to have such inspiring role models in my life and I hope to someday return the favour.

CONTRIBUTION TO THE LITERATURE

This thesis presents the research of Megan A. Bryanton in collaboration with her thesis supervisor Dr. Martin Bilodeau. The sum of this work resulted in the following contributions to the literature.

Manuscripts to be submitted and included in this thesis:

Bryanton, M.A. and Bilodeau, M. Compensatory Alterations in Joint Kinetics during Repetitive Sit-to-Stand Exercise in Young and Older Adults.

Bryanton, M.A. and Bilodeau, M. The Role of Thigh Muscular Efforts in Limiting Sit-to-Stand Capacity in Healthy Young and Older Adults.

Bryanton, M.A. and Bilodeau, M. Age- and Intensity-dependent Alterations in Muscular Control of Chair Rise Strategies with Dynamic Knee Extensor Fatiguing Exercise.

Published manuscripts included in this thesis:

Bryanton, M.A. and Bilodeau, M. (2016). Postural Stability with Exhaustive Repetitive Sit-To-Stand Exercise in Young Adults. *Human Movement Science, 49*, 47-53.

Related published or submitted manuscripts:

Grant, T., **Bryanton, M.A**., Taylor, M., Sveistrup, H., Bilodeau, M., Knoefel, F., Goubran, R. and Jutai, J. (2014). Sit-to-stand (STS) timing among older adults in their homes: Two measurement approaches. *Gerontechnology*, *12(*3), 153-158.

TABLE OF CONTENTS

PAGE

Chapter 2: Review of the literature

Chapter 8: General Discussion

LIST OF TABLES

PAGE

Manuscript 1

Manuscript 2

Manuscript 3

PAGE

LIST OF FIGURES

PAGE

Manuscript 1

Manuscript 2

Manuscript 3

Manuscript 4

PAGE

Appendix B

CHAPTER 1

INTRODUCTION: HEALTHY AGING IN CANADA

According to the Ottawa Charter on Health Promotion (Mahler et al., 1986), Canada views health as a resource for everyday life. Therefore, the concept of health in older populations extends beyond the absence of disease, and also includes the preservation of autonomy (Gill et al., 1998; Laporte et al., 1999). The ability to perform activities of daily living (ADL) has a significant impact on one’s functional independence and thereby quality of life. This is especially so in regards to older persons with reduced movement capabilities, which will impact their ability to continue to live in their homes independently and comfortably (Gill et al., 1998; Laporte et al., 1999; Reid & Feilding, 2012). For instance, simply getting up and out of bed or rising from a chair, is a problem for 6-8% of community dwelling adults and for up to 63% of adults living in nursing homes (Alexander et al., 2001). Moreover, age-related declines in functional movement skills will ultimately lead to earlier dependence on long-term care services due to the increased likelihood of negative health-related outcomes such as falling, injury, and even accidental death (Lazaro et al., 2010; Morita et al., 2005).

In Canada, older adults over the age of 60 represent approximately 15% of our population, which is expected to grow to 20% in the next 30 years. Those 85 years and older are the fastest growing age group: projected to increase from 702,000 in 2013 to 2.9 million in 2056 (Public Health Agency of Canada [PHAC], 2014). Our population is aging as people are living longer, healthier lives; however, despite longer life expectancies, the fundamental aging process has remained unchanged, and there will be more people living with age-related disabilities (Sheppard, 2002). Since aged persons 75 years and older are the heaviest users of the health care system (Sheppard, 2002; PHAC, 2014), this projected growth poses a challenge for governments due to limited human and fiscal resources to provide all older adult Canadians with adequate access to health care services (Denton, 1998; Sheppard, 2002). Therefore, a shift from a curative to preventative focus in the care for older persons is necessary in order to alleviate the burden of escalating health care demands (PHAC, 2014; SSCA, 2009). This will in turn require a greater understanding of the relationships between the aging process and functional independence for the establishment of effective preventative and restorative program for our rapidly aging Canadian population.

Age-related declines in muscular performance have an undeniable association with loss of functional mobility and increased dependence on others (Muhlberg & Sieber, 2004; Roos et al., 1997; van Roie et al., 2011). The sit-to-stand (STS) is a multi-articular movement involved in numerous ADL that relies on the competencies of both the musculoskeletal and postural control systems, and the capacity to perform it has been used as a predictor of disability in older adults (Akram & McIlroy, 2011; Buatois et al., 2008; Schultz et al., 1992; Tiedmann et al., 2008). Significantly higher, and near maximal muscular efforts, have been observed in older persons when rising from a chair in comparison to their younger counterparts (Doorenbosch et al., 1994; Hortobagyi et al., 2003; Hughes et al., 1996). As well, fatigue may more readily develop with repetitive activity, and unfavourable compensatory movement strategies may result when rising from a seated position , which may increase the risk of falling and injury (Carter et al., 2001; Carville et al., 2007; Ikezoe et al., 2011; Manini et al., 2007; Puniello, McGibbon & Krebs, 2001; Sparto et al., 2007b). However, a direct relationship between strength reserves of lower extremity musculature and associated motor strategies when older persons rise from a seated position remains unclear and requires further evaluation.

The aim of this thesis was to evaluate alterations in muscular contributions at the ankle, knee, and hip to STS performances in older adults compared to young adults. Specifically, alterations in STS joint mechanics and muscular coordination strategies were determined with both repetitive multi-joint STS exercise and isolated dynamic knee extensor fatigue. In doing so, we aimed to determine the role of KE contractile performance on the chair rise strategies with aging. This research adds to our understanding of how the neuromuscular system is able to cope with impaired force generating capabilities to sustain movement performance and how this may be impacted with aging, particularly during the STS task.

Following a review of literature of the current body of knowledge regarding the effects of fatiguing exercise and aging on human movement performance, with a focus on the STS (Chapter 2), the research objectives and hypothesis for each study involved in this thesis compilation will be presented in Chapter 3. Four manuscripts will then be presented (Chapters 4-7), followed by a brief general discussion of the main research findings of these individual studies and how they relate (Chapter 8). Lastly, a description of the contribution of each investigator to the respective manuscript (Chapter 9) will be presented, as well as a reference list (Chapter 10) and an appendix containing ethics documentation (A) and supplemental data (B).

CHAPTER 2

REVIEW OF LITERATURE

THE CONTROL OF HUMAN MOVEMENT

Force Production and Mechanisms of Muscular Fatigue

The functional unit of human movement, the motor unit, consists of a single peripheral motor neuron and all the muscle fibers that it innervates (Lieber, 2007). Motor units have been classified based on their contractile speed and fatigability and are associated with the histochemical or biochemical profile of their muscle fibers (Scott, Stevens, & Binder-Macleod, 2001). Typically, small motor neurons with low threshold voltages innervate small type I fatigue resistant oxidative muscle fibers with low twitch tensions, termed slow-twitch (ST) motor units. In contrast, larger motor neurons innervate larger type II highly-fatigable, non-oxidative muscle fibers that generate large, faster tensions, known as fast-twitch (FT) motor units. The central nervous system (CNS) has two strategies which increase or sustain force output from a muscle: rate coding and recruitment. Rate coding is the phenomenon accomplished via increased motor unit firing frequencies, resulting in summative forces and is the adopted strategy of slow-twitch motor units. The second strategy to alter force generation is increasing the total number of active motor units at a given time, according to “Heneman’s size principle” (Boyas & Guevel, 2011; Enoka et al., 1992; Fuglevand et al., 1993; Henneman,1985; Lieber, 1992; Milner-Brown et al., 1973). Relative contributions of recruitment versus rate coding in grading force differ considerably between muscles. Muscles that have high type I fiber proportions, such as muscles of the hand, require precise gradation of force for dexterity purposes and rely on rate-coding mechanisms to modulate force output; whereas large mixed-muscle groups such as the quadriceps, show considerable variation between recruitment and rate-coding contributions (Bilodeau et al., 2003; Lieber, 1992; Milner-Brown et al., 1973).

It is known that with sustained activity, there are several different sites along the activation pathway of motor units where dysfunction may occur which would lead to a decrease in force output. Neuromuscular fatigue, which can be defined as "any reduction in the force-generating capacity of the total neuromuscular system, regardless of the force required in any given situation" (Gandevia, 1992), can be classified based on the location of the mechanism(s) involved. Any dysfunctions located distal to the neuromuscular junction are considered peripheral fatigue mechanisms; whereas any alterations located proximal to the neuromuscular junction are classified as central fatigue mechanisms (Boyas & Guevel, 2011b; Enoka, 1992; Gonzalez-Izal et al., 2012).

Peripheral fatigue, also referred to as muscle fatigue, is attributed to any perturbations to elements of muscle fiber excitation, contraction, and relaxation (Boyas & Guevel, 2011b; Enoka, 1992; Gonzalez-Izal et al., 2012; Lieber, 1992), and can involve depletion of energy sources as well as accumulation of metabolic by-products which can inhibit cellular processes associated with contractile function (Fitts, 2008; Silverthorne, 2007). Ultimately, the intensity and duration of muscle activity will determine the capacity of active fibers to sustain a desired force output and in turn the mechanisms responsible for and characteristics of reduced muscular force generating abilities (Allen & Westerblad, 2001; Lieber, 1992; Williams & Ratel, 2009).

Despite the regulatory capabilities of the CNS to maintain force output during prolonged contractions, muscles appear to eventually experience a reduced capacity to be voluntarily activated (Gondeva, 2001; Gondeva et al., 1996; Tanaka & Watanabe, 2012; Williams & Ratel, 2010). Underlying mechanisms remain unclear; however such central fatigue has been proposed to be a protective mechanism in central motor command to prevent complete cellular failure and preserve muscle integrity (Boyas & Guevel, 2011b; Enoka et al., 2011; Gonzalex-Izal et al., 2012). Central fatigue is most commonly observed during prolonged exhaustive low-intensity exercise (Sogaard et al., 2006; Tanaka & Watanabe, 2012) and may also manifest during high-intensity intermittent efforts, to a lesser extent (Gondeva et al., 1996; Kent- Braum & Ng, 1999). For example, Kent-Braun et al. (2002) reported that during brief high-intensity exertion, central fatigue was estimated to be responsible for up to 20% of total declines in maximal voluntary contractions (MVCs); whereas remaining force declines were attributed to peripheral factors. In contrast, central fatigue due to low intensity sustained contractions for significantly longer durations have been shown to be responsible for up to 60% of force declines (Sogaard et al., 2006). Interestingly, Kennedy et al. (2011) showed that not all muscles are affected similarly: during alternating isometric contraction of the ankle musculature central fatigue contributed to force declines in the plantar-flexors and peripheral mechanisms were solely present in the dorsi-flexors. These investigators suggested that central fatigue in the ankle plantar-flexors may have been related to the multiple muscles comprising the Triceps surae, requiring synergistic activities and neural control. The dorsi-flexors are, in contrast, primarily comprised of one muscle, the tibialis anterior. Regardless, both central and peripheral factors may be attributable to force declines during fatiguing exercise. Lastly, susceptibility to reduced voluntary activation with fatigue may also vary with age; older participants appear to exhibit greater central fatigue during prolonged low force contractions in comparison to their younger counterparts (Bilodeau et al., 2001; Yoon et al., 2008). For example, Bilodeau et al. (2001) found that older particpants demonstrated marked declines in central actvitation of the elbow flexors at the end of a sustained contraction of 35% MVC until failure, which was not observed in younger participants. However, this fatigue-related neuromuscular decline with aging is not apparent at higher intensities (80% MVC) (Yoon et al., 2008). Researchers Yoon et al. (2008) have also suggested that age differences in susceptibility to central fatigue may be more related to increased endurance capabilities of aging muscle and subsequent longer task times until failure.

Biomechanical investigations on the effect of fatigue on muscular performance have generally defined it as an inability to maintain a desired force output (Bigland-Ritchie, 1981); however the concept of fatigue encompasses numerous aspects of the neuromuscular system, including muscle contractile properties, recruitment strategies, recovery, and overall work performance (Williams & Ratel, 2009). Impairments in force control/steadiness and joint position sense are also consequences of muscular fatigue (Bellew & Fender, 2006; Enoka & Duchateau, 2008; Forestier & Nougier, 1998; Forestier, Teasdale, & Nougier, 2002; Fortier & Basset, 2012; Lattanzio & Petrella, 1998; Missenard, Mottet, & Perry, 2009; Paillard, 2012; Petrella et al., 2005; Skinner et al., 1986). Considering this, a decline in anyone of these capabilities will influence the ability to perform various movements of daily living. This will be discussed in the subsequent sections.

The Sit-to-Stand: Biomechanical Analyses and Effects of Fatigue

Biomechanical Analyses of Human Movement. Human movement involves multi-joint tasks and the contribution of several muscle groups whose force generation is controlled by the nervous system (Winter & Eng, 1995). Biomechanical techniques for estimating muscle force contributions at a joint during multi-segment movements involve a combination of kinetic and kinematic analyses to calculate net joint moments (NJM; Newton meters (Nm)) using inverse dynamics techniques (Bryanton et al., 2015; Nigg & Herzogg, 2007; Robertson et al., 2004;

Winter & Eng, 1995). A moment, or torque, is the rotating effect of force created when applied to a certain moment arm distance from an axis of rotation. The moment arm is the perpendicular distance between the force line of action and the axis of rotation and in the human system, and will be dependent on segment geometries during a dynamic multi-articular movement. Therefore, the moment produced at a joint during a multi-articular task represents the net effort of all agonist and antagonist muscle forces acting at that joint (Nigg & Herzogg, 2007; Robertson et al., 2004; Winter & Eng, 1995).

Kinetic measurements of mechanical work (Joules (J)) performed at a joint is in turn a function of this net moment loading and the associated joint excursions. Therefore, while NJM calculations tell us *what* muscle groups may be contributing, quantification of work reveals *how* they are contributing to the movement. Mechanical or external work is performed when mechanical energies have been developed to produce enough force on a segment to induce joint rotation via muscular contraction (i.e. internal work); therefore biomechanical investigations involving calculations of joint work aid in understanding the flow of energy that causes the movements we observe during a multi-articular task (DeVita, Helseth, & Hortobagyi, 2007; Robertson & Winter, 1980; Robertson et al., 2004; Siegel, Kepple, & Stanhope, 2004; Winter, 2009). Since it is the scalar product of the vector quantity of the applied force and the displacement vector of the motion, positive mechanical work is performed when force is applied in the same direction in which the joint movement is occurring, such as when concentrically ascending from a seated position and energy produced by musculature is transferred to the limb segment. In contrast, negative work or work absorption, occurs when the force is being applied in the opposite direction of the movements, such as when muscles are eccentrically loaded against the gravitational effects of body weight and energy is transferred from the segment and absorbed by musculature (DeVita, Helseth, & Hortobagyi, 2007; Robertson et al., 2004; Robertson & Winter, 1980). Since human movement can be performed in a wide variety of ways, because of the kinematic degrees of freedom available in a multi-joint task (Winter & Eng, 1995), measurements of NJM and mechanical work may aid in understanding the origins of a movement strategy in a multi-articular task of daily living.

Due to limitations in inverse dynamic calculations of joint kinetics, the extent to which a muscle is active cannot be inferred (Bryanton et al., 2012; Bryanton et al., 2015; Nigg & Herzog, 2007; Toussant et al., 1992). Moreoever, since kinetic measures cannot account for the amount of co-contraction of antagonist muscle occurring at a joint, the true loading of an agonist muscle may be under-estimated (Bryanton et al., 2012; Bryanton et al., 2015; Toussaint et al., 1992; Winter & Eng, 1995). For example, Bryanton et al. (2012; 2015) showed that during squatting exercise, as barbell load increased there was no change in the knee extensor (KE) NJM produced, but an increase in the hip extensor (HE) NJM occurred; however once co-contraction of the hamstrings was accounted for by modeling its contribution to hip extension, it was revealed that the extensor moment generated by the quadriceps at the knee was substantially higher than KE NJM values. Consequently, the true loading at a joint may be underestimated because antagonist activity in not incorporated into computations. This particularly raises concerns when comparing joint efforts between tasks that involve differing levels of co-contraction (Jacobs et al., 1996). This further holds true for kinetic measures involving the integration of net joint loading integrated over time (impulse) and/or angular displacement (work, power). Furthermore, although both the unit of mechanical work and energy is Joules, external work is not a measure of the amount of energy expended by musculature to perform a given task, which is evident during an isometric contraction that may require considerable musculature efforts; however no joint rotation occurs and measures of mechanical work are therefore zero (Robertson et al., 2004; Zatsiorsky, 2002). Considering this, simple net joint kinetic quantification may not reveal the true nature of limiting factor muscle during multi-joint movement and may lead to misinterpretation if it is not fully understood.

A complimentary measurement technique in biomechanical investigations in understanding the origins of multi-joint movement is through the use of surface electromyography (EMG). Surface EMG is a feasible and non-intrusive method to study neural control of movement that involves the detection of electrical signals of active motor units of a muscle that lies beneath electrodes place on the skin. However many factors can influence signal components and lead to misinterpretation of the results (Cifrek et al., 2009; DeLuca et al., 1984; Farina, Merletti, & Enoka, 2004; Hug, 2011). The characteristics of the signals obtained have been shown to depend on the membrane properties of the muscle fibers, as well as their firing frequencies (Farina et al., 2004; Hug, 2011). For example, fatiguing exercise causes a shift in the muscle signal’s power spectrum towards lower frequencies and increased signal amplitudes (Cifrek et al., 2009; DeLuca et al., 1984). Other limitations include cross-talk between adjacent muscles, which occurs when the EMG signal is contaminated by nearby muscles’ electrical activity (Farina, Merletti & Enoka, 2004; Hug, 2011). Despite these limitations, normalization of the signal amplitude relative to standardized maximal contraction amplitudes can be performed in order to reduce such possible errors and provide indirect estimates of neural drive to a muscle that can be compared between persons and different task conditions (Gross et al., 1998; Hug, 2011). Moreover, surface EMG can be used in understanding muscular coordination responsible in producing a particular movement by evaluating the distribution of activation intensities and temporal patterns within or between muscle synergies (Hug, 2011). Since research has shown that muscles are activated in short bursts that are timed to take advantage of the force and geometry between adjacent segments (Hug, 2011), a combination of kinetic and surface EMG analyses of human movement may provide a more complete analyses of human movement origins.

Sit-to-Stand Mechanics and Alterations with Fatigue. Rising from a seated position (i.e., the Sit-to-Stand; STS) is a complex weight bearing multi-articular movement and basic skill associated with a number of activities of daily living (ADL) such as getting out of bed, toileting, and so on. A successful STS transition involves the preparatory horizontal displacements of center of mass (COM) before transitioning to the ascending phase once contact is lost, followed by a transfer of upper body momentum to the lower extremity and increased vertical COM accelerations until a fully extended upright posture had been reached (Akram & McIlroy, 2011; Mourey et al., 2000; Roebrock et al., 1994). From a mechanical standpoint, rising from a chair requires the development of adequate resistive torques about the ankle, knee, and hip joints via muscular actions performed by the ankle plantarflexors (APF), KE, and HE, respectively (Schultz, Alexander, & Ashton-Miller, 1992). After seat-off, monoarticular agonist muscle groups such as the soleus (SOL), vasti (lateralis; VL, medialis; VM, intermedius, VI), and gluteus maximus (GMax) are concentrically active; whereas biarticular muscles such as the hamstrings (biceps femoris long head; BF, semitendinosis; ST, semimembranosus; ST), the gastrocnemius (medial; GM and lateral; GL), and the rectus femoris (RF) have much lower shortening velocities and are hypothesized to function mainly as joint stabilizers and to transfer energy among segments (Escamilla, 2001; Rao et al., 2009; Robertson et al., 2008; Roebrock et al., 1994). Wretenberg and Arborelius (1994) found that the KE contributed to approximately 72% of total lower extremity concentric STS work, while the HE had significantly lower work outputs that contributed to ~ 27% of total concentric work. In turn, energy absorption was performed by eccentric actions of the HE and hip flexors, but appeared to be minimal in the young male adult participants when ascending from a seated position.

When measures are normalized with respect to standardized maximal contractions, an uneven distribution of muscular efforts has been reported during the STS (Beiryla et al., 2007; Burnfield et al., 2012; Gross et al., 1998). For example, Burnfield et al. (2012) noted that during the ascending phase of the unassisted STS, VL EMG values peaked at 63% of their isometric MVC in healthy adults; whereas hamstring and GMax peaked at 14% and 21%, respectively. Bieryla et al. (2007) had similar findings, noting greater KE NJM relative intensities (i.e., normalized to maximum NJM) were required (78.4% MVC NJM); whereas those of the APF and HE were significantly lower (27.9% and 26.3% MVC NJM respectively).

It is understandable that the more muscles involved during prolonged tasks, the greater the extent of whole body (global) fatigue that will be accumulated; however this is not a perfectly linear association and are based on the assumption that all muscles are working to the same extent. Similarly to the STS task, Bryanton et al. (2012) found that squatting exercise involved an uneven distribution of relative intensities of muscular effort between the ankle plantar-flexors (APF), KE, and HE. This corroborates with findings of Isear et al. (1997), who found that average concentric EMG activation intensities of the quadriceps during the squat were substantially higher (~65% MVC) than those of the hamstrings, gluteus maximus (~5-10% MVC), and the gastrocnemius (~10% MVC). An uneven distribution of muscular efforts during a multi-articular task would likely lead to greater accumulation of fatigue in a particular muscle group with repetitive actions if it is required to work at higher relative efforts, which will in turn influence the type of fatigue accumulated and associated decrements in contractile performance (Chiu et al. 2004; Williams & Ratel, 2009).

The body is characterized by a number of muscles and joints, all of which must be coordinated to perform functional movements. Due to the redundancy of the human musculoskeletal system, there are more muscles than required to cause a particular joint motion and the CNS may employ different neuromuscular strategies in order to spare excessive contractile failure of a particular muscle group (Bonnard et al., 1994; Nigg & Herzogg, 2007; Winter & Eng, 1995). Therefore, compensatory shifting of loading demands onto less involved muscle groups may occur in order to distribute joint efforts more evenly and improve movement efficiency to prolong task performance (Bonnard et al., 1994; Forestier & Nougier, 1998; Hortobagyi et al., 2003; Puniello et al., 2001; Savelberg et al., 2007; van der Heijden et al., 2009; Yoshioka et al., 2007). Fuller et al. (2009) characterized several reorganizations of muscle activity patterns during sustained shoulder exercise such as modification between co-active agonist-antagonist muscle pairs, improved inter-muscular coordination within agonist muscle groups, and reduced trans-joint inhibition of synergists. Bonnard and colleagues (1994) found that in order to sustain prolonged hopping performance, their participants exhibited two distinct compensatory muscle strategies with fatigue accumulation in the APF musculature: increased muscle contribution across joints such as increased activity of the RFand VL at the knee, and earlier pre-activation of the gastrocnemius (GAS) at the ankle. Therefore, it can be speculated that the CNS is capable of modifying inter-joint coordination in order to maintain movement performance despite localized impairments in muscular performance during a multi-articular task.

Compensatory shifting of joint loadings may also result in observable changes in movement kinematics. For example, Sparto et al. (1997a) and Fogleman and Smith (1995) observed that movement patterns during repetitive lifting changed from a “leg lift” to a “back lift” strategy, which was characterized by reductions in peak knee flexion angle, greater hip flexion, and a stooped lifting posture. Investigators suggested that this was due to compensatory shifting to larger, stronger hip and lower back muscle.This increased hip and back extensor role is however more biomechanically stressful, increasing unwanted compressive forces onto lumbar vertebrae (Sparto et al., 2007a; Sparto et al., 2007b; Toussaint et al., 1995). With this, although prolonged activity may lead to alterations in movement strategies to cope with or even prevent primary mover muscle fatigue accumulation, it may also result in undesirable kinematics and increased risk of inherent injury.

Repetitive activity may also be associated with the adoption of movement strategies in order to maintain postural stability, as muscle fatigue has been shown to interfere with both motor and sensory functions (Bellew & Fender, 2006; Enoka & Duchateau, 2008; Forestier & Nougier, 1998; Forestier, Teasdale, & Nougier, 2002; Fortier & Basset, 2012; Lattanzio & Petrella, 1998; Missenard, Mottet, & Perry, 2009; Paillard, 2012; Skinner et al., 1986; Sparto et al, 2007b). Dynamic multi-joint movements of daily living such as walking or raising one’s arm, involve the displacement of one’s COM, where its vertical projection (i.e., center of gravity; COG) must remain within one’s postural limits of stability in order to prevent oneself from tipping or falling (Rothwell, 1998). The STS is a transfer task that involves the displacement of the COM over a rapid reduction in support surface once contact is lost with the seat (Akram & McIlror, 2011; Alexander et al., 1991; Shultz et al., 1992). After this, the foot is the most distal segment of the lower extremities and provides a small base of support over which balance is to be controlled, and biomechanical alterations in the support surface will most likely influence segment movement strategies in order to optimize COM positioning prior to contact being lost with the seat (Alexander et al., 1991; Rothwell, 1986). Therefore, the STS task is not only demanding in terms of its large force requirements, but also because it challenges postural systems as it requires the precise control of one's COM over a quick reduction in support surface (Bernardi et al., 2004; Doorenbosche et al., 1994; Mourey et al., 2000; Schultz et al., 1992).

For balance to be maintained, the CNS must integrate positional orientation information from the body and subsequently generate appropriate muscle contractions aimed at maintaining body posture against gravity and counteracting de-stabilizing forces during movement (Sturnieks et al., 2008; Yim-Chiplis & Talbot, 2000). In turn, the quality of sensory information obtained dictates the efficacy of the motor strategy to prevent the body from tipping or falling (Horak et al., 1986; Shumway-Cook & Woollacott, 2001; Yim-Chiplis & Talbot, 2000). Sensory information used by the CNS to monitor body orientation is provided by three important systems and their respective receptors: the visual, vestibular, and somatosensory systems. Vision provides two forms of input regarding an individual's surroundings by identifying movements of the objects within their environment and where and how the body is positioned in space (Shumway-Cook & Woollacott, 2001). In turn, the vestibular system provides information obtained from receptors located in the inner ear semicircular canals and fluid filled membranous sacks called the saccule and the utricle, involved in detecting fast angular accelerations of the head, and the pull of gravity or to translational movements of the head, respectively (Silverthorn, 2007; Sturnieks et al., 2008). The last source of sensory information for postural control, the somatosensory system, provides important information regarding the position of body segments relative to each other in space (Sturnieks et al., 2008; Shumway-Cook & Woollacott, 2001; Yim-

Chiplis & Talbot, 2000). It is obtained from receptors located in muscles, tendons, joints, and cutaneous tissue, which are referred to as proprioceptors. Muscle spindles lie within muscle bellies and are stimulated during active muscle stretch, and Golgi tendons are located within tendons and are therefore stimulated during active and passive tendon lengthening. Other forms of somatosensory input obtained regarding body orientation are through mechanoreceptors such as joint receptors that detect capsule stretching and changes in length, while cutaneous sensory receptors located on the soles of the feet provide information on center of pressure (COP) positioning that is essential for monitoring postural stability during ambulating or standing on firm surfaces (Horak et al., 1989; Silverthorne, 2007; Shumway-Cook & Woollacott, 2001). No one sense (visual, vestibular, somatosensory) by itself can provide the CNS with sufficient enough information regarding position and motion of the body in space; however due to their redundancies, the CNS weights/re-weights each source of input depending on its reliability and importance for stabilization of posture (Jeka et al., 2000; Lundin et al., 1993; Oie et al., 2002; Vuillerme et al., 2002) and the somatosensory system provides the quickest and largest component in balance control sensation (Horak & Nasher, 1986).

Measures of postural sway have been valuable in understanding the effects of muscle fatigue on the control of balance in humans (Paillard, 2012).To quantify postural sway, either the displacement of COM is measured using motion analysis techniques, or the displacement of the COP is collected using force platform ground reaction force (Ruhe et al., 2010). With a repetitive lifting protocol, Sparto et al. (2007) found that in addition to a 31% decline in lifting power, postural stability also declined in their participants, as indicated by increases in anterior-posterior COP excursions. This was in turn reflective of increased excursions in trunk COM as the multi-articular fatigue task progressed. Muscle fatigue negatively impacts the accuracy of somatosensory input to accurately correct body posture during a dynamic task, due to declines in joint position sense, as well as delays in force-generating capabilities, and impaired force control (Forestier & Nougier, 1998; Forestier et al., 2002; Huffenus et al., 2006; Lattanzio & Petrella, 1998; Missenard, Mottet, & Perry, 2009; Sandrey & Kent, 2008; Skinner et al., 1986; Vuillerme et al., 2007). Therefore increased excursons of COP or COM with repetitive lifting exercise was suggested to reflect fatigue-related impairements in controlling body sway. However, Kennedy, Guevel, and Sveistrup (2012) reported two distinct postural control mechanisms due to ankle muscle fatigue; an increase or decerased in COP sway were both used to control COM. Therefore, COP control was a modulated variable in order for COM positioning to remain stable in the face of fatigue during upright stance.

Additionally, Barbieri and collegues (2013) found that after having young male participants perform exhaustive STS exercise, the accumulation of fatigue, which was indicated by reduced leg press maximal isometric force, caused an adaptive response in their gait kinetic and kinematic parematers such as increased step widths during subsequent gait testing, to widen their base of supports in order to compensate for impaired balance control; however it is unclear how the multi-articular STS fatigue protocols specifically deterred lower extremity performances in the two aforementioned investigations. Since substantially higher quadriceps efforts are required to stand up from a chair in comparision to the ankle and hip musculature (Bieryla et al., 2007; Burnfield et al., 2012; Gross et al., 1998), Barbieri et al. (2013) hypothesized that greater accumulation of fatigue in the KE was primarily responsible for the impaired dynamics stability during gait in their investigation. Unfortunately, no postural nor muscule activity measures were performed during the course of the STS fatigue protocol in either of these investigations to confirm this notion.

A common muscular control strategy adopted in order to improve stability during quiet standing and reduce COP sway area towards postural extremes, is through increased rigidity of the system to prevent excessive body sway via increased co-contraction of agonist-antagonist pairs. This increased joint stiffness is suspected to help regulate motion at a joint when faced with reduced force control capabilities of the agonist, and would be associated with an increase in the frequency of the corrections made to control excessive body sway (Caron, 2003; Caron, 2004; Corbeil et al., 2003; Gribble & Hertel, 2004a; Gribble & Hertel, 2004b). However, Nagai et al. (2013) found that co-activation of the tibialis anterior (TA) and SOL at the ankle during quiet stance was inversely associated with dynamic control capabilities. They hypothesized that a negative consequence of such a stabilization strategy would be that although increased rigidity would restrict one's "dynamic range" of body sway, it may also compromise the individual's ability to adjust to an unexpected perturbation if COM was to deviate outside of the BOS (Allum et al., 2002; Ge, 1998; Hortobagyi et al., 2009; Tucker et al., 2008). Interestingly, Psek and Caferelli (1993) found that declines in force output with repetitive knee extension exercise were in part due to increased coactivity of the hamstring despite increase VL EMG activity, regardless of the hip extensor requirements. Considering this, although increased antagonist activity during dynamic exercise may be deemed inefficient, the CNS may prioritize joint integrity over task endurance capacities if necessary.

In summary, muscle fatigue negatively impacts the ability to perform dynamic human movement performance through declines in force generating capabilities, as well as the ability to control body posture. In turn, the extent to which this will impact movement capabilities will be dependent on the nature of the task and the duration that it is performed. Lastly, this will likely determine the compensatory strategy adopted to either improve movement efficiency or to improve postural stability in order to sustain task performance during prolonged multi-joint exercise.

AGING AND DETERMINANTS OF SIT-TO-STAND CAPABILITIES

Aging of the Human Neuromuscular System

Aging (≥60 years) is associated with an unavoidable decline in muscle mass known as sarcopenia, which has been shown to be a predictor of disability and loss of functional autonomy in older adults due to associated declines in muscular strength, power, and force control (Bassey et al., 1992; Ikezoe et al., 2011a; LeRoche et al., 2010; Muhlberg &Sieber, 2004; Petrella et al., 2005). Sarcopenia is characterized by reductions in both muscle fiber diameter and numbers, and appears to preferentially impact type II muscle fibers, thereby increasing type I fiber proportions from approximately 40% in 20-30 year old individuals to 55% in 60-65 year old individuals and continuing to increase with further aging (Lynch et al., 1999). Although its etiology remains unclear, evidence suggests that neural re-modelling may precede muscle loss (Deschenes et al., 2010). Motor units undergo a variety of age-related changes, declining in numbers to approximately half that of younger adults under the age of 30. Accelerated nerve tissue loss, de-myelination of axons, thinning of dendrite branches, and remodeling of the neuromuscular junction have been suggested to be responsible for slowing of signal transmission and selective attrition of larger motor units with higher activation thresholds (Norris et al., 1953; Ochoa & Mair, 1969; Sato et al., 1985; Wagmen & Lesse, 1952). As larger motor neurons are generally more vulnerable to attrition, this would subsequently lead to denervation of type II fibers which they innervate (Doherty et al., 1993; Kent-Braun & Ng, 1999; Lynch et al., 1999).

Declines in type II fiber proportions may be due to fiber-type transformation indicated by the increased presence of myosin isoforms co-expression, where they begin to resemble slower fiber types due to their re-innervations by remaining less vulnerable smaller motor neurons (Gannon et al., 2005; Roos et al., 1997). This notion is supported by similar muscle profile shifting observed in cross-re-innervation studies of inherently distinct muscles (Buller et al., 1960), as well as in chronic stimulation studies (Kernall et al., 1987; Lieber, 1986). It is understandable then that mixed muscle containing greater quantities of type II fibers will be most affected. For example, the effects of sarcopenia are most apparent in KE musculature; whereas more homogeneously slow muscles such as the soleus are significantly less impacted with aging (Ikeda et al., 2005; Ikezoe et al., 2011a; Ikezoe et al., 2011b; Lynch et al., 1999).

The influence of this motor unit loss on contractile strength is exhibited by the significant relationship found to exist between maximal voluntary torques and the estimated number of motor units in older subjects (Doherty et al., 1993). However, Larsson and Bruce (1986) postulated, based on multiple regression analysis, that type II fiber atrophy could not account for all of the decline in strength measures associated with age. Despite documented losses of approximately 50% within motor unit populations in older persons compared to their younger counterparts, strengths tend to be only reduced by approximately one third (Doherty et al., 1993; Kent-Braun et al., 2002). This suggests the presence of age-dependent motor unit recruitment strategies and firing patterns that may be related to more homogenous slow muscle profiles (Bilodeau et al., 2001; Kent-Braun et al., 2002; Roos, Rice, & Vandervoort, 1997; Vandervoort, 2002).

The ability of a muscle to sustain force during repetitive tasks will be dependent on both the metabolic properties of the muscles recruited and their respective activity patterns (Enoka & Stuart, 1992; Leiber, 1992). When subjected to similar relative (isometric) loads, older persons have a greater ability to resist fatigue than younger adults due to increased type I fiber proportions of aging muscle and associated recruitment and firing strategies (Bilodeau et al., 2001; DeLuca et al., 1982; Enoka et al., 2003; Hunter et al., 2005; Kent-Braum & Ng, 1999; Watanabe et al., 2011); however this may be dependent on contraction type (Avin & Law, 2011; Callahan, Foulis, & Kent-Braun, 2009). In a meta-analyses of age-related differences in endurance capabilities performed by Avin and Law (2011), investigations that involved dynamic contractions to induce muscular fatigue in young and older adults demonstrated no age differences (effect size=0.05) and this held true regardless of the intensity of the contractions involved. Activities of daily living involve the contribution of multiple muscle groups that require varying contraction types (isometric, concentric, eccentric) and intensities to execute (Burnfield et al., 2012; Hortobagyi et al., 2003; Wretenberg & Arborelius, 1994); therefore it is unclear how aging may differently affect the ability to repeatedly perform common tasks of daily living that are essential for autonomy. This is particularly relevant when investigating the role of contractile performance capabilities in mixed muscles of the lower extremities such as the KE with aging (Fujita et al., 2011; Hughes et al., 1996; Petrella et al., 2005; Puniello et al., 2001).

Movement Performance with Aging: Co-contraction and Fatigue

Higher levels of co-contraction are commonly exhibited in older individuals for a given movement task compared to younger adults (Fujita et al., 2011; Hakinnen et al., 1998; Hortobagyi et al., 2003; Nagai et al., 2013). Hortobagyi et al. (2003) observed that the amount of hamstring EMG activity relative to the VL EMG was 1.6 –fold greater in older persons than in young adults during the STS; as relative effort in the ADLs increased, hamstring co-activity significantly increased as well. With increased contribution of HE musculature to chair rise performance in older adults, this would also involve increased activity of bi-articular hamstring musculature whose actions aid in extension at the hip in addition to flexion at the knee (Bryanton et al., 2015). Some investigators suggest that co-contraction of biarticular muscles may be beneficial to STS performance as it is a multi-joints task; as the knee and hip extend when rising from a chair, the opposing force acting upon the hamstrings is transferred to the hip, assisting with hip extension (Voronov, 2004). Doorenbosche et al. (1994) however, noted that despite reductions in knee extensor NJMs by 25% in a hip versus knee dominant STS strategy, it was not indicative of vastii muscle activity, which increased by 35%. As previously mentioned, a limitation of inverse dynamics processes to calculate NJMs is that they represent the forces generated by all agonist and antagonist muscles acting upon a single joint. Therefore, sufficient KE strength would be required to take advantage of a biarticluar STS strategy (Bryanton et al., 2015; Doorenbosche et al., 1994). This would in turn be counterproductive in older adults, and greater hamstring involvement may also play a limiting role in STS capabilities. An alternative explanation for greater co-contraction levels with aging is that older persons may utilize the associated increased joint stiffness of co-contraction to compensate for impaired force control steadiness, muscle coordination, and somatosensory acuity with aging (Kallio et al., 2012; Laidlaw et al., 2000; Missenard, Mottet, & Perry, 2008; Missenard, Mottet, & Perry, 2009). Together, age-dependent motor control strategies may therefore prioritize stability over efficiency. It is unclear, however, how these motor strategies may impair an older person’s ability to perform prolonged multi-joint exercise, or repeated ascending actions on a daily basis.

Age-Related Changes in Sit-to-stand Perfomance

Previous research involving STS kinematics and kinetic comparisons between physically healthy young and older adults show similar patterns of joint motions; however older persons typically generate lower joint forces, particularly at the knee (Gross et al., 1998; Hortobagyi et al., 2003; Hughes et al., 1996; Scarborough et al., 2007). Gross et al. (1998) observed that stronger young adults in their investigation had earlier hip and knee flexion-extension reversals prior to seat-off, yet peak ankle, knee, and hip joint torques were not statistically different between age groups when rising from a set seat height of 18 cm. In contrast, Hortobagyi et al. (2003) observed that older adults had significantly lower knee joint moments when rising from a chair height normalized to 25% of their total heights. Together, this highlights the importance of standardized chair height for accurate comparisons of STS capabilities between investigations, as not normalizing ascent heights with respect to an individual's anthropometrics may mask important age-dependant features for a successful chair rise (Demura & Yamada, 2007; Hughes et al., 1996; Janssen et al., 2002; Schenkman, Riley, & Pieper, 1996). Considering this, determinants of STS performance measures may be chair-related (seat-off, arm rests, chair type, etc.) and/or strategy-related (speed, body position, training, etc.) (See Janssen et al. (2002) for a review).

Combined with age-related declines in maximal force generating abilities and selective sarcopenia of anterior thigh musculature, previous investigators have attributed KE strengths as a determining factor in STS limitations in older populations (Corrigan & Bohannon, 2001; Eriksrud & Bohannon, 2003; Hortobaygi et al., 2003; Hughes et al., 1996; Puniello et al., 2001; Savelberg et al., 2007; van der Heijden et al., 2009). Hughes et al. (1996) noted that when standing from a chair, the older adult group, who had 50% lower KE strengths than the young adults, reached near maximal relative efforts in the KE (≥80%), and reached 97% MVC at the lower chair heights for those older adults who were actually able to successfully rise. Using surface EMG, Gross et al. (1998) also observed that older participants generally had higher lower extremity peak activation ratios with respect to standardized isometric contractions; however statistical significance was only found in the Rectus femoris of the KE (Young: 0.80 ± 0.03, Old:

1.50 ± 0.62). This lack of statistical findings may again be attributed to these investigators not normalizing seat heights with respect to subject heights or limb lengths, and warrants further investigation.

KE strength has been commonly used as a predictor of functional capabilities in older adults (Bassey et al., 1992; Bernardi et al., 2004; Corrigan & Bohannon, 2001; Eriksrud & Bohannon, 2003; Ikezoe et al., 2011b; Manini et al., 2007). For example, reduced KE strength is a major predictor of peak vertical velocities in motor impaired older adults when ascending from a chair (Bernardi et al., 2004). Moreoever, Riley et al. (1997) observed that failed STS attempts in older adults were less energetic (i.e., generated less momentum), and this was associated with a reduced ability to produce sufficient knee torques around hip lift-off times. In the aging literature, older persons generally have KE strength approximately 30-50 % lower than the younger participants (Brech et al., 2013; Fujita et al., 2011; Greve et al., 2013; Gross et al., 1998; Hortobagyi et al., 2003; Hughes et al., 1996; Perry et al., 2007).

A reduced ability to produce adequate KE torques with aging has been suggested to cause shifting of loading demands to less affected muscle groups to compensate such as the HE or APF (Devita & Hortobagyi, 2000; Puniello et al., 2001). Savelberg et al. (2007) and Van der Heijden et al. (2009) attempted to determine the role of muscle strength reserves in STS strategy in young adults through simulation of muscle weakness by having participants wear a weighted vest during testing protocols. Van der Heijden et al. (2009) found that when young participants were specifically asked to adopt a hip dominant STS strategy through increased forward torso leaning prior to ascending from a chair, they were able to reduce KE NJM by 6% and transferred effort to HE and APF muscles. To corroborate, Yoshioka et al. (2007) simulated peak joint moments during the STS task and determined that the hip and knee values were complementary; when joint moment requirements were shifted to the hip, due to minimized KE contribution, this manifested kinematically with an exaggerated forward torso lean and in turn greater COP forward sway due to greater amounts COG relocation during this hip strategy. By rotating the torso forward to a greater extent prior to seat-off, this would reposition one's COM more anteriorly over the feet and redistribute mechanical demands across the lower extremities (Mathiyakom et al., 2005). Moreover, this would require less anterior movement of the knees, lessen demands on the KE musculature, and increase the external moment arm distances at the hip and the ankle (Chiu et al., 2016; Chiu et al., 2006; Flanagan & Salem, 2005; Fry et al., 2003).

Consequently, shifting of loading demands to the larger and stronger HEs with aging may also result in compensation strategies that manifest as undesirable kinematics (Hortobagyi et al., 2003; Puniello et al., 2001; Savelberg et al., 2007; Yoshioka et al., 2007). For example, Puniello et al. (2001) determined that the relative strength between the KE and HE in older persons was a significant predictor of their lifting strategy; participants who had stronger KE adopted a more upright posture when lifting an object; whereas those with relatively stronger HE preferred a hip dominant, forward torso leaning strategy. To corroborate, Scarborough et al. (2007) found that KE strength was also a significant predictor of chair-rise torso positioning, while Alexander et al. (1991) found that older participants who were required to use their hands to succesffuly stand from a chair flexed their trunks more in preparation for seat-off in comparision to young and abled older adults. Although a compensatory hip dominant strategy may aid in an older adult's ability to remain autonomous, increased forward torso leaning is an unfavorable movement strategy. Coppozza et al. (1985) noted increased spinal compressive loads between joints L3-L4 vertebrae in accordance with increased forward torso leaning. As a result, this would likely lead to unwanted chronic lumbar loading throughout the day, and would likely increase risk of lower back ailments into senescence.

Although many older adults have adequate strengths to perform the STS task (Schultz et al., 1992; Yoshioka et al., 2007), it is apparent that they perform activities of daily living that involve ascending from a seated position near their functional strength limits on a frequent basis. STS capacity (i.e., the ability to perform repeatedly) has also been shown to be an effective measurement tool utilized by rehabilitative professionals in predicting disability with aging (Bohanon, 1995; Jones et al., 1999; Petrella et al., 2005). With this, it is expected that the greater activation intensities required by the associated quadriceps muscles would cause older persons to accumulate fatigue more readily in comparison to their younger counterparts. Therefore, with repetitive daily actions, a hip-compensatory strategy would be favourable to cope with and prevent excessive accumulation of fatigue of the KE with efforts of 80% MVC or higher.

In addition to muscle weakness, the inability to maintain one’s balance is also a precursor to reduced functional mobility in older adults (Carter et al., 2002; Toebers et al., 2012). To maintain balance during the STS, muscle efforts of both primary movers and postural muscles are required (Gantchev et al., 1996; Goulart & Valls-Sole, 1999; LeRoche et al., 2010; Shummway-Cook &Woollacott, 2001; Sturnieks et al., 2008). When characterizing temporal characteristics of muscle activity, Goulart and Valls-Sole (1999) noted that during the STS, the TA was activated first as a feedforward anticipatory postural adjustment (APA) prior to movement execution, while the SOL was activated last and remained active during the standing phase. Consequently, muscles groups of the lower extremity have been described to have distinctly different roles when ascending from a seated position; the primary role of hip and knee musculature is to generate sufficient force for joint extension; whereas the ankle musculature played a more predominant role in maintenance of posture (Corbeil et al., 2001; Doorenbosche et al., 1994). However, since KE performance has also been shown to be a significant predictor of fall risk in older adults (Brech et al., 2013; Carter et al., 2002; Carville et al., 2007; Hurley et al., 1998), this does suggest that thigh musculature may also play an underrepresented role in the control of body posture. This notion is supported by Ryushi et al. (2000) who found that strengthening of the KE significantly improved posterior limits of stability in older adult participants.

Declines in postural control with aging have been attributed to degeneration of somatosensory acuity as well as reduced anticipatory control to avoid instability and to recover from a loss of balance (Ribeira, Mota, & Oliveira, 2007; Willott, 1999). Reduced sensitivity of muscle spindles with aging is caused by an increase in capsular thickness, and a decrease in the number of intrafusal fibers, leading to reduced joint position sense at the knee (Bullock-Saxton et al., 2001; Madhavan & Shields, 2005; Petrella et al., 1997; Skinner et al., 1984; Shaffer & Harrison, 2007). As a result, older adults have more difficulty stabilizing body posture compared to their younger counterparts, leading to increased fall occurrence. Ultimately, this challenge is further exacerbated from repetitive daily actions, as fatigue accumulation has also been shown to be detrimental to not only muscular contractile strength and control, but also to somatosensory sensitivity of muscle spindles (Corbeil et al., 2003; Fortier & Basset, 2012; Hurley et al., 1998; Paillard, 2012).

Increased preparatory torso leaning and hip flexion prior to seat-off has also been proposed to be a strategy adopted in older individuals due to an increased concern over falling backwards (Alexander et al., 1991; Hernandez, Ashton-Miller & Alexander, 2012; Papa & Cappozzo, 2000; Van der Heijden et al., 2009). In addition to shifting of muscle loading demands, alterations in COP and body sway during the STS may be reflective of age-related postural strategies in older adults related to modifications in the control of horizontal COM motions (Akram & McIlroy, 2011; Buckley et al., 2009; Fugimoto & Chou, 2012; Mourey et al., 2000; Reisman et al., 2002). When rising from a chair, older adults (≥75 years) have lower COM horizontal and vertical velocities at seat off to prevent disequilibrium over a rapidly reduced BOS (Mourey et al., 2000), and appear to employ segment movement strategies in order to optimize COM positions prior to losing contact with their seat. Schultz et al. (1992) observed that at moment of seat-off, older adults had COP positions that were more anterior at mid-foot positions; whereas younger adults' COP positions were located posterior to the ankle. This more anterior COP location at seat-off was present in all older adults regardless of their physical capabilities; however relocation was to an even greater extent in older disabled individuals. A more anterior floor reaction force can be explained by the fact that older adults tend to rotate their upper body segments, thighs, and legs significantly more than young adults prior to seat off which, in turn, reduces the distance between vertical projection of COM and COP locations at mid foot as a stabilization strategy (Alexander et al., 1991; Buckley et al., 2009; Nocera et al., 2010; Papa & Cappozzo, 2000; Schultz et al., 1992). Young adults are able to tolerate greater separation of COM and COP vertical projections compared to older adults. As a result, reduce postural limits of stability (LOS) margins have been suggested to be indicative of postural impairements in which a more conservative control strategy is being adopted to compensate for this with aging (Buckley et al., 2009; Prado et al., 2011). This may explain why COP is positioned more anteriorly prior to seat-off in older adults, as the mid-foot would be a stable position furthest away from LOS boundaries, and would limit threats to postural stability (Buckley et al., 2009; Prado et al., 2011; Schultz et al., 1992).

SUMMARY

In summary, the current literature relating age-related declines in muscle performance to STS capabilities has demonstrated numerous links regarding the role of KE sarcopenia in older adults and their functional status; however the true nature of this relationship remains unclear due to the cross-sectional nature of many aging studies. In turn, although potential adaptive changes in movement control during the STS associated with aging may look atypical, they may be in fact optimal with respect to the performance of everyday activities to compensate for age-related declines in muscular strength, to prevent fatigue, and to improve postural stability. This review of literature also highlights the ability of the neuromuscular system to adapt in a task-specific way when faced with fatigue and aging. To understand neuromuscular control of human movement due to prolonged multi-joint exercise and/or declines in muscle performance, it is important to expand our understanding of the flexibility of the nervous system in creating movements that are efficient and extend performance duration. It is apparent that during a multi-joint task such as the STS, the CNS must take into account both musculoskeletal and environmental variables in determining the movement control strategy adopted when faced with impairments in KE force generating capabilities with repetitive exercise. In turn, reorganizations in muscle contributions and motor control strategies due to fatigue may be age-dependent. With this, a multi-faceted approach through investigating biomechanical and neurophysiological variables associated with STS capacities is necessary in order to further understand compensatory mechanisms and the origins of these adaptations; this is the focus of this thesis.

CHAPTER 3

RESEARCH OBJECTIVES AND HYPOTHESES

This thesis is comprised of four manuscripts, with the following objectives: a) to pilot a fatigue protocol design, while assessing changes in postural variables reflective of dynamic stability during a repetitive STS task in young adults (Manuscript 1); b) to investigate alterations in multi-joint movement control and mechanical loading strategies due to fatiguing STS exercise in young and older adults (Manuscript 2); c) to test the association between thigh muscles' force generating capabilities and STS capacities in young and older adults (Manuscript 3); and d) to study alterations in neuromuscular variables associated with STS muscle control strategies in young and older adults due to impaired force generating capabilities of the KE following isolated fatigue (Manuscript 4).

Manuscript 1 Research Questions and Hypotheses

Previous research has indicated that muscle fatigue due to repeated bouts of physical activity can have negative residual effects on balance (Chaubet & Paillard, 2012; Paillard, 2012); however postural analyses during multi-joint forms of exercise involved in everyday settings and during the physical activity itself are limited. In turn, it is unclear how stabilization strategies manifest to improve postural stability during dynamic activities of daily living (ADL) such as rising from seated position (i.e., the sit-to-stand; STS). The purpose of this investigation was to evaluate dynamic postural stability before, during, and after prolonged multi-joint STS exercise in healthy young adults. Center of pressure (COP) acquisitions were collected during repetitive STS exercise to determine COP path length excursion when ascending, and its positioning at seat-off (i.e., the most unstable instant when one's support surface area is rapidly reduced). In turn, voluntary limits of stability (LOS) testing was performed before, immediately after, and 10 minutes after STS exercise as a measure of voluntary lean range and reduced ability to control balance at postural limits. It was hypothesized that prolonged STS exercise would impair postural stability as indicated by increased total COP path excursions during the chair rise, and would be accompanied by increased COP sway velocities at extreme LOS. In turn, the adoption of stabilization strategies would be reflected by a more anterior COP position at seat-off, towards the mid-foot (i.e., most stable position; Schultz et al., 1992), as well as a reduced voluntary dynamic lean range amplitudes as a means to prevent COP devations towards outer support surface boundries provided by the feet (Blasyzyck et al., 2009).

Manuscript 2 Research Questions and Hypotheses

Valuable information can be gained from comparing movement control strategies in young and older adults during the sit-to-stand (STS), and it has been a widely researched movement in biomechanical investigations (Bohannon, 1995; Tiedman et al., 2008). Calculations of maximal joint kinetics during the STS are commonly reported in young and older adults (Greve et al., 2013; Gross et al., 1998; Hughes et al., 1996); however measures of peak performances only provide an instantaneous view of muscular control strategies when ascending from a seated position. Through considering the role of muscular contributions both in preparation for loss of contact with the seat, as well as while ascending vertically, this may provide valuable information regarding the underlying mechanisms responsible for compensatory strategies with multi-articular fatigue, and how this may be impacted with aging. The purpose of this study was to compare alterations in ankle, knee, and hip kinetics and their ditributions across the lower extremities in young and older adults, during the course of a repetitive STS exercise. Combined 3D motion analysis and force plate data allowed calculations of joint excursions, net joint moments, and mechanical net joint work performance during both preparatory (initiation of movement until contact is lost with the seat) and ascending (seat-off until full upright posture is achieved) STS phases. An uneven distribution of muscular efforts across the lower extremtities has been previously documented during the STS (Bieryla et al., 2007; Burnfield et al., 2012); therefore it was hypothesized that greater knee extensor (KE) relative efforts required to rise from a seated position would lead to greater impairments in KE force generating capabilities with sustained activity, and a compensatory shifting of loading demands to the hip and ankle would result. In turn, since aging has also been previously associated with a redistribtuon of joint torques during gait (DeVita & Hortobagyi, 2000), it was hypothesized that lower KE NJM and work outputs would be associated with greater hip extensor contributions to older participants' STS performances. This would then also increase to a greater extent in older compared to younger adults with sustained activity due to age-related declines in KE strength reserves.

Manuscript 3 Research Questions and Hypotheses

STS capacity is a commonly used tool in rehabilitative settings for indirect measures of lower extremity strength and risk of disability with aging (Jones et al., 1999; Petrella et al., 2005); however it unclear as to how muscular performance limits one's ability to repeatedly rise from a seated position. The purpose of this investigation was to determine the role of thigh muscular effort requirements (Quadriceps Femoris and Bicep Femoris % MVCs) in limiting the capacity to perform repetitive STS exercise in young and older adults (i.e., total task time). It was hypothesized that reduced KE strength reserves with aging (Fujita et al., 2011; Greve et al., 2013; Hughes et al., 1999) would be reflective of significantly higher quadriceps EMG activation intentsities in older adults when rising from a chair. Moreoever, it was expected that quadriceps efforts requirements would be a significant predictor of total STS exercise endurance times.

Lastly, it was also expected that greater co-actvity of the hamstrings in older persons (Horotagyi et al., 2003) may also limit STS capacities by further increasing KE force requirements in order to balance the flexor-effect of the hamstrings at the knee (Bryanton et al., 2015).

Manuscript 4 Research Questions and Hypotheses

Available KE strength has been repeatedly associated with STS performance variables and functional independence in older persons (Manini et al., 2007; Scarborough et al., 2007); however it is unclear how reduced force generating capabilities of a primary agonist muscle such as the KE may influence muscular control strategies amongst the lower extremities during chair rise. The aim of this final investigation was to evaluate age-dependent alterations in surface EMG muscular activation requirements across the lower extremities with reduced KE force generating capabilities due to isolated dynamic fatiguing exercise. It was hypothesized that KE fatigue would increase one's reliance on non-fatigued ankle and hip musculature when subsequently asked to rise from a seated position. In turn, it was expected that the degree of the compensatory muscle strategy presented would be related to the extent to which force generating capabilies are compromised, and would be more prominent in older participants with lower KE strength reserves.

Through understanding a muscle's ability to contribute during a multi-joint task, and why unfavorable compensation strategies manifest, this research was intended to elucidate how age-related declines in muscle performance determine the ability of older adults to safely perform common daily tasks, such as standing from a chair and getting out of the bed. Specifically, this research revealed the nature of compensatory movement strategies with repetitive activity, and how young and older adults may alter their STS strategy differently with multi-articular versus isolated fatiguing exercise. Lastly, it demonstrated how force generating capabilities of the KE musculature reflect STS muscular control strategies adopted, and how reduced KE strength reserves with aging limit an older person’s ability to repeteadly rise form a seated position.

CHAPTER 4

MANUSCRIPT 1:

Postural Stability with Exhaustive Repetitive Sit-To-Stand Exercise in Young Adults

Megan Bryanton, Martin Bilodeau

(Human Movement Science, 49(2016), 47-53)

Postural Stability with Exhaustive Repetitive Sit-To-Stand Exercise in Young Adults

[1,3]Megan Bryanton, [2,3]Martin Bilodeau

[1]School of Human Kinetics, University of Ottawa, ON, CA

[2]School of Rehabilitation Sciences, University of Ottawa, ON, CA

[3]Aging and Movement Laboratory, Bruyère Research Institute, ON, CA

Submission Type: Original Article

Disclosure of Funding: This research was partially funded by the Canada Foundation for Innovation (M. Bilodeau) and a Faculty of Health Sciences Admission's scholarship to M. Bryanton

ABSTRACT

Previous research has indicated that muscle fatigue due to repeated bouts of physical activity can have negative residual effects on balance; however investigations using multi-joint forms of exercise involved in everyday settings and determination of how control of posture is altered during the physical activity itself are limited. The purpose of this investigation was to evaluate alterations in postural stability before, during, and after prolonged multi-joint STS exercise in healthy young adults. Center of pressure (COP) acquisitions were collected during repetitive STS exercise, while voluntary limits of stability (LOS) testing was performed before, immediately after, and 10 minutes after STS exercise. By 50% total STS exercise time, fatigue resulted in increased anterio-posterior (y) and medio-lateral (x) COP path lengths (p=0.003 and p=0.018 respectively) and an anterior shift of COP at seat-off towards the mid-foot (p=0.010). No significant change in LOS mean amplitude was found after STS exercise; however a significant fatigue effect resulted in increased COPy sway velocity at maximal lean positions (p=0.006), but returned to PRE values after 10 minutes of rest. Declines in postural stability during repetitive STS exercise was associated with reduced control of COP, as well as a reduced ability to stably control COP at extreme postural limits; however, 10 minutes was adequate in young adults for recovery. These results may have important implications for monitoring fall risk due to acute bouts of exercise induced muscle fatigue from repetitive multi-joint activities such as the STS.

Keywords: posture; dynamic stability; limits of stability; exercise; fatigue;

1. Introduction

Performing physical activities, either through exercise or repetitive daily actions has been shown to be beneficial for the maintenance of functional mobility of the lower extremity (French et al., 2010). However the associated accumulation of muscular fatigue can have negative consequences for balance control and prolonged physical activity can increase the risk of falling during the activity itself and residual effects on balance control may remain after the cessation of exercise (Chaubet & Paillard, 2012; Paillard, 2012). Postural control is commonly described as the ability to maintain or restore balance, reflected by a greater ability to control body sway, and commonly evaluated using acquisitions of either body centre of mass (COM) or center of pressures (COP) with respect to the base of support (Pollock, Durward, Rowe, & Paul, 2000; Ruhe, Fejer, & Walker, 2010).

Previous investigations have indicated that with fatiguing exercise, and increase in COP sway area and velocity reflects poorer balance capabilities during quiet standing (Ruhe et al., 2010); however, the influence of fatigue on postural stability during dynamic tasks is less explored. In comparison to bouts of quiet standing, multi-joint transfer tasks of daily living involve large displacements of COM and require that segment positions are controlled in an accurate and coordinated fashion to prevent COP from deviating outside of one’s functional postural boundaries about the base of support, or limits of stability (LOS). Sparto, Parnianpour, Reinsel and Simon (1997) investigated the effects of prolonged repetitive lifting on joint dynamics and postural stability in young adults by measuring anterio-posterior (A-P) excursions of COP and trunk COM. They noted significantly increased A-P COP excursions by the end of the lifting protocol, which was reflective of COM trunk excursion. Thus, COP movements during dynamic repetitive lifting were reflective of whole body control dynamics, and may be a feasible measurement technique to detect instability during multi-joint tasks.

Another commonly investigated multi-joint task is the sit-to-stand (STS) due its association with muscular performance of the lower extremities and functional capabilities (Bohannon, 1995; Lazaro, Gonzalez, Latorre, Fernandez, & Ribera, 2011; Tiedemann, Shimada, Sherrington, Murray, & Lord, 2008). The ability to rise from a seated position is a basic, but challenging skill associated with numerous activities of daily living that requires the development of relatively high muscular efforts even in healthy young adults (Bieryla, Anderson, & Madigan, 2009; Hortobágyi, Mizelle, Beam, & DeVita, 2003), which may lead to substantial accumulation of fatigue with repetitive actions. Additionally, STS exercise is especially demanding in terms of its reliance on balance control capabilities in order to achieve an upright standing position as it requires the precise control of COM over a rapid reduction in support surface the moment contact is lost with the seat (Akram & McIlroy, 2011; Doorenbosch, Harlaar, Roenbroeck, & Lankhorts, 1994; Fugimoto & Chiu, 2012; Shultz, Alexander, & Ashton-Miller, 1992). Therefore it is understandable why its capacity has been shown to be a predictor of disability in populations experiencing functional declines (Tiedemann et al., 2008). Consequently, determining indicators of compromised postural control during the STS warrants further investigation.

Considering this, it would be beneficial to evaluate COP control capabilities not only before and after exercise, but also during a STS fatiguing task itself and the ability to recover after the cessation of exercise. The purpose of this investigation was to evaluate alterations in dynamic postural stability during exhaustive STS exercise in young adults through evaluation of COP excursions with respect to protocol progression. In turn, to see if this is associated with any stabilization strategies to cope with instability, COP positions at the moment contact is lost with the seat was also evaluated since this is the most unstable point in time during the STS. Secondly, to confirm that such supposed instability was associated with reduction in balance control during another postural task, LOS testing was performed prior to and immediately after the cessation of STS exercise. Lastly, to test the ability to recover from any postural instability, LOS testing was also performed 10 minutes afterwards. We hypothesized prolonged STS exercise would result in increased COP path excursions when ascending from a seated position and would be directly related to the adoption of preparatory stabilization strategies when losing contact with the seat, through the anterior relocation of COP towards the mid-foot, away from posterior boundaries of stability. This would also be associated with reduced LOS performance immediately after multi-joint exercise to prevent COP from deviating toward extreme postural limits and reduce risk of falling due to reduce control of COP about one's base of support.

2. Methods

2.1. Participants

Ten health young adult men (n=6) and women (n=4) between the ages of 18-35 years (26.4 ± 3.6 yrs.) from a convenience sample of the university community participated in this investigation. Participants were instructed to refrain from any strenuous lower extremity activities prior to visiting the laboratory. The study was approved under the University of Ottawa and Bruyère Continuing Care Institutional Review Boards and prior to testing, written informed consent was obtained from each participant.

2.2. Procedures

2.2.1. Limits of Stability (LOS) Testing

The LOS task was performed on an AMTI Acu-Gait force platform (Watertown, MA) where net ground reaction forces were collected at a sampling rate of 100 Hz using NetForce v. 2.2 (AMTI, Watertown, MA). Participants were asked to stand barefoot with feet together on the platform to measure their maximal voluntary range of antero-posterior (A-P) COP displacement (Blasyzyck, Cieslinska-Swider, Plewa, & Zahorska-Markiewicz, 2009), which was calculated using BioAnalysis 2.3 software (AMTI, Watertown, MA). To do so, participants were instructed to lean forward toward their toes and then heels, over the largest possible amplitude by rotating about the ankle, maintaining full contact between their feet and the plate (i.e., avoiding toes or heels off), and while keeping their body as rigid as possible. Each maximum lean position was maintained for 10 s in order to determine average COP acquisitions about the feet over the sustained period. The LOS testing was performed before (PRE), after (POST), and 10 minutes after (RECOV) a fatiguing STS exercise protocol. A total of three successive leaning trials were performed at each of the three time points in order to be further averaged in subsequent analyses.

2.2.2. STS Fatigue Protocol

Subjects were seated on an armless and backless bench (29 cm x 42.5 cm), and the height was adjusted to 80% of the participants' lower leg lengths in order to ensure adequate muscular efforts to induce fatigue in the young adult participants (Hughes, Myers, & Schenkman, 1996; Janssen, Bussmann, & Stam, 2002). A pressure sensitive switch was incorporated into the front of the bench to indicate when contact with the seat was lost during the STS. This trigger was synchronized with a force plate into Spike2. Lastly, participants' feet were positioned shoulder width apart, barefoot, with heal and toe positions marked on the force platform to ensure that the feet did not move during the fatigue protocol.

Prior to standing, subjects were instructed to sit in a comfortable erect posture with their arms folded across their chest to deter the use of compensatory arm swinging. For each STS repetition, subjects were instructed to stand up from the bench to a fully extended erect posture, to pause briefly, and then to return to the initial seated position while maintaining foot contact with the force platforms at all times. STS repetitions were performed in synchronization to the beat of an audible metronome set to 35 beats per minutes (first beat signaled to ascend and the next to descend) until: a) they could no longer maintain the given pace for 5 consecutive beats,

b) volitional exhaustion occurred, or c) a 30 minute cut-off time was reached (Barbieri, dos Santos, Vitório, van Dieën, & Gobbi, 2013). This pace was selected as it was a comfortable pace for participants, yet it prevented recovery between STS ascending and descending phase repetitions to induce fatigue. Strong verbal encouragement was provided when needed, especially during the later stages of the fatigue protocol to ensure maximal STS times. Lastly, a modified 10-point Borg scale (Borg, 1982) was administered every minute to monitor the participants' perceived exertion (0 = no effort and 10 = maximal effort) in order for the researcher to evaluate the extent of exercise progression (i.e., if they were feeling fatigue and if they were getting close to exhaustion).

2.3. Data Analysis

During the STS exercise, 10 repetitions were taken at the beginning (START; 0%), halfway (HALF; 50%), and end (END; 100%) points of the fatigue protocol for each participant for analyses. From this, postural variables were calculated and averaged over the 10 STS repetition, which included: a) COP coordinates at moment of *seat-off* relative to average foot length: *0%foot*=heel, *50%foot*=mid-foot, *100%foot*=distal end of 2nd toe, and b) total COP path lengths (PL), separated into COPy and COPx displacements per STS ascent repetition (cmrep^{-1}). Data analysis used to evaluate alterations in LOS performance included measurements of the amplitude of maximal voluntary A-P COP leaning (i.e. distance between average position held in anterior position and that of the posterior lean positions), and ranges were normalized with respect to total foot length (%foot). Secondly, average COPy and COPx sway velocities (cms^{-1}) over the 10 s held lean positions were also calculated, and then further averaged between the two forward and backward lean attempts as an indication of the participant's ability to maintain extreme postural limits without falling or stepping.

To test the effects of STS exercise on LOS performance, repeated measures analyses of variance (ANOVAs) (fatigue; PRE vs POST vs RECOV) were used for COP A-P dynamic ranges and sway velocities. Statistical testing for STS COP positions at seat-off, as well as COPx and COPy path lengths, used ANOVAs with one repeated-measure of time (START, HALF, END). Secondly, Pearson product-moment correlation coefficient analyses were performed in order to determine the relationship between COP *seat-off* position and path lengths with STS exercise progression. Where appropriate, Tukey HSD was used for post-hoc comparisons. The alpha level was set *a priori* at $\alpha=0.05$.

3. Results

3.1. Sit-to-Stand Exercise

Statistical analyses of STS postural data found a significant time effect for COPy at seat-off (p=0.010, F= 6.555). Post hoc analyses showed a significant anterior shift in COP *seat-off* position towards the center of foot (i.e., 50% foot length) from 32.73 ± 7.95% (START) to 41.76 ± 17.48% by the HALF time point (p=0.037). By the END time point, a position of 47.62 ± 16.48% foot length was observed which was significantly different from the initial START position (p=0.012); however this final COPy *seat-off* position was not significantly different from HALF time point positions (p=0.224) (Table 1 and Fig.1). Similar results were found for COPy and COPx path lengths (PL), when compared to initial (START) values, as significantly greater COP excursions per STS repetition were found by HALF (COPy-PL: p=0.003, COPx-PL: p=0.018) and END (COPy-PL: p=0.019, COPx-PL: p=0.017) values. Furthermore, no significant differences were again observed between HALF and END points (COPy-PL: p=0.146; COPx-PL: p=0.985) (Fig. 2). Correlation analyses also found significant positive relationships between COPy-PL and COPx-PL (r= 0.520, p=0.003) and between COPy-PL and

COPy at seat-off (r=0.386, p=0.028) but not for COPx-PL and COPy at seat-off (although a trend toward significance was seen; r=0.323, p=0.062).

Lastly, Borg scale ratings of perceived exertion significantly increased as STS exercise progressed (START vs. HALF; p=0.000, START vs. END; p=0.000, and HALF vs. END; p=0.000), with group average ratings starting at 1.55 (±1.07) (i.e. easy) at the beginning of the protocol, which increased to 7.05 (±1.78) and 8.6 (±1.96) by halfway and end points respectively (i.e. really hard). Finally, group mean total STS exercise time was 23.2 (± 9.2) minutes, where 6 out of the 10 participants reached the 30 minute cut-off time.

3.2. Limits of Stability Testing

A significant fatigue effect was found to be significant for COPy sway velocity (p=0.000, F=15.028), while trends towards significance were found for both mean A-P LOS (p=0.076, F=2.978) and COPx sway velocity (p=0.064, F=3.210). Posthoc analyses showed that the significant increase in COPy sway velocity occurred between PRE and POST measures (p=0.002), with a subsequent significant decrease between POST and RECOV (p=0.000) time points. Moreover, there was no significant difference between PRE and RECOV measures (p=0.179); 10 minutes of recovery was adequate to restore COPy velocity to initial PRE values (Fig. 3).

4. Discussion

The primary purpose of this investigation was to examine how repetitive multi-joint STS exercise influences postural control in young adults through characterizing COP excursions. Our findings demonstrated that prolonged STS exercise resulted in increased COP path lengths that were directly associated with an anterior compensatory shift in COP towards the center of the foot away from the ankle in preparation for the rapid reduction in support surface when ascending from a seated position. An increase in COP excursions about the feet when rising from a chair would suggest a reduced ability to control whole body dynamics due to fatigue as greater deviations and variability of COP occurring between starting (seated) and ending (standing) body positions (Hernandez, Ashton-Miller, & Alexander, 2012; Sparto et al., 1997). Furthermore, when rising from a seated position, a COP position at mid-foot is considered to be the most stable position away from the extreme LOS in preparation for a rapid reduction in support surface once contact is lost with the seat (Akram & McIlroy, 2011; Mourey, Grishin, d'Athis, Pozzo, & Stapley, 2000; Shultz et al., 1992). This may suggest that a stabilization strategy to improve postural stability was adopted in preparation for seat-off and narrowed postural boundries. For example, during the STS, older adults also tend to have more anterior COP positions towards the mid-foot in preparation for seat-off in comparison to younger adults (Alexander, Shultz, & Warwick, 1991; Shultz et al., 1992). This is attributed to the fact that older adults tend to favor COM positions over their feet prior to losing contact with their seat by rotating their body segments forward due to age-related declines in balance capabilities (Pappa & Cappozzo, 2000). Together, this strategy has the potential to improve stability and prevent postural limits from being stressed (Blaszczyk et al, 2009; Hernandez, Ashton-Miller & Alexander, 2012).

It should be noted that a significant anterior shift in COP was only seen between the START to HALF (50% total time) time points. This was also noted for COP path lengths when participants stood up, where significant increases were seen in both A-P (COPy) and M-L (COPx) planes from START (0%) to HALF (50%) time points, with no further changes past this time (Fig. 2) and suggests that a stabilization strategy was adopted by participants by the halfway point of fatiguing exercise and participants were able to continue STS exercise until exhaustion. Muscle fatigue negatively impacts postural stability through altering sensory information provided to the central nervous system from muscle afferents, as well as force generation and control capabilities (Chaubet & Paillard, 2012; Missenard, Mottet, & Perry, 2009; Paillard, 2012). Although it is suspected that the accumulation of fatigue in the lower extremity musculature and contractile failure may be responsible for the cessation of exercise when volitional exhaustion was reached, it is unlikely that insufficient force was responsible for changes in COP measurements since no further change was seen past 50% total STS time. It is more likely that compromised afferent somatosensory input regarding joint position sense for accurate corrective muscle actions to control posture were responsible for decrements in postural stability at this point in time.

The secondary objective of this investigation was to evaluate the effects of multi-joint fatiguing exercise on a different postural task that stressed functional postural limits, and to determine short-term recovery capabilities of the young adult participants. Previous investigations have found that reductions in LOS are indicative of compromised postural capabilities as individuals experiencing functional declines will utilize a conservative control strategy to prevent COP from deviating towards postural extremes about their feet (i.e. base of support) (Blaszczyk et al., 2009; Corbeil, Simoneau, Rancourt, Tremley, & Teasedale, 2001; Hernandez et al., 2012). In this investigation, although not statistically significant, a trend towards a reduction in voluntary A-P LOS range was observed. Together, exhaustive STS exercise resulted in anterior shifting COP towards the middle of the foot at to seat-off during the fatigue protocol itself, may indicate that participants adopted a stiffening strategy to restrict COP deviations immediately after the cessation of exercise. An alternative explanation for the anterior shift in COP during the STS may be due to a compensatory increase in toe involvement to control COP about the feet in order to improve balance control rather than a compensatory restricting COP to the mid-foot (Bisiuax & Moretto, 2008; Vueillerm & Pinsault, 2007). For example, Bisiaux and Moretto noted an anterior shift in plantar pressure distribution towards the forefoot rather that middle of the foot during gait after fatiguing running exercise. Therefore, previous research that have suggested that an anterior shift in COP when losing contact with the seat is adopted in order to stabilize oneself may be misleading and requires further investigation.

A significant increase in COPy sway velocity at extreme voluntary A-P postural limits was also found after repetitive STS exercise. Therefore, declines in the control of COP was present immediately after repetitive STS exercise that was indicated by an increase in the number of corrections made while attempting to stably maintain maximal anterior and posterior lean positions during upright stance, particularly in the sagittal plane (Hernandez et al, 2012; Prado, Mauro, & Duarte, 2011; Shummway-Cook & Woollacott, 1995; Winter, 1996). Lastly, COPy sway velocities returned to pre-fatigue levels after 10 minutes of rest was provided to participants, thus recovery periods were brief in young adults after exhaustive STS exercise.

Furthermore, although a trend towards an increase in COPx sway velocities was observed after fatiguing STS exercise, this was not found to be significant. Fatigue due to STS exercise may have therefore been primarily accumulated in musculature that control sagittal body sway such as ankle plantar-flexor and knee extensor musculature (Barbieri et al., 2013), whereas medial-lateral sway controlled predominately by hip and trunk musculature through a loading/unloading strategy may have been affected to a lesser extent (Shummway-Cook & Woollacott, 1995; Winter, 1996). It has been previously shown that STS movement requires significantly higher levels of KE efforts compared to that at the ankle and hip (Bieryla et al., 2009; Burnfield et al., 2012), and it is possible that increased COPy sway velocities during LOS testing immediately after repetitive STS exercise may be attributable to greater accumulation of fatigue in KE musculature (Barbieri et al., 2013). Since the control of COP position within the BOS is primarily reliant on ankle musculature (Corbeil et al., 2001; Doorenbosch et al, 1994) the amplitude of the A-P voluntary LOS may not have been affected by the STS fatigue protocol if significantly lower efforts were required by the ankle musculature compared to those at the knee. This notion is corroborated by Mademli, Arampatzis, and Karamanidis (2008) who found that LOS was not affected by knee extensor and flexor fatigue in young and older adults. In turn, other repetitive multi-joint movements that require greater ankle plantar-flexor efforts such as running or jumping may have a greater influence on the amplitude of A-P LOS amplitudes compared to the STS exercise protocol used in this investigation. Regardless, fatigue of thigh musculature may negatively impact dynamic postural stability that may not be revealed through traditional LOS amplitude measures. Unfortunately muscle activity levels were not measured in this investigation, therefore the extent to which participants' muscles groups were fatigued and how they may have been responsible for decrements in stability remain unclear and warrants future investigation.

STS exercise has recently been used as a functional training task and its effectiveness has been investigated in populations experiencing neuromuscular declines (Cheng, Wu, Liaw, Wong, & Tang, 2001; French et al., 2010; Liao, Liu, Liu, & Lin, 2007). For example, Cheng et al. showed that repetitive sit-to-stand balance training improved symmetry of body weight distribution in patient with hemiplegic stroke; whereas Liao et al. found that loaded STS exercise improved functional muscle strength and motor abilities in children with mild spastic diplegia. Therefore, the results of our investigation may have important implications for monitoring fall risk due to acute bouts of exercise-induced muscle fatigue and have applications to rehabilitative settings that utilize STS exercise as a tool to improve lower extremity function. A limitation of our investigation was that it involved healthy young adults whose postural control is not compromised and are not representative of populations that would benefit from this form of functional training exercise. However, since postural alterations due to STS exercise were found in young adults, it is expected that this would be exacerbated in patients with functional disabilities. Furthermore, 10 minutes of rest was sufficient for postural stability to be recovered after STS exercise in young adult participants and is recommended to reduce risk of falling and injury after continuous moderate- intensity exercise bouts of up to 30 minutes. However, this may be insufficient for other populations experiencing neuromuscular declines, as well as after much lower, sub-maximal occupational tasks performed for longer than 30 minutes (Paillard, 2012).

In summary, this investigation demonstrated that declines in postural control were induced from muscle fatigue due to repetitive STS exercise in young, healthy adults. By approximately the halfway time point of the exhaustive protocol, participants demonstrated compensatory anterior shifting of COP to prepare for loss of contact with the seat, from the ankle towards the middle of the foot. Secondly, although the amplitude of the young adult participants' LOS was not compromised immediately after the cessation of the exhaustive protocol, their ability to stably control COP at extreme A-P lean positions was negatively affected. Lastly, ten minutes of rest provided sufficient recovery time for young adult participants involved in this investigation.

Conflict of interest statement

None of the authors have financial or other conflicts of interest in regards to this research.

REFERENCES

Akram, S. B., & McIlroy, W. E. (2011). Challenging horizontal movement of the body during sit-to-stand: Impact on stability in the young and elderly. *Journal of Motor Behavior*; *43*(2), 147-153.

Alexander, N. B., Schultz, A. B., & Warwick, D. N. (1991). Rising from a chair: Effects of age and functional ability on performance biomechanics. *Journal of Gerontology, 46*, M91-M98.

Barbieri, F. A., dos Santos, P. C. R., Vitório, R., van Dieën, J. H., & Gobbi, L. T. B. (2013). Effect of muscle fatigue and physical activity level in motor control of the gait of young adults. *Gait & posture*, *38*(4), 702-707.

Bieryla, K. A., Anderson, D. E., & Madigan, M. L. (2009). Estimations of relative effort during sit-to-stand increase when accounting for variations in maximum voluntary torque with joint angle and angular velocity. *Journal of Electromyography and Kinesiology, 19*, 139-144.

Bisiaux, M., & Morretto, P. (2008). The effects of fatigue on plantar pressure distribution in walking. *Gait & Posture, 28*, 693-698.

Blaszczyk, J. W., Cieslinska-Swider, J., Plewa, M., & Zahorska-Markiewicz, A. (2009). Effects of excessive bodyweight on postural control. *Journal of Biomechanics*, *42*, 1295-300.

Bohannon, R. W. (1995). Sit-to-stand test for measuring performance of lower extremity muscles. *Perceptual and Motor Skills*, *8*0(1), 163-166.

Borg, G. A. V. (1982). Psychological bases of perceived exertion. *Medicine and Science in Sports and Exercise*, *14*(5), 377-381.

Burnfield, J. M., Shu, Y., Buster, T. W., Taylor, A. P., McBride, M. M., & Krause, M. E. (2012). Kinematic and electromyographic analyses of normal and device-assisted sit-to-stand transfers*. Gait & Posture, 36*(3), 516-522.

Chaubet, V., & Paillard, T. (2012). Effects of unilateral knee extension muscle fatigue induced by stimulated and voluntary contraction on postural control during bipedal stance. *Neurophysiologie Clinique/ Clinical Neurophysiology, 42*, 377-383.

Cheng, P. T., Wu, S. H., Liaw, M. Y., Wong, A. M. K., & Tang, F. T. (2001). Symmetrical body-weight distribution training in stroke patients and its effects on fall prevention. *Archives of Physical Medicine and Rehabilitation, 82*(12), 1650-1654.

Corbeil, P., Simoneau, M., Rancourt, D., Tremley, A., & Teasedale, N. (2001). Increased risk of falling associated with obesity: Mathematical modeling of postural control. *IEEE Trans Neural Syst Rehabil Eng, 9*, 126-36.

Doorenbosch, C. A. M., Harlaar, J., Roenbroeck, M. E., & Lankhorts, G. J. (1994). Two strategies transferring from sit-to-stand: The activation of monoarticular and biarticular muscles. *Journal of Biomechanics*, 27(11), 1299-1307.

French, B., Thomas, L., Leathley, M., Sutton, C., McAdam, J., Forster, A., & Watkins, C. (2010). Does repetitive task training improve functional activity after stroke? A Cochrane systematic review and meta-analysis. *Journal of rehabilitation medicine*, *42*(1), 9-15.

Fugimoto, M., & Chou, L. (2012). Dynamic balance during sit-to-stand movement: An examination with centre of mass acceleration. *Journal of Biomechanics, 45*, 543-548.

Hernandez, M. E., Ashton-Miller, J. A., & Alexander, N. B. (2012). Age-related changes in speed and accuracy during rapid targeted center of pressure movements near the posterior limits of base of support. *Clinical Biomechanics, 27*, 910-916.

Hortobágyi, T., Mizelle, C., Beam, S., & DeVita, P. (2003). Old adults perform activities of daily living near their maximal capabilities. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *58*(5), M453-M460.

Hughes, M.A., Myers, B.S., & Schenkman, M.L. (1996). The role of strength in rising from a chair in the functionally impaired elderly. *Journal of Biomechanics, 29*, 1509-1513.

Janssen, W. G., Bussmann, H. B., & Stam, H. J. (2002). Determinants of the sit-to-stand movement: a review. *Physical Therapy*, *82*(9), 866-879.

Lazaro, M., Gonzalez, A., Latorre, G., Fernandez, C., & Ribera, J. M. (2011). Postural stability in fallers versus non fallers. *European Geriatric Medicine*, *2*(1), 1-5.

Liao, H. F., Liu, Y. C., Liu, W. Y., & Lin, Y. T. (2007). Effectiveness of loaded sit-to-stand resistance exercise for children with mild spastic diplegia: A randomized clinical trial. *Archives of Physical Medicine and Rehabilitation, 88*(1), 25-31.

Mademli, L., Arampatzis, A., & Karamanidis, K. (2008). Dynamic stability control in forward falls: Postural corrections after muscle fatigue in young and older adults. *European Journal of Applied Physiology*, *103*, 295-306.

Missenard, O., Mottet, D., & Perry, S. (2009). Factors responsible for force steadiness impairments with fatigue. *Muscle & Nerve, 40*, 1019-1032.

Mourey, F., Grishin, A., d'Athis, P., Pozzo, T., & Stapley, P. (2000). Standing up from a chair as a dynamic equilibrium task: A comparison between young and elderly subjects. *Journal of Gerontology: Biological Sciences*, *55A* (9), B425-B431.

Paillard, T. (2012). Effects of general and local muscle fatigue on postural control: A review. *Neuroscience and Biobehavioural Reviews*, *36*, 162-176.

Pappa, E., & Cappozzo, A. (2000). Sit-to-stand motor strategies investigated in able-bodied young and elderly subjects. *Journal of Biomediatrics*, *33*(9), 1113-1122.

Pollack, A. S., Durward, B. R., Rowe, P. J., & Paul, J. P. (2000). What is balance? *Clinical Rehabilitation, 14*(4), 402-406.

Prado, J.M., Mauro, C.M., & Duarte, M. (2011). Age-related difference on weight transfer during unconstrained standing*. Gait and Posture, 33*(1), 93-97.

Ruhe, A., Fejer, R., & Walker, B. (2010). The test-retest reliability of centre of pressure measures in bipedal static task conditions- a systematic review of literature. *Gait & Posture*, *32*(4), 436-445.

Shultz, A. B., Alexander, N. B., & Ashton-Miller, J. A. (1992). Biomechanical analyses of rising from a chair. *Journal of Biomechanics, 25*(12), 1383-1391.

Shummway-Cook, A., & Woollacott, M.H. (1995). *Motor control: Theory and practical applications*. Lippincott Williams and Wilkins.

Sparto, P.J., Parnianpour, M., Reinsel, T.E., & Simon, S. (1997b). The effect of fatigue on multi-joint kinematics, coordination, and postural stability during a repetitive lifting test. *Journal of Orthopaedic and Sports Physical Therapy Association, 25(*1), 3-12.

Tiedemann, A., Shimada, H., Sherrington, C., Murray, S., & Lord, S. (2008). The comparative ability of eight functional mobility tests for predicting falls in community-dwelling older people. *Age and Ageing*, *37*, 430-435.

Vuillerme, N., & Pinsault, N. (2007). Re-weighting of somatosensory inputs from the foot and the ankle for controlling posture during quiet standing following trunk extensor muscles fatigue. *Experimental Brain Research*, *183*, 323-327.

Winter, D.A. (1996). Unified theory regarding A/P and M/L balance in quiet stance. *Journal of Neurophysiology*, *75*, 2334-2343.

LIST OF FIGURES

Fig. 1. Raw force plate data for COP seat-off coordinates (cm) of a participant (starting from far left) at the START, HALF and END time points of the repetitive STS exercise. Dashed lines denote average mid-foot location.

Fig. 2. Average COPy and COPx path lengths per repetition during the ascending phase of the STS with fatigue protocol progression. Bars denote SDs.*s indicate significant difference from start.

Fig. 3. Group mean COPy and COPx sway velocities (cm/s) at maximal voluntary lean positions during dynamic range testing with fatigue condition. Error bars denote SDs. *s denotes significant difference from pre-fatigue and recovery conditions*.*

Table 1. Pearson Correlation Coefficients (r) and Group Mean (± SD) COP Path Lengths (PL) per STS Repetition (cm/rep) and COPy (% foot length) Positions at Moment of *Seat-off* with STS Exercise Protocol Progression (% total time)

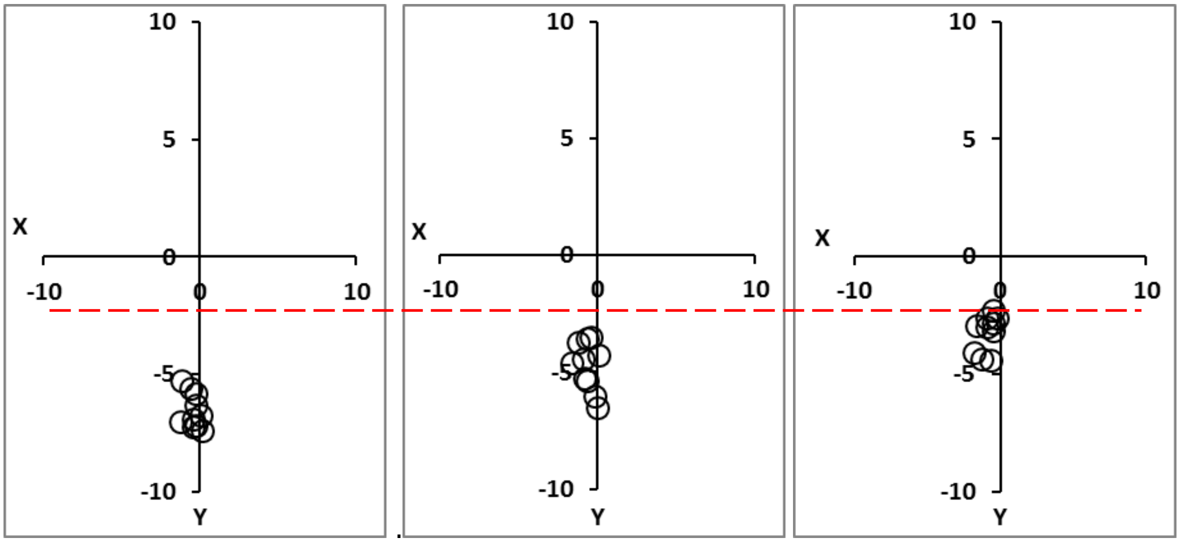
Measure	COPy-off	COPy-PL	COPx-PL	START (0%)	HALF (50%)	END (100%)
COPy-off	----	0.386$^{\#}$	0.323	32.73 (7.95)	41.76 (17.48)*	47.62 (16.48)*
COPy-PL	0.386$^{\#}$	----	0.520$^{\#}$	18.10 (2.80)	24.64 (5.77)*	21.40 (4.99)*
COPx-PL	0.323	0.520$^{\#}$	----	14.35 (3.01)	20.73 (6.21)*	20.94 (5.91)*

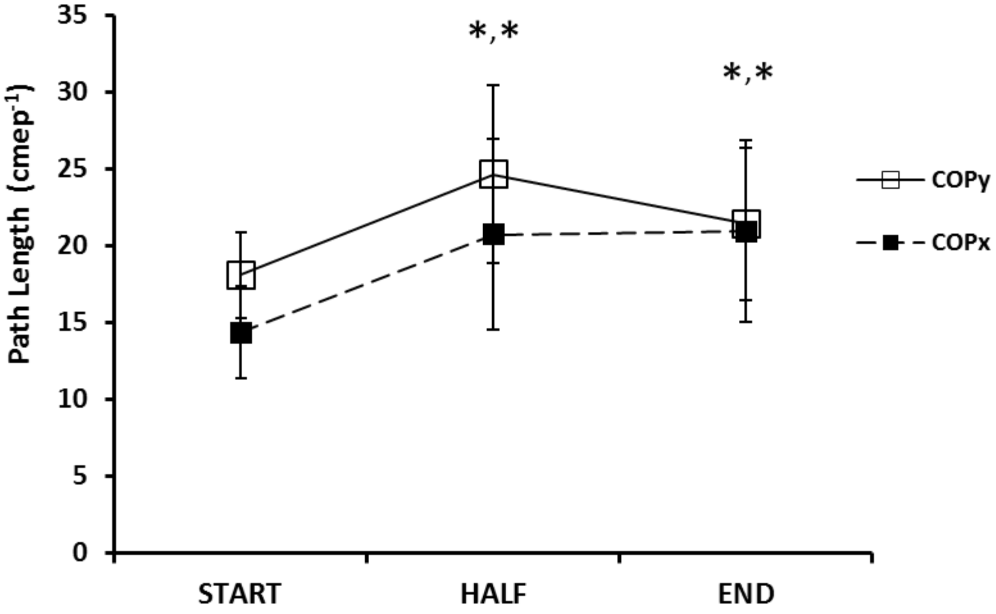
*Note.**s denote significant difference from START. $^{\#}$ denotes significant correlation.

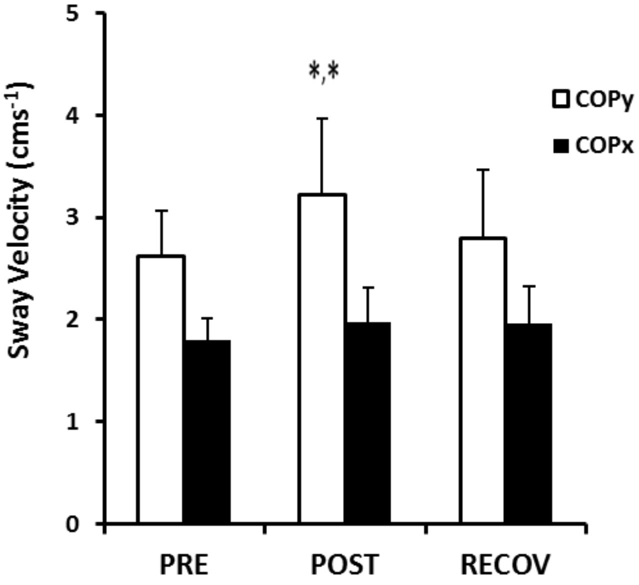
Table 2. Group mean (±SD) COP A-P dynamic range (%foot), and COP sway velocities (cm/s) during LOS testing with respect to fatigue conditions.

Measure	PRE	POST	RECOV
A-P Range	59.19 (7.63)	55.67 (6.02)	54.99 (6.21)
COPy	2.62 (0.45)**	3.23 (0.74)*	2.79 (0.68)**
COPx	1.80 (0.21)	2.00 (0.33)	1.96 (0.36)

Note. * indicates significant difference from PRE conditions, ** indicates significant difference from POST conditions.


10
5
X
0
-10
0
10
-5
-10
Y
10
5
X
0
-10
0
10
-5
-10
Y
10
5
X
0
-10
0
10
-5
-10
Y


Path Length (cmep-1)
35
30
25
20
15
10
5
0
START
HALF
END
,
,
COPy
COPx


Sway Velocity (cms-1)
5
4
3
2
1
0
,
COPy
COPx
PRE
POST
RECOV

CHAPTER 5

MANUSCRIPT 2:

Compensatory Alterations in Joint Kinetics during Repetitive Sit-to-Stand Exercise in Young and Older Adults

Megan Bryanton, Martin Bilodeau

Compensatory Alterations in Joint Kinetics during Repetitive Sit-to-Stand Exercise in Young and Older Adults

[1,3] Megan Bryanton, [2,3] Martin Bilodeau

[1]School of Human Kinetics, University of Ottawa, ON, CA
[2]School of Rehabilitation Sciences, University of Ottawa, ON, CA
[3]Aging and Movement Laboratory, Bruyère Research Institute, ON, CA

Submission Type: Original Article

Disclosure of Funding: This research was partially funded by the Canada Foundation for Innovation (M. Bilodeau) and a Faculty of Health Sciences Admission's scholarship to M. Bryanton

Abstract

The sit-to-stand (STS) is an essential skill for functional independence; unfortunately, many older adults experience difficulty rising from a seated position due to declining muscle reserves. Strength limitations due to aging may also result in compensation strategies through shifting of mechanical demands from one joint to another with repetitive multi-joint exercise. The purpose of this investigation was to compare alterations in ankle, knee, and hip kinetics and their distributions across the lower extremities during repetitive STS exercise in healthy young and older adults. To do so, ankle, knee, and hip net joint kinetics were collected as young (18-35 years; n=10) and older (60-75 years; n=12) adult participants performed a repetitive STS exercise protocol. Result showed that although aging caused a redistribution of joint loading demands when ascending from a seated position, the way in which multi-joint STS exercise influence joint kinetics was invariant with aging. Net joint moment and mechanical work performed by the knee extensors progressively declined throughout the exercise protocol, but was not compensated for with increased hip extensor losding with fatiguing STS exercise. The results of this investigation allude to an important role of force generating capabilities for the knee extensors in limiting STS capacities with aging.

Keywords: multi-joint fatigue, knee extensors, aging, kinetics, mechanical work, moments

Introduction

Age-related declines in physical function and increased occurrence of disability in those 60 years of age and older has become a growing concern; our aging population poses a challenge to already limited human and fiscal resources in order meet these increasing health care demands (Denton, 1998; Sheppard, 2002; SSCA, 2009). Reductions in lower extremity strength and overall muscle function have been shown to be an unavoidable consequence of aging, leading to declines in the ability to perform everyday tasks required for autonomy, and in turn impaired quality of life (Carter et al., 2002; Hortobagyi et al., 2003; Hughes et al., 1996; Hurley, Rees & Newham, 1998; Ikezoe et al., 2011a; Ikezoe et al., 2001b; Manini et al., 2007). Particularly, the ability to rise from a seated position is an essential skill for functional independence as it is required for numerous daily activities such as getting out of a bed, toileting and so on. Unfortunately, many older adults in their latter years experience difficulty when performing the sit-to-stand movement (STS) due to declining muscle reserves, and its capacity (i.e., ability to perform repeatedly) has been used in rehabilitative settings as an important predictor of disability with aging (Akram & McIlroy, 2011; Buatois et al., 2008; Jones et al., 1999; Schultz, Alexander, & Ashton-Miller, 1992; Tiedman et al., 2008).

From a mechanical stand point, the STS is a complex, weight-bearing, multi-articular movement that requires coordinated horizontal and then vertical displacement of one’s center of mass (COM) through the development of large ankle plantar flexors (APF), knee extensors (KE), and hip extensors (HE) net joint moments (NJM) to achieve a standing posture (Schultz et al., 1992). Gross et al. (1998) found that regardless of ascent speed, healthy young and older adults produced similar peak extension moments about the hip, knee, and ankle when rising from a chair. However, when represented with respect to maximal values (MVC), near maximal KE

NJM relative muscular efforts ranging from 80-100% MVC have been observed in older adults over the age of 65; whereas substantially lower knee efforts are required by younger counterparts (35-40% MVC) (Hortobagyi et al., 2003; Hughes et al., 1996, Savelberg et al., 2007, van der Heijden et al., 2009). Therefore, it is expected that although older adults have adequate strength to perform the STS task, they may be performing activities of daily living that involve ascending from a seated position near their functional strength limits on a frequent basis.

Strength limitations have also been shown to result in compensation strategies through shifting of mechanical demands from one joint to another (Hortobagyi et al., 2003; Puniello et al., 2001; Savelberg et al., 2007; van der heijden et al., 2009; Yoshioka et al., 2007). In healthy adults of various ages, Bieryla et al. (2007) found that the KE NJM presented greater relative efforts during the STS (~77%MVC NJM) compared to the APF and HE (~25% and ~22%MVC NJM, respectively); therefore compensatory shifting from KE to less active musculature could occur in order to cope with declines in force producing capabilities in a primary agonist muscle group. It is likely that this would in turn result in the adoption of undesirable kinematics in order to spare the more active KE, especially with repetitive actions (Fogelman & Smith, 1995; Sparto et al., 2007a; Sparto et al, 2007b). A more upright torso position characteristic of a dominant vertical rise STS strategy requires significantly larger KE resistive torques to stand from a chair in comparison to an exaggerated torso lean STS strategy (Scarbourough, McGibbon, & Krebs, 2007). Consequently, increased forward flexion has been suggested to reduce KE requirement by transferring loading demands to the stronger and less active HE. Therefore this “hip-dominant” strategy exhibited in older populations experiencing functional declines may be a consequence of greater declines in force generating capabilities in the KE musculature in comparison to other lower extremity musculature with aging (Hughes & Schenkman, 1996;

Hughes et al., 1994; Mathiyakom et al., 2005; Puniello et al., 2001; Savelberg et al., 2007; Scarbourough et al., 2007; Yoshioka et al., 2007; van der Heijden et al., 2009). In turn, with repetitive daily actions, this hip-compensatory strategy may also be favorable to cope with and prevent excessive accumulation of fatigue of the KE if efforts of 80% or higher are required. Similarly, Sparto et al., (1997a) and Fogelman and Smith (1996) noted changes from an upright leg lift to a back lift strategy during prolonged lifting exercise in young adults, which was characterized by earlier knee and delayed hip extension and these authors speculated that this change in strategy was adopted to more evenly distribute joint efforts with fatigue. Regardless, it is apparent that a change in movement loading strategy which results in undesirable kinematics may be more dependent on the force generating capabilities of a single muscle group, the KE.

Based on the previously described research, altered timings of joint flexion-extension reversals, as well as a change in the amount of joint excursions in preparation for and after seat-off would reflect a change in STS movement strategy. While NJM kinetic measures represent the loading requirements about a joint, mechanical work is a function of this net muscular effort and the associated joint excursion or displacement (Robertson et al., 2004; Winter, 2009). Therefore, calculations of mechanical work can provide a thorough evaluation of energy requirements for the entirety of a specific movement. During drop landings, Moolyk, Carey and Chiu (2013) found that more ankle work was due to participants having a more plantar flexed position, whereas more knee work was due to greater KE NJM requirements in absorbing energies during eccentric loading. Therefore, the amount of mechanical work performed at a joint will be affected by both alterations in joint kinematics and resistive torques. Calculations of mechanical work produced by the hip, knee, and ankle over the STS phase can depict the type of muscle actions (concentric or eccentric) occurring during different phases of the transfer task, and the relationship between energy being produced or absorbed (DeVita, Helseth &Hortobagyi, 2007; Wretenberg & Arborelius, 1994). For example, Wretenberg and Arborelius (1994) found that during the STS, the KE contributed to approximately 72% of total lower extremity concentric work, while hip extensors had significantly lower work outputs that contributed to ~ 27% of total concentric work. To our knowledge, such analyses have not been compared between young and older adults. Additionally, it is unclear how differences in movement kinematics due to fatiguing exercise may be related to the amount of mechanical work performed by each joint in young versus older adults.

Since STS strategy has been used as an indicator of an individual's functional status, the quantification of a joint's contribution to a movement may reveal valuable information regarding the underlying mechanisms behind coordinative strategies during a repetitive multi-joint fatiguing activity, even prior to any observable onset of functional decline. It is expected that the pattern of loading and energy production across the ankle, knee, and hip joints during the STS with aging may provide valuable information related to the challenging nature of the task. The purpose of this investigation was to compare alterations in ankle, knee, and hip kinetics and their distributions across the lower extremities during repetitive STS exercise in healthy young and older adults, in order to detect age-dependent compensatory strategies that may exist with prolonged multi-articular fatigue. While previous investigations have primarily looked at peak joint kinetic values during the STS (Gross et al., 1998), such discrete biomechanical measures do not provide a comprehensive picture of the loading dynamics throughout different phases of a multi-joint movement (Chiu, Bryanton, & Moolyk, 2014). Therefore in addition to peak NJM data, average NJMs values produced, as well as mechanical work performaned at the ankle, hip and knee, were also calculated over the duration of two distinct phases of the STS: the preparatory (prior to seat off) and ascending (after seat-off) phases.

Methods

Participants

Twenty four healthy adult men and women between the ages of 18-35 (young adult, n=10; 5 females) and 60-85 (older adult, n=12; 6 females) from the community participated in this investigation. Exclusion criteria included having previous lower extremity or lower back orthopedic and musculoskeletal injuries that prevented the exercise from being performed safely, as well as taking any medications that may affect balance. Participants were instructed to refrain from any strenuous lower extremity activities prior to visiting the laboratory. Ethics approval was obtained from the University of Ottawa and Bruyere Research Institute Research Ethics Boards, and informed consent was obtained prior to testing. In addition to individual anthropometrics of height and body weight, the Godin Leisure-time questionnaire (Godin & Sheppard, 1997) was administered and scores were calculated as an indication of the type and frequency of physical activity levels in young and older participants.

Procedures

STS Fatigue Protocol: Subjects were seated on an armless and backless bench (24” x 24”), and the height was adjusted to 80% of the participants’ lower leg lengths in order to ensure similar and adequate muscular efforts to induce fatigue in both the young and older adult participants (Bryanton & Bilodeau, *Chapter 3*; Hughes et al., 1996; Janssen, Bussmann, & Stam, 2002). An AMTI Acu-Gait force platform (Watertown, MA) was fixed on top of the bench to provide an indication of when there was contact with the seat with the buttocks. Participants’ feet were positioned shoulder width apart on two additional Bertec force platforms (Bertec

Corporations, Columbus, OH). Prior to standing, subjects were instructed to sit in a comfortable erect posture with their arms folded across their chest to deter the use of compensatory arm swinging. For each STS repetition, subjects were instructed to stand up from the bench to a fully extended erect posture, to pause briefly, and then to return to the initial seated position while maintaining foot contact with the force platforms at all times. Initial foot placement was marked on the force platform to prevent shifting of feet during the course of the fatigue protocol. STS repetitions were performed in synchronization to the beat of an audible metronome set to 30 beats per minutes (first beat signaled to ascend and the next to descend) until: a) they could no longer maintain the given pace for 5 consecutive beats, b) volitional exhaustion occurred, or c) a 30 minute cut-off time was reached (Barbieri et al., 2013). This pace was piloted prior to this investigation and was selected as it was a comfortable pace for all participants, yet it prevented recovery between STS ascending and descending phase repetitions to induce fatigue. Strong verbal encouragement was provided when needed, especially during the later stages of the fatigue protocol to ensure maximal STS times. Lastly, a modified 10-point Borg scale (Borg, 1982) was administered every minute to monitor the participants' perceived exertion (0 = no effort to 10 = maximal effort) in order for the researcher to evaluate the extent of exercise progression (i.e., if they were feeling fatigue and if they were getting close to exhaustion).

Motion Analysis: All trials were performed in a motion analysis laboratory (the Motion Control Laboratory, University of Ottawa) with seven optoelectronic cameras (Vicon Motion Capture system, Oxford Metrics, Oxford, UK) and simultaneous ground reaction forces were collected at 960 Hz. For motion analysis, a six degree-of-freedom retro-reflective cluster marker set was worn by participants (Figure 1) (Bryanton et al., 2012). Briefly, this marker set included calibration and tracking markers placed on the participant's trunk and pelvis, as well as left and right thighs, legs, and feet (Figure 1). Calibration markers were used only during static calibration trials to define proximal and distal end of segments. This included markers at the foot (1^{st} and 5^{th} metatarsals), ankle (medial and lateral malleoli), knee (medial and lateral femoral epicondyles), and hip (greater trochanters) to define joint centers. Cluster tracking markers were used for both static calibration and dynamic STS trials, consisting of three to four markers fixed to rigid plastic plates, were placed on the foot, leg, and thigh. Tracking of the pelvis involved the use of additional markers placed on the left and right posterior superior iliac spines, and left and right iliac crests. From this, rigid links connected by frictionless pin joints were used to represent the pelvis, thigh, legs, and foot segments. All markers were placed by the same investigator who had previously demonstrated high test-re-test reliability in placing these markers prior to the investigation.

All data were digitally filtered using a Butterworth filter with a cut-off of 6Hz. Data were processed in Visual 3D software (Germantown, MD) to determine segment and joint kinematics. Briefly, derivatives were calculated using the finite differences techniques. A ZXY Cardan sequence relative to the laboratory frame was use to determine rotations of the foot, leg, thigh and pelvis segments. Joint angles and velocities were then determined using XYZ Cardan sequence and defined as the motion of the distal relative to the proximal segment (Figure 2). Inverse dynamics procedures were then performed using ground reaction forces and moments carried up the shank to the pelvis were used to calculate NJM at the ankle, knee, and hip (refer to Appendix B, Figure B11 for equations), with moments expressed in the coordinate system of the distal segment. Segments were modeled as conical frustra, where proximal and distal joint center markers were used to determined segments lengths and the radii of each end of the frusta, and segments masses were determined using body masses and Dempster’s equations. In addition to peak NJM values, average joint moments and change in joint rotations in the sagittal plane were calculated over two distinct phases using participants kinematics and force plate data: a) the preparatory phase (defined as the time between the start of forward displacement of the torso while seated until contact is lost with the seat indicated by bench force plate (Fz=0), and b) the ascending phase (defined as the time between loss of off contact with the seat until full body extension and upright standing posture is reached as indicated bby full hip, knee and ankle extension). Mechanical work performance at the ankle, knee, and hip was calculated as the time integral of the net joint power between the two aforementioned time points of interest for preparatory and ascending phases (Moolyk et al., 2013; Purkiss & Robertson, 2003; Robertson et al., 2004; Winter, 2009). All measures were averaged between limbs, and kinetics were then normalized with respect to body weight (kg).

Data Analysis

In order to normalize data with respect to each participant's respective total STS task times, ankle, knee, and hip joint kinematic and kinetic measures were averaged over 5 repetitions at 0, 25, 50, 75, and 100% of total STS exercise time for each individual. Joint kinetics were then summed to represent a total support moment stance and work. From this, the percent (%) contribution of each joint to the total lower extremity support moment and work was also calculated for the ascending phase (Flanagan and Salem, 2008; Kepple et al., 1997; Moolyk et al., 2013; Winter, 1980). For example, hip contribution to total summed support stance moment was calculated as:

$$\textit{Hip Contribution (\%)} = \textit{NJM at Hip} / (\textit{Total NJM; Ankle NJM} + \textit{Knee NJM} + \textit{Hip NJM}) * 100 \qquad (1)$$

For measures of work, absolute values were in turn used for contribution analyses (Moolyk et al., 2013). For example, hip contribution to total lower extremity work was calculated as:

$$\text{Hip Contribution (\%)} = [\text{Work at Hip}] / (\text{Total Work; } [\text{Ankle}] + [\text{Knee}] + [\text{Hip}]) * 100 \qquad (2)$$

Statistical Analysis

Separate t-tests were performed for Godin Leisure-time questionnaires, as well as total STS tasks time, in order to test for age group differences. A mixed model ANOVA with one between subjects (age; Young vs. Old) and one repeated measure (time; 0, 25, 50, 75 and 100% total STS time) factors was used for statistical analyses for all motion data for each joint; this included joint angular displacement, NJMs and mechanical work, and % contributions during the preparatory and ascending phases. Where appropriate, Tukey HSD for post-hoc comparisons was performed. The alpha level was set *a priori* at $\alpha=0.05$. Cohen's effect sizes were then calculated to determine magnitudes of differences for univariate main effects.

Results

Subject Characteristics

During testing, subject data from two young adult participants were lost due to equipment issues and marker slipping. Therefore, subsequent statistical analyses involved a total of 22 participants (n=10 young (5 females) and n=12 old (6 females). This sample size allowed detection of moderate within and between subject effect size while minimizing type I error to 5% and type II error to 17% (Power= 83%). T-tests showed that young and older adult subjects had similar Godin Leisure-time scores (t(20):0.343, p=0.735) but total STS tasks times differed significantly (t(20):3.457, p=0.002). Therefore although the two groups were matched for physical activity level, young adults had significantly longer total task times as shown in Table 1.

Angular Displacement

For all joint angle and phase statistical analysis except for change in preparatory hip angle, Mauchly's tests of sphericity were significant (p<0.05), and Greenhouse-Geisser correction were used. In preparation for seat off, a significant increase in ankle dorsi-flexion (p<0.001, d=0.711) and hip flexion (p<0.001, d=0.872) was observed during the course of the repetitive STS exercise, while knee angular displacement was decreased (p=0.027, d=0.432) near the end of the fatigue task. No age main effects were found at any joint (ankle; p=0 492, d=0.157, knee; p=0.517, d=0.146, hip; p=0.775, d=0.063) with no interactions (p>0.10) (Table 2A). During the ascending phase, joint extension displacement significantly decreased at the ankle (p=0.023, d=0.462) for both age groups, and knee and hip ascending joint displacements remained unchanged (p=0.104, d=0.346 and p=0.130, d=0.322, respectively). An age main effect was observed at the hip (p=0.040, d=0.492), but not the ankle (p=0.807, d=0.055) or knee (p=0.291, d=0.244) with no significant interactions (p>0.10), indicating that older adults performed less hip extension when rising from a chair at all time points (Table 2B, Figures 3 & 4).

Peak STS Net Joint Moments

For all peak NJM values, Mauchly's tests of sphericity were significant (p<0.05), and Greenhouse-Geisser corrections were used. Peak NJM values during repetitive STS exercise showed a significant increase at the ankle (p=0.018, d=0.473) and decrease at the knee (p<0.001, d=0.836), while the hip remained unchanged (p=0.173, d=0.297). Age main effects were also observed at the ankle (p=0.015, d=0.597) and knee (p=0.003, d=0.760) but not the hip (p=0.290, d=0.244), with no significant time x age interactions (p>0.10). Post hoc analyses showed that peak APF NJMs during repetitive STS exercise increased primarily during the beginning of the exercise protocol; however they were larger in older adults at all time points. Peak knee extensors moments declined with exercise progression in both age groups to the same extent, but were lower in older adults at all time points. Peak hip extensor moment remained unchanged and were similar between groups (Table 3).

Averaged Net Joint Moments with Respect to STS Phase

For all average NJM over preparatory and ascending phases, Mauchly's tests of sphericity were significant ($p<0.05$), and Greenhouse-Geisser corrections were used. During the preparatory STS phase, a significant time main effect was observed at the knee ($p=0.015$, $d=0.472$) but not at the ankle ($p=0.704$, $d=0.132$) or hip ($p=0.270$, $d=0.259$), while age main effects were found at the ankle ($p=0.045$, $d=0.478$) and knee ($p=0.038$, $d=0.495$), but not the hip ($p=0.133$, $d=0.350$), where older adults had signficaintly lower preparatory KE NJM values, but higher NJM average loading by the APF. No time x age interactions were found to be statistically significant at any joint ($p>0.10$). Post-hoc analyses showed that the average amount of KE NJM loading before seat-off declined by the 50% total time point in both young and older adults (Figure 5).

During the ascending phase, significant time main effects were in turn observed at the ankle ($p=0.002$, $d=0.560$) and the knee ($p=0.004$, $d=0.530$), but not the hip ($p=0.274$, $d=0.257$). Significant age main effects were also found during the ascending phase at the ankle ($p=0.003$, $d=0.747$) and the hip ($p=0.014$, $d=0.600$), but not at the knee ($p=0.209$, $d=0.291$), with no interactions ($p>0.10$), however a trend for a time x age interaction was observed at the knee ($p=0.071$, $d=0.362$). Older adults had significantly higher ankle and hip NJM relative to their body weight compared to young adult participants at all time points regardless of any fatigue-time effects. Despite higher values in older adults, post-hoc analyses showed that APF NJM increased initially from 0% to 25% total time points in both groups, but did not continue to increase beyond this point. Lastly, declines in average KE NJM were also observed between as repetitive STS exercise progressed (Figure 6).

For NJM contributions (%) analyses, Mauchly's tests of sphericity were significant for the ankle and knee during the ascending phase, while all joints measure were significant during the preparatory phase ($p<0.05$), and Greenhouse-Geisser corrections were used. Relative to total lower extremity summed support moment, no significant time main effects were found during the preparatory phase (ankle; $p=0.368$, $d=0.225$, knee; $p=0.465$, $d=0.201$, hip; $p=0.607$, $d=0.150$). Significant time main effects were observed during the ascending phase at the ankle ($p=0.001$, $d=0.590$) and knee ($p<0.001$, $d=0.631$). Hip NJM contributions remained at approximately 40% of the total support moment ($p=0.250$, $d=0.266$), while a tradeoff was observed between the ankle and knee from 0-25% total time points where ankle contributions increased while knee contributions decreased in both young and older adults. Interestingly, significant age group differences at all joints during the ascending phase (ankle; $p=0.034$, $d=0.508$, knee; $p<0.001$, $d=1.18$, hip; $p=0.005$, $d=0715$); older adults had similar larger hip andankle % contributions compared to young adults when ascending and significantly lower knee contributions at all time points (Figure 9). Lastly, significantly lower knee joint contributions were also observed in older adults during the preparatory phase ($p=0.013$, $d=0.607$); however age differences were not observed at the hip in preparation for seat-off ($p=0.106$, $d=0.378$) and a trend towards significance was seen at the ankle ($p=0.056$, $d=0.452$) (Table 4). Thus, older adults had significantly lower KE contributions during both the preparatory and ascending phases of the STS, however this declined to the same extent as exercise progressed.

Net Joint Work Performed with Respect to STS Phase

For all average net joint work over preparatory and ascending phases, Mauchly's tests of sphericity were significant ($p<0.05$), and Greenhouse-Geisser corrections were used. During the preparatory phase, a significant time main effect was observed only at the knee ($p<0.001$, $d=0.661$) (ankle; $p=0.391$, $d=0.212$, hip; $p=0.267$, $d=0.261$). A significant age main effect was found only at the hip ($p=0.033$, $d=0.512$) (ankle; $p=0.204$, $d=0.293$, knee; $p=0.198$, $d=0.299$), suggesting that older adults performed work absorption via eccentric loading of the HE when preparing for seat-off, in comparison to positive concentric work performed at the hip by young adults. No time x age significant interactions were found at any joint ($p>0.10$). In preparation for seat-off, repetitive STS exercise reduced net joint work output at the knee in both age groups to the same extent (Figure 7).

During the ascending phase, concentric hip, ankle, and knee mechanical work was predominately performed, and a significant time main effect was found at the ankle ($p=0.015$, $d=0.475$) and the knee ($p<0.001$, $d=0.731$), and a trend was observed at the hip ($p=0.079$, $d=0.366$). No significant ascending age effects were observed at any joint, except for a trend at the knee ($p=0.053$, $d=0.459$) and ankle ($p=0.085$, $d=0.405$) (hip; $p=0.177$, $d=0.313$), with no interactions ($p>0.10$). Therefore, repetitive STS exercise caused increased work performed at the ankle and hip from 0-25% total STS times, whereas KE work continued to decline for the duration of the fatigue protocol. Values were similar between young and older adults at all time points for all joints (Figure 8).

Net joint work contributions (%) to total absolute lower extremity work output in that significant time main effects were observed during the preparatory phase at the knee ($p=0.013$, $d=0.445$) and hip ($p=0.032$, $d=0.397$) (ankle; $p=0.143$, $d=0.330$), and during the ascending phase at all joints (ankle; p=0.004, d=0.540, knee; p<0.001, d=0.796, hip;p<0.000, d=0.713). Age main effects were found during the ascending phase for all joints (ankle; p=0.049, d=0.469, knee; p=0.003, d=0.766, hip; p=0.026, d=0.539), but not during the preparaotory phase (ankle; p=0.389, d=0.196, knee; p=0.115, d=0.368, hip; p=0.194, d=0.301); older adults had significantly greater APF and HE and lower KE contributions to total lower extremity work in comparison to young adult subjects at all time points when ascending from a seated position. No significant interactions were found for either phase (p>0.10); therefore with fatigue, both young and older adults increased ankle contributions from 0-25% total time and hip contributions throughout the STS protocol, as KE contributions decreased with time due to fatigue during the ascending phase only (Figure 10 and Table 5).

Table 1. Subject Characteristics (± *SDs*)

Group	**Age (yrs)**	**Body mass (kg)**	**Height (cm)**	**GLTQ**	**Total Time (min)**
Young (*n= 10)	25.5 (*5.2*)	72.5 (*17.7*)	172.5 (*13.1*)	50.8 (*24.0*)	26.6 (*5.15*)
Old (n=12)	66.8 (*4.9*)	73.8 (*14.0*)	171.2 (11.2)	46.4 (*33.8*)	15.8 (*9.1*)

Table 2A. Group Mean Change in Ankle, Knee and Hip angles (deg; ± SD) (Negative Values Denote Flexion Directionality) (n=10 young; n=12 old) during the Preparatory Phase

		% Total STS Time				
		0	**25**	**50**	**75**	**100**
Ankle	Young	-3.2 (1.1)	-3.9 (1.7)	-4.2 (1.3)	-4.3 (1.7)	-4.4 (1.7)
	Old	-3.0 (2.1)	-4.6 (3.2)	-5.2 (3.8)	-5.2 (3.4)	-5.5 (3.6)
		b,c,d,e	*a,e*	*a*	*a*	*a,b*
Knee	Young	5.1 (2.7)	3.9 (3.6)	3.8 (3.9)	3.3 (4.6)	2.8 (4.6)
	Old	3.6 (2.4)	2.0 (5.2)	2.9 (5.5)	2.7 (4.6)	1.8 (5.4)
		e		*e*	e	*a,c,d*
Hip	Young	-11.1 (3.8)	-13.9 (6.0)	-16.5 (5.9)	-17.7 (5.0)	-17.3 (6.4)
	Old	-11.4 (3.5)	-15.1 (5.0)	-14.9 (4.9)	-16.5 (4.1)	-15.9 (4.4)
		b,c,d,e	*a,d*	*a,d*	*a,b,c*	*a*

[a] denotes significant difference from 0%, [b] denotes significant difference from 25%, [c] denotes significant difference from 50%, [d] denotes significant difference from 75%, [e] denotes significant difference from 100%.
** denotes significant age group difference from young.*

Table 2B. Group Mean Change in Ankle, Knee and Hip angles (deg; ± SD) (Negative Values Denote Flexion Directionality) (n=10 young; n=12 old) during the Ascending Phase

		% Total STS Time				
		0	**25**	**50**	**75**	**100**
Ankle	Young	16.0 (4.6)	15.6 (5.5)	14.3 (6.2)	13.4 (6.1)	12.8 (5.8)
	Old	15.6 (4.3)	15.4 (5.9)	15.1 (6.6)	15.0 (6.8)	14.1 (7.3)
		e	*c,d,e*	*b,e*	*b*	*a,b,c*
Knee	Young	89.9 (10.0)	91.1 (13.3)	89.9 (12.9)	89.3 (13.2)	90.0 (12.5)
	Old	86.1 (9.8)	87.4 (9.4)	85.9 (18.8)	84.1 (10.7)	81.0 (12.1)
Hip	Young	80.6 (16.3)	81.8 (18.3)	85.2 (17.0)	86.9 (17.4)	84.4 (22.3)
	Old	69.1 (11.1)	73.1 (11.6)	72.6 (10.2)	69.2 (10.6)	68.0 (12.6)
		*	*	*	*	*

[a] denotes significant difference from 0%, [b] denotes significant difference from 25%, [c] denotes significant difference from 50%, [d] denotes significant difference from 75%, [e] denotes significant difference from 100%.
** denotes significant age group difference from young.*

Table 3. Peak Net Joint Moments (±SD) in Young and Older Adult Participants during Repetitive STS Exercise. Positive Values Indicate APF, KE, and HE NJM

		% Total STS Time				
		0	**25**	**50**	**75**	**100**
Ankle	Young	0.30 (0.03) *c,de*	0.27 (0.05)	0.29 (0.05) *a*	0.31 (0.07) *a*	0.34 (0.09) *a*
	Old	0.33 (0.08) **,c,d,e*	0.41 (0.12) *	0.43 (0.15) **,a*	0.43 (0.15) **,a*	0.44 (0.15) **,a*
Knee	Young	1.22 (0.21) *b,c,d,e*	1.18 (0.18) *a,d,e*	1.14 (0.20) *a,d,e*	1.11 (0.18) *a,b,c*	1.10 (0.19) *a,b,c*
	Old	1.00 (0.08) **,b,c,d,e*	0.91 (0.13) **,a,d,e*	0.92 (0.13) **,a,d,e*	0.90 (0.14) **a,b,c*	0.88 (0.13) **a,b,c*
Hip	Young	0.83 (0.19)	0.79 (0.17)	0.85 (0.21)	0.87 (0.19)	0.86 (0.19)
	Old	0.87 (0.19)	0.98 (0.33)	0.94 (030)	0.92 (0.30)	1.02 (0.28)

[a] denotes significant difference from 0%, [b] denotes significant difference from 25%, [c] denotes significant difference from 50%, [d] denotes significant difference from 75%, [e] denotes significant difference from 100%.
** denotes significant age group difference from young.*

Table 4. Preparatory Phase Joint Contributions (%) to Summed Average Lower Extremity Support Moment (±SD) in Young and Older Adult Participants. Negative values indicate a flexor contribution.

		% Total STS Time				
		0	**25**	**50**	**75**	**100**
Ankle	Young	-0.03 (7.5)	-0.5 (7.4)	1.0 (9.9)	1.8 (9.5)	2.0 (8.0)
	Old	6.0 (9.0)	7.4 (12.5)	8.7 (11.5)	10.0 (11.2)	9.0 (10.9)
Knee	Young	74.2 (17.9)	76.6 (16.8)	72.2 (20.7)	69.4 (24.5)	67.9 (25.0)
	Old	47.8 (34.5) *	51.9 (22.2) *	49.1 (22.5) *	52.2 (22.8) *	45.2 (19.7) *
Hip	Young	25.9 (17.0)	23.9 (18.0)	26.9 (21.6)	28.9 (23.7)	30.1 (26.0)
	Old	46.2 (40.0)	40.6 (21.7)	42.2 (24.3)	37.4 (27.0)	45.8 (24.0)

** denotes significant difference from the young adult group*

Table 5. Preparatory Phase (*Absolute Values*) Joint Contributions (%) to Total Lower Extremity Work (±SD) in Young and Older Adult Participants.

		% Total STS Time				
		0	**25**	**50**	**75**	**100**
Ankle	Young	2.9 (2.9)	7.6 (14.6)	4.4 (4.1)	4.2 (2.5)	4.9 (5.9)
	Old	3.6 (3.1)	8.8 (16.2)	7.4 (6.8)	8.3 (8.3)	9.5 (9.9)
Knee	Young	75.3 (14.9) *c,d,e*	65.8 (28.2)	61.63 (18.9) *a*	61.7 (25.3) *a*	57.4 (25.1) *a*
	Old	63.0 (23.0) *c,d,e*	53.8 (28.5)	50.7 (28.6) *a*	43.3 (28.1) *a*	40.5 (30.5) *a*
Hip	Young	21.8 (14.0) *d,e*	26.6 (20.5)	34.0 (18.0)	34.1 (24.5) *a*	37.6 (27.3) *a*
	Old	33.3 (21.0) *d,e*	37.4 (27.5)	41.9 (28.6)	48.4 (30.1) *a*	50.0 (31.8) *a*

[a] denotes significant difference from 0%, [b] denotes significant difference from 25%, [c] denotes significant difference from 50%, [d] denotes significant difference from 75%, [e] denotes significant difference from 100%.

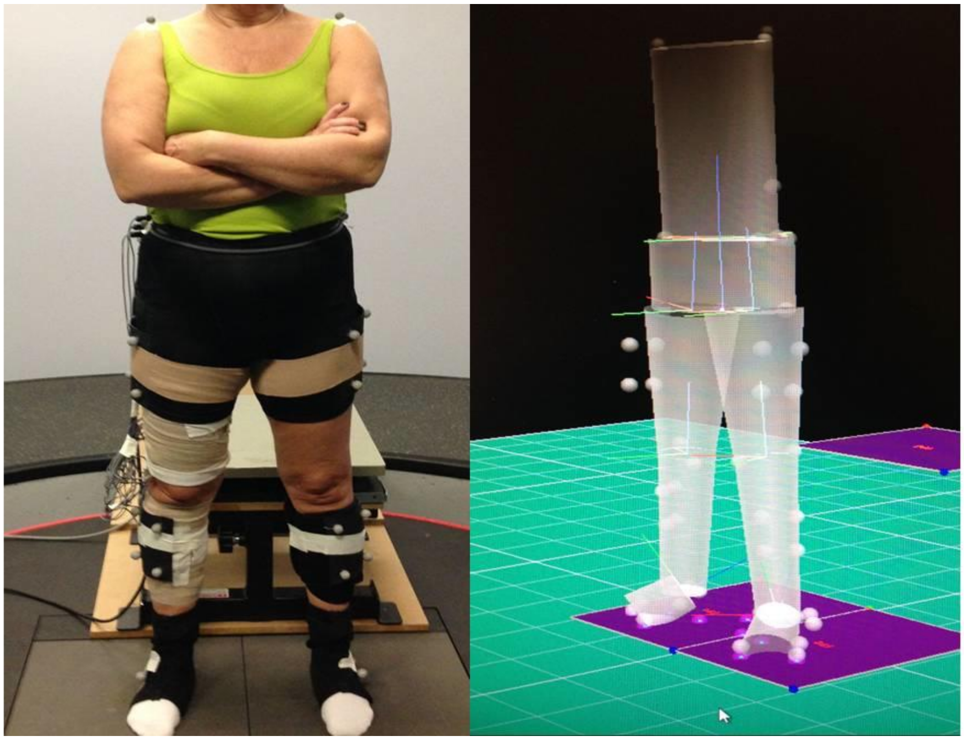


Figure 1. 6 degree-of-freedom retro-reflective marker cluster set and calibration markers

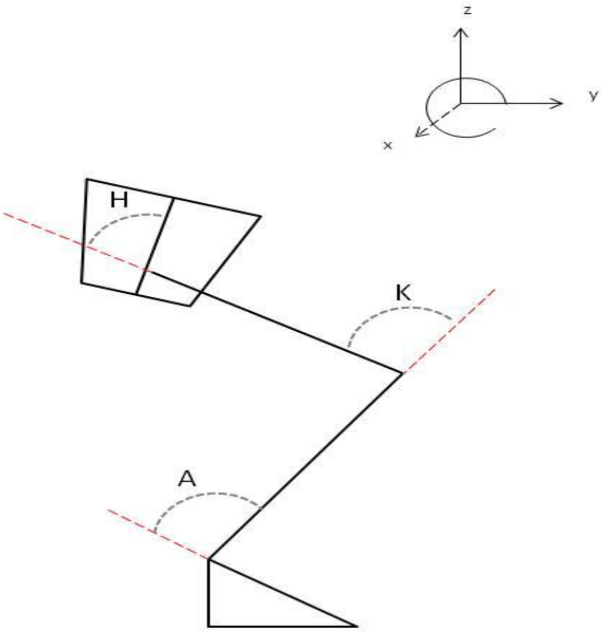


Figure 2. Schematic diagram representing ankle (A), knee (K) and hip (H) joint angle references relative to distal segment.

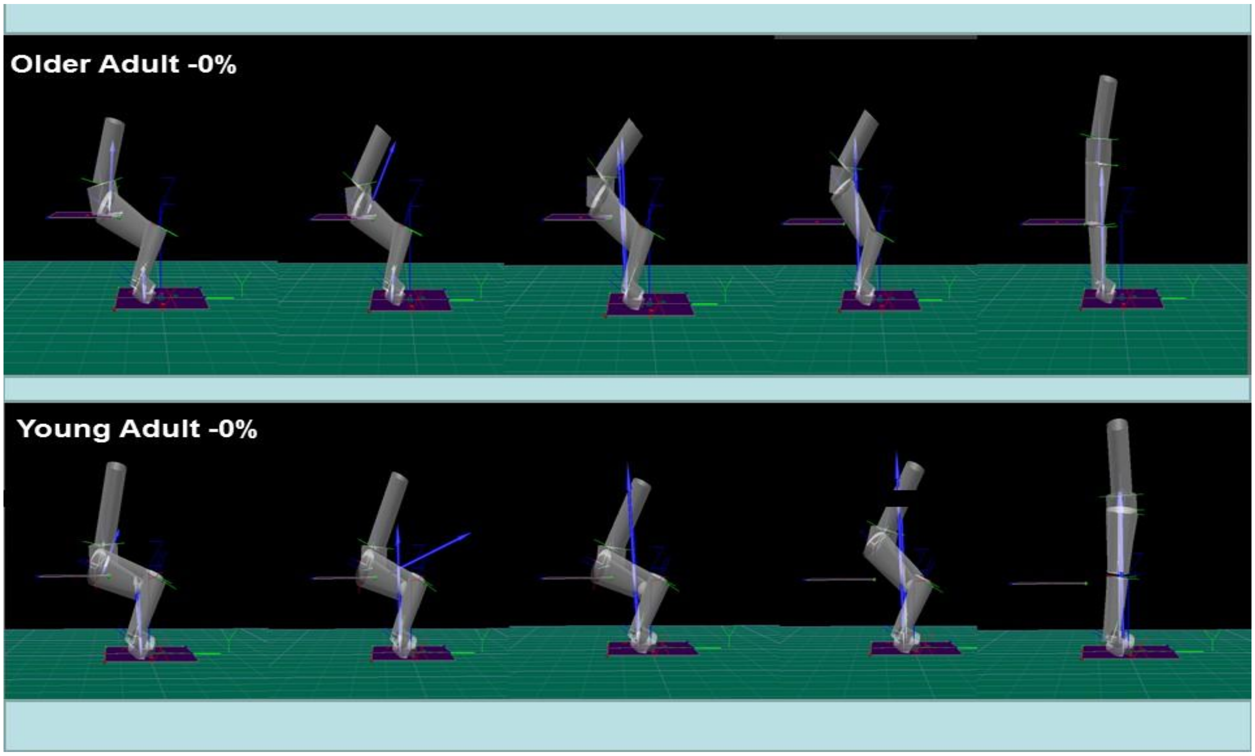


Figure 3. STS kinematics and of young and older adult participant at the start (0% total time) of the STS exercise protocol.

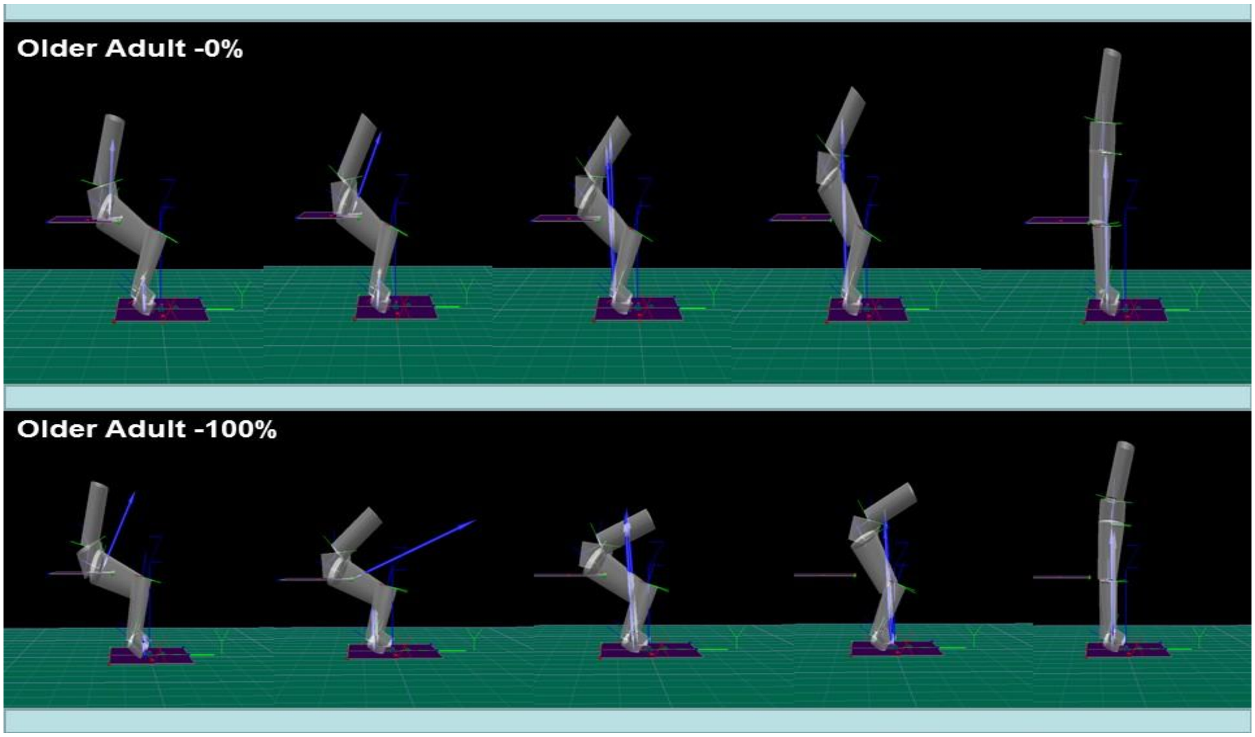


Figure 4. STS kinetics of an older adult participant at the start (0%) and end (100% total time) of the STS exercise protocol.

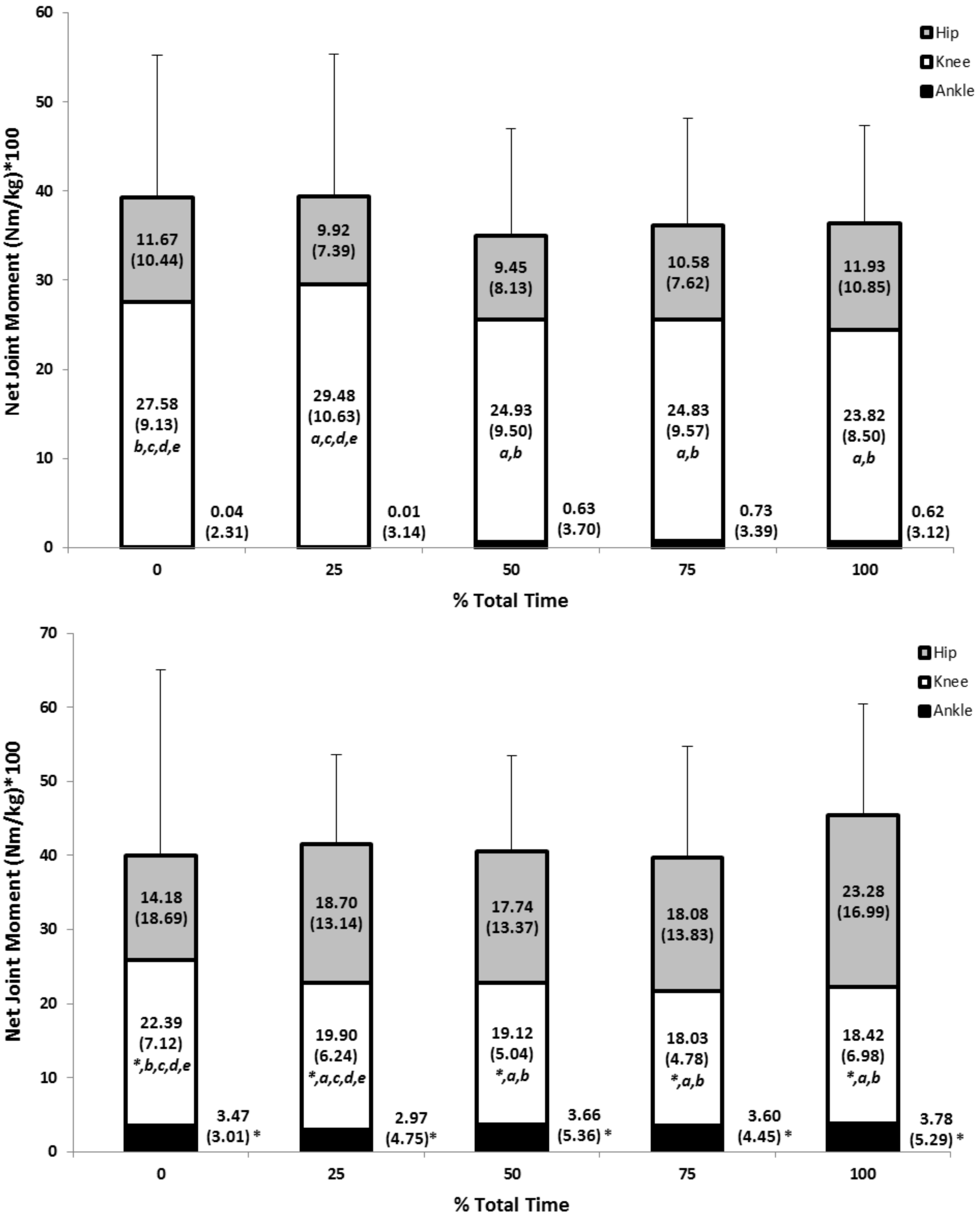


Figure 5. Young (top) and older (bottom) adult average net joint moment (±SD) produced over the preparatory phase during repetitive STS exercise. Error bars represent stand deviations for total support stance moment. *[a] denotes significant difference from 0%, [b] denotes significant difference from 25%, [c] denotes significant difference from 50%, [d] denotes significant difference from 75%, [e] denotes significant difference from 100%. * denotes significant age group difference from young.*

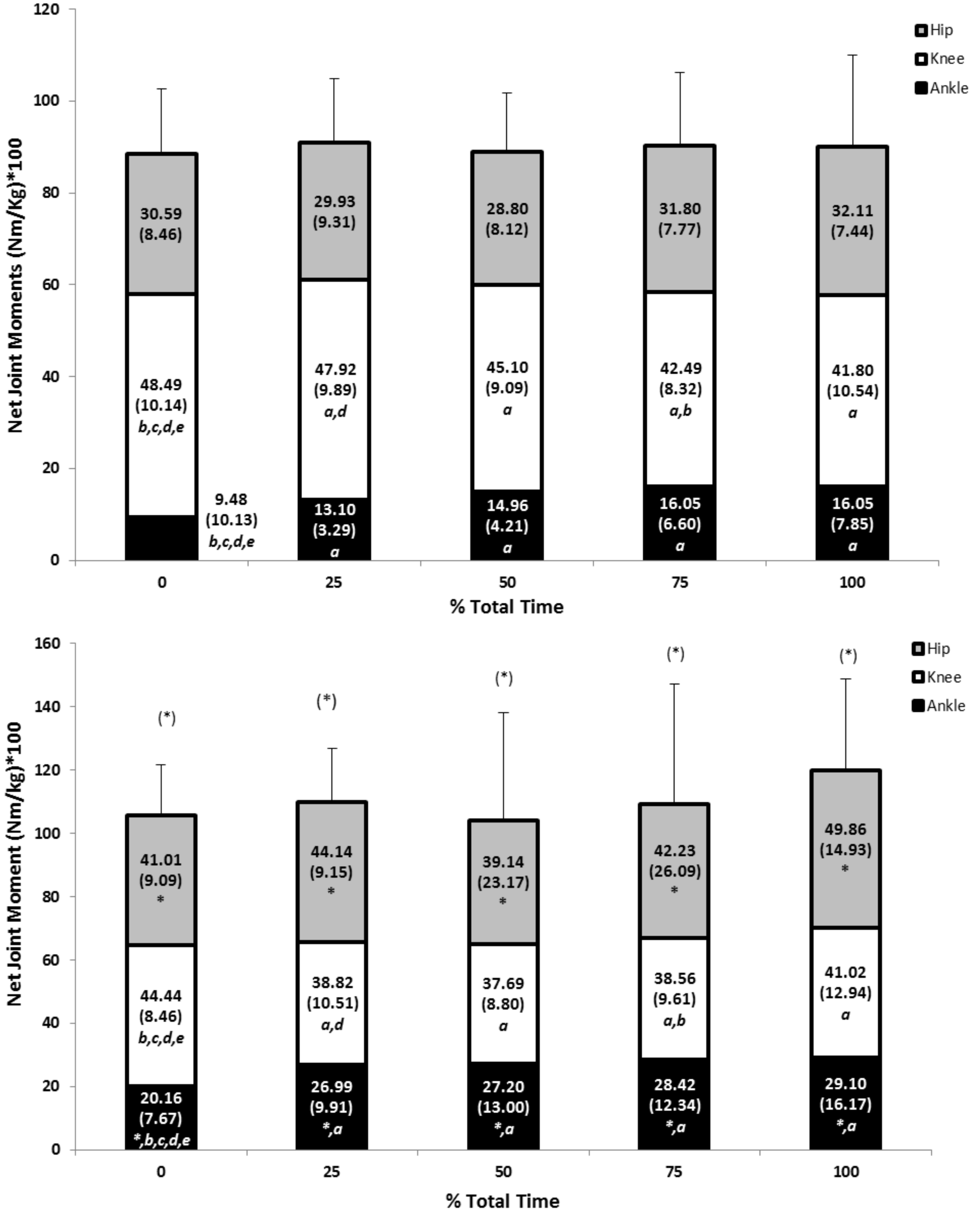


Figure 6. Young (top) and older (bottom) adult average net joint moment (±SD) produced over the ascending phase during repetitive STS exercise. Error bars represent stand deviations for total support stance moment. [a] *denotes significant difference from 0%,* [b] *denotes significant difference from 25%,* [c] *denotes significant difference from 50%,* [d] *denotes significant difference from 75%,* [e] *denotes significant difference from 100%.* denotes significant age group difference from young.*

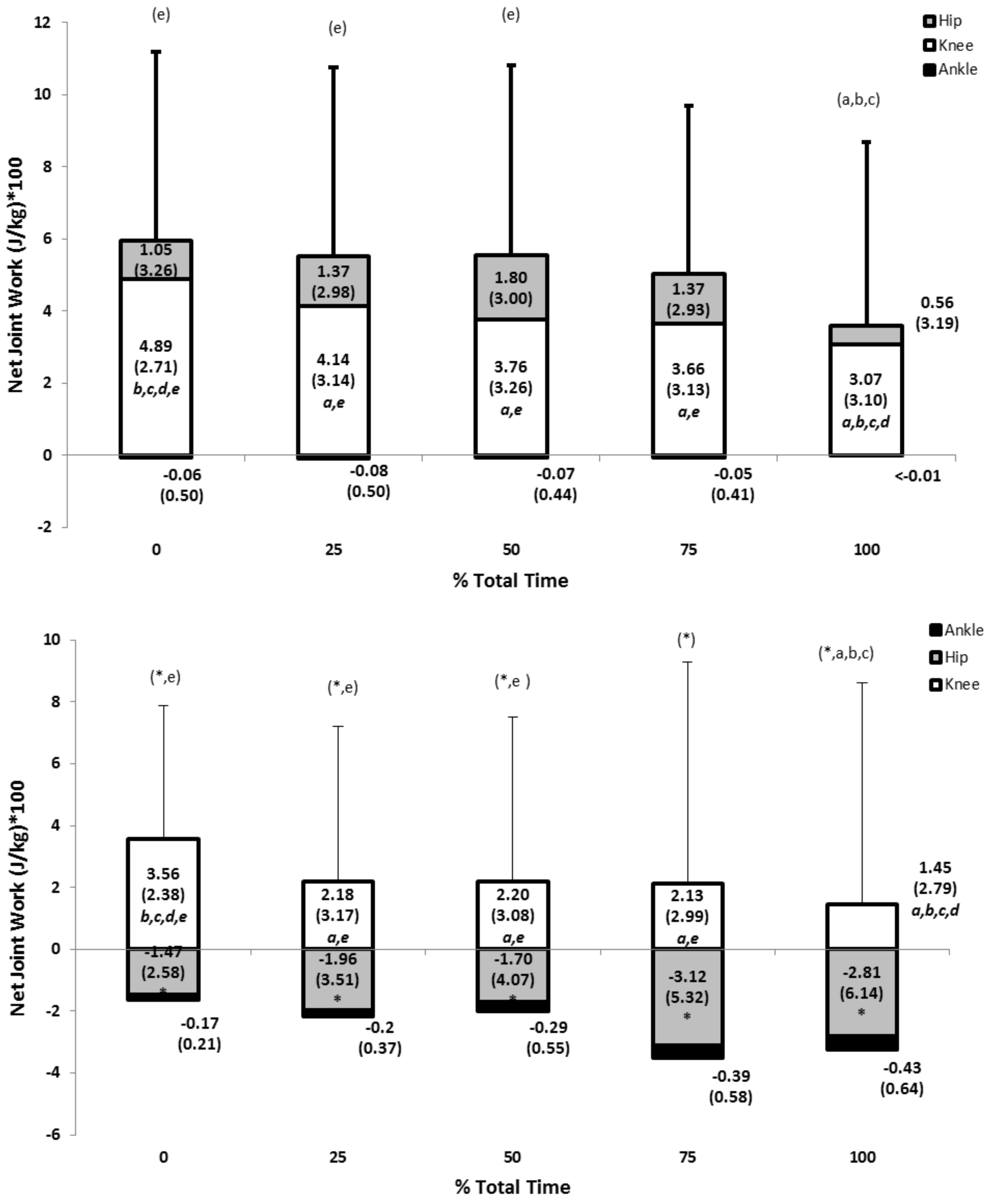


Figure 7. Young (top) and older (bottom) adult average net joint work (±SD) performed over the preparatory phase during repetitive STS exercise. Error bars represent stand deviations for total lower extremity work. ^{a} *denotes significant difference from 0%,* ^{b} *denotes significant difference from 25%,* ^{c} *denotes significant difference from 50%,* ^{d} *denotes significant difference from 75%,* ^{e} *denotes significant difference from 100%.* denotes significant age group difference from young.*

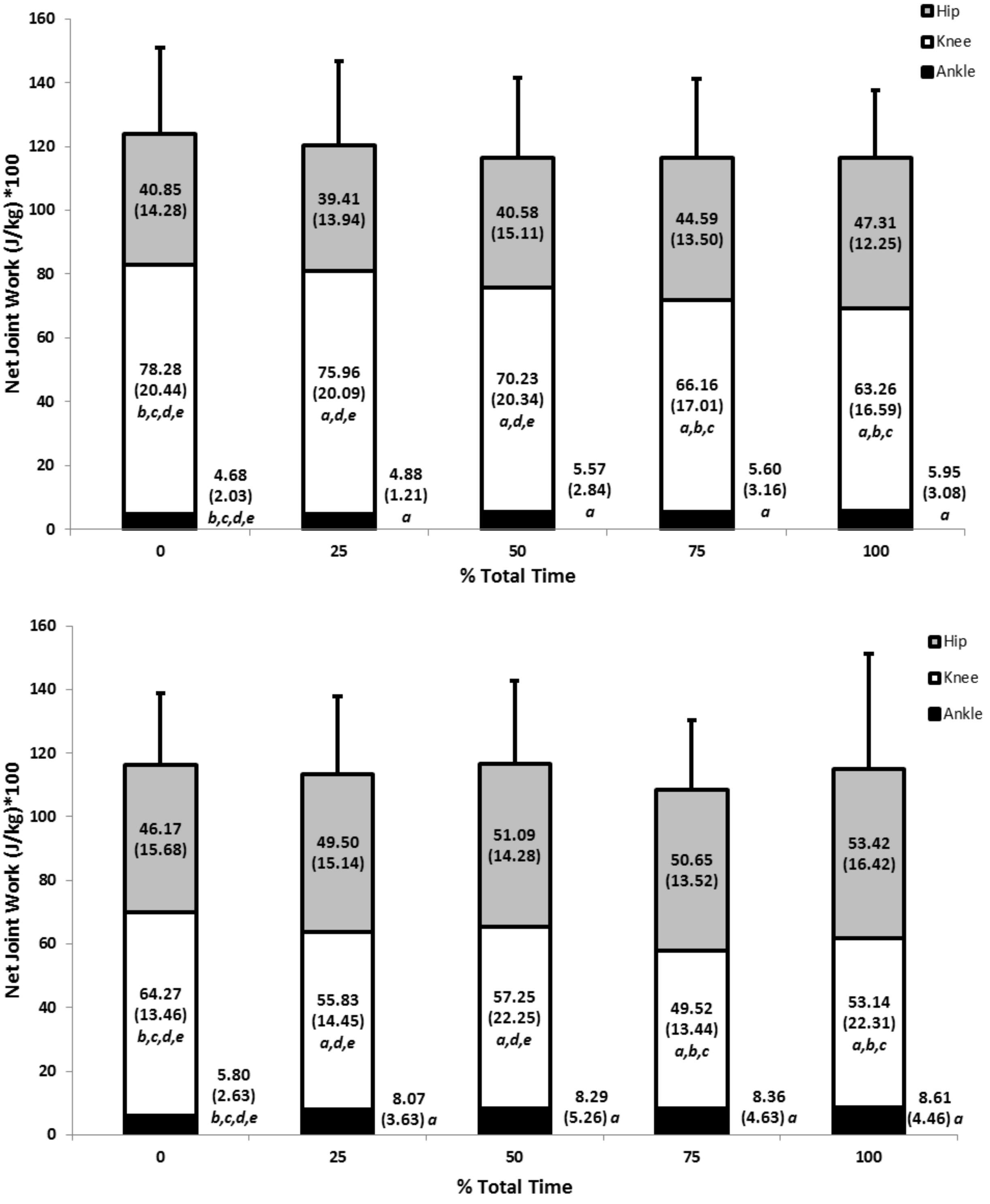


Figure 8. Young (top) and older (bottom) adult average net joint work (±SD) performed over the ascending phase during repetitive STS exercise. Error bars represent stand deviations for total lower extremity work. [a] *denotes significant difference from 0%,* [b] *denotes significant difference from 25%,* [c] *denotes significant difference from 50%,* [d] *denotes significant difference from 75%,* [e] *denotes significant difference from 100%.* denotes significant age group difference from young.*

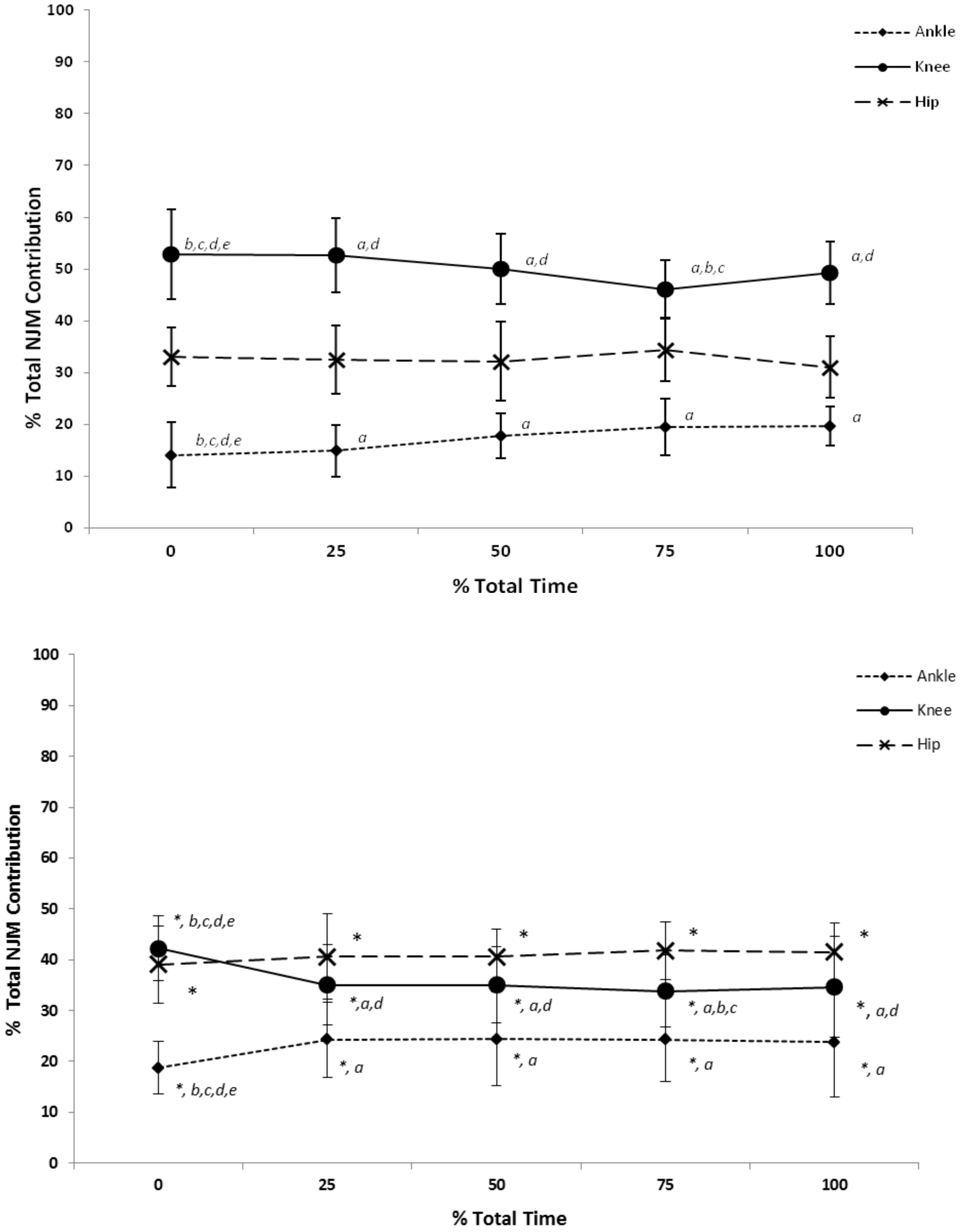


Figure 9. Young (top) and older (bottom) adult joint contributions to average ascending lower extremity support moment with repetitive STS exercise. Error bars denote SDs. ^{a} *denotes significant difference from 0%,* ^{b} *denotes significant difference from 25%,* ^{c} *denotes significant difference from 50%,* ^{d} *denotes significant difference from 75%,* ^{e} *denotes significant difference from 100%.* denotes significant age group difference from young.*

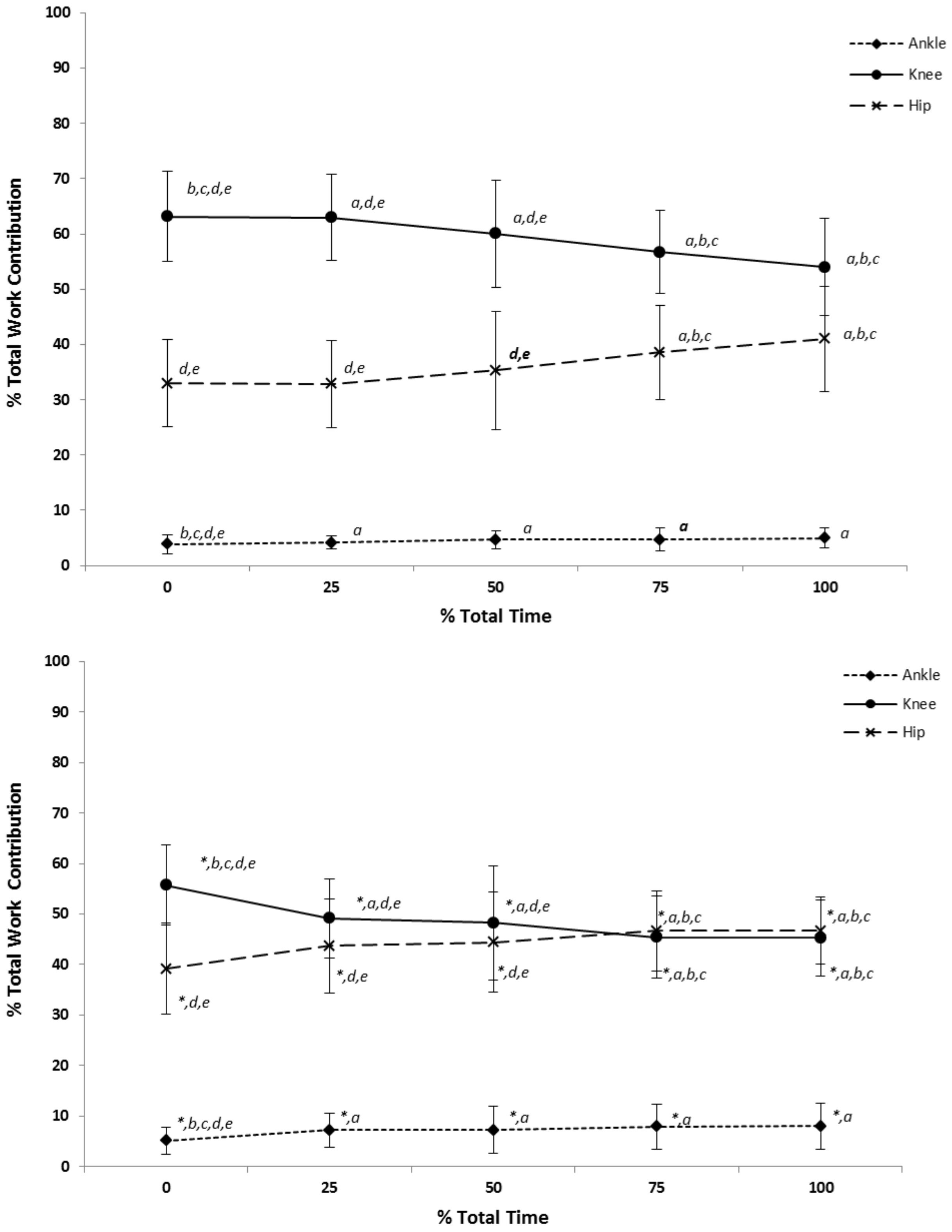


Figure 10. Young (top) and older (bottom) adult joint contributions to total lower extremity work produced over the ascending phase during repetitive STS exercise. Error bars denote SDs. ^{a} *denotes significant difference from 0%,* ^{b} *denotes significant difference from 25%,* ^{c} *denotes significant difference from 50%,* ^{d} *denotes significant difference from 75%,* ^{e} *denotes significant difference from 100%.* denotes significant age group difference from young.*

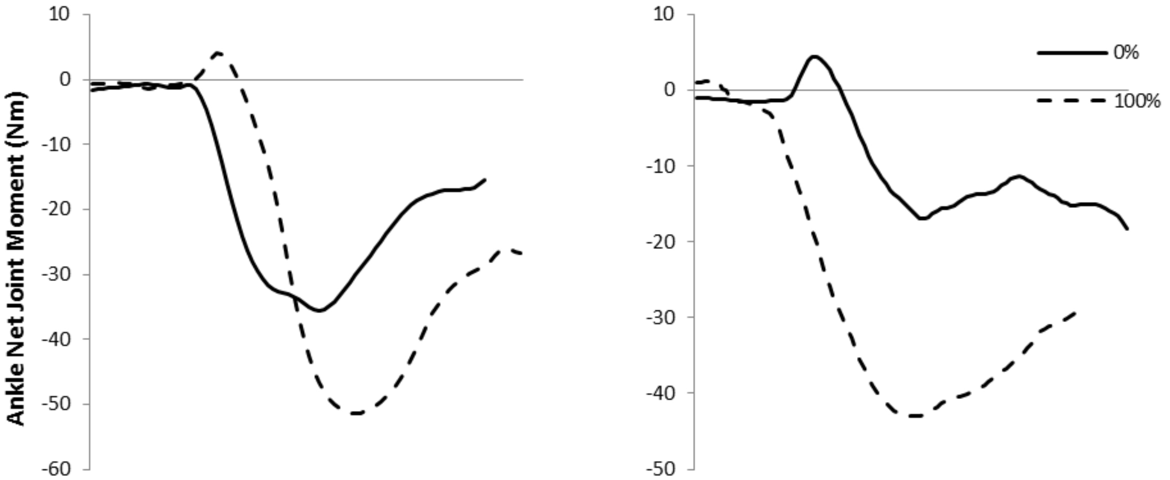


Figure 11. Ankle net joint moment curve in a single Young (left) and older (right) adult at the start (0%) and end (100%) of the repetitive STS exercise protocol (averaged over 5 repititions). Negative values indicate ankleplantar flexor moment.

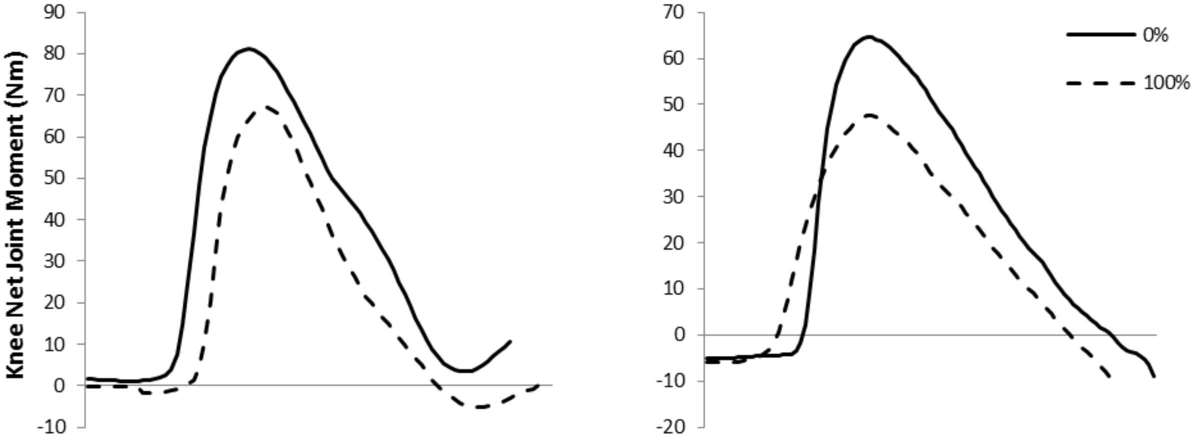


Figure 12. Knee net joint moment curve in a single Young (left) and older (right) adult at the start (0%) and end (100%) of the repetitive STS exercise protocol (averaged over 5 repetitions). Negative values indicate a knee flexor moment.

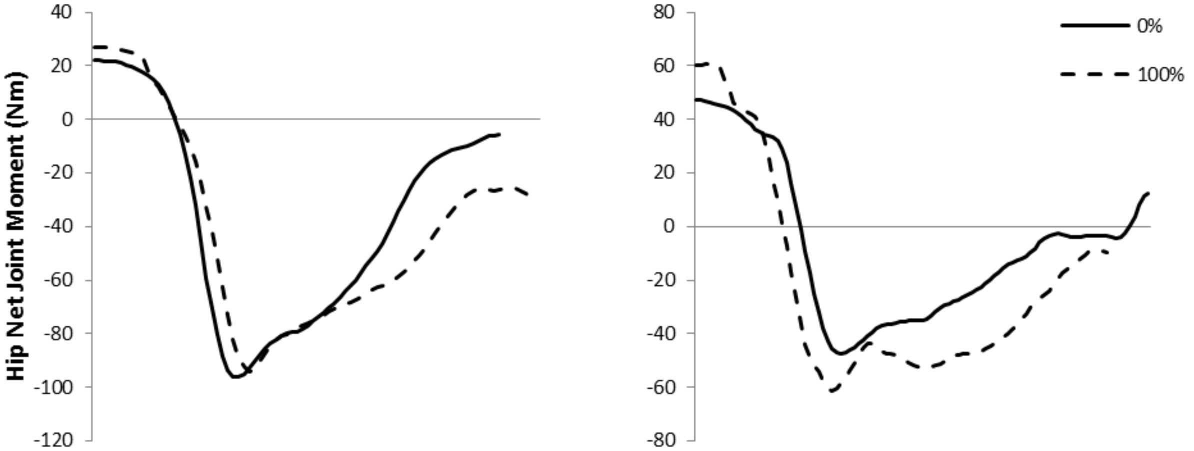


Figure 13. Hip net joint moment curve in a single Young (left) and older (right) adult at the start (0%) and end (100%) of the repetitive STS exercise protocol (averaged over 5 repetitions). Negative values indicate hip extensor moment.

Discussion

This investigation compared alterations in joint loading and mechanical work produced at the ankle, knee, and hip of young and older adults during repetitive STS exercise. In doing so, we aimed to determine if compensatory STS strategies were adopted during multi-joint fatigue and if they differed with aging. The major finding of this investigation was that although the distributions of joint kinetics across the lower extremities differed between young and older adults, the way in which they changed during repetitive STS exercise was similar. It was also apparent that joint contributions during the ascending phase of the STS were primarily related to torque generating capabilities of the KE, which progressively declined to the same extent as the multi-joint fatiguing exercise progressed in both age groups.

Repetitive STS exercise resulted in progressive declines in peak values, as well as average preparatory and ascending KE NJMs in both younger and older adult participants. Interestingly, no time dependent increases in any HE NJM measures were observed, as previous research has suggested (Flanagan & Salem, 2008; Savelberg et al., 2007; Van der Heijden et al., 2009; Yoshioka et al., 2007). Increased ankle loading was found only between 0-25% of normalized total STS exercise time points for peak and average ascending APF NJMs values. Therefore, compensatory shifting of loading demands to the HE was not observed, as resistive torques at the knee continued to decline with multi-articular fatigue. Moreover, since this trend occurred in both young and older adult participants, the way in which STS exercise impaired joint kinetics at the knee only did not differ with aging, and both groups fatigued in the same manner as it progressed. Riley et al. (1997) found that failed STS attempts in older adults were less energetic (less momentum generated), which were also associated with a reduced ability to produce sufficient knee torques around lift-off. Together, it appears that STS capacities may have been limited by an inability to produce sufficient KE joint moments with repetitive STS exercise.

Age main effects revealed that older adults had significantly lower peak and average preparatory KE NJMs; whereas average ascending values were not statistically different from those of the young adults. Age-related declines in KE strengths and power producing capabilities may have prevented older participants from attaining similar peak values as rapidly as compared to their younger counterparts (Petrella et al., 2005; Devita & Hortobagyi, 2000). In accordance with Newton's second law, the impulse-momentum relationship states that a change in momentum (the vector product of mass and velocity) is equal to the impulse of the resulting force in that direction (the product of force and duration of application) (Robertson et al., 2004). Considering this, if a given force is applied to an object for a sustained period of time, a greater speed (or momentum) of that object may be achieved compared to when a similar force is applied for a shorter time interval. Therefore, declines in peak force generating capabilities of older adults was compensated for by sustaining KE moments for a longer portion of the ascending phase in order to achieve similar KE impulses when rising from a seated position (See Appendix Figure B9) (DeVita & Hortobagyi, 2000). As shown in Figure 12, this trend is also demonstrated when comparing the area under the KE NJM curve (i.e., KE joint impulse) between the young and older participant, as well as with STS exercise. Previous biomechanical comparisons of functionally abled versus disabled older populations have been limited to peak or instantaneous kinetic analyses (Alexander et al., 1991; Hortobagyi et al., 2003; Chen, Chang, & Chou, 2013; Greve et al., 2013; Gross et al., 1998; Schultz et al., 1992); therefore, the results of this current investigation suggest that accounting for time-dependent characteristics of an NJM curve during the STS task is warrented.

At the hip, the opposite relationship was found; older participants attained similar peak HE NJM, but had higher average HE NJM ascending phase values at all time points. Again this would suggest that older adults produced HE moments over a longer duration of the STS cycle (Figure 13) which would result in their larger hip joint impulses (See Appendix Figure B9). This is supported by researchers DeVita and Hortobagyi (2000), who also found that in addition to aging being associated with a redistribution of joint torques from the ankle and knee to the hip, older adults elevated their HE torque outputs by exerting a net extensor moment longer into the stance phase compared to young adults. Our results, therefore, indicate that although fatiguing STS exercise did not result in a compensatory redistribution of NJM loading demands to the hip, this phenomenon of greater HE contributions to STS ascent is age-dependent, and presented in older participants regardless of the presence of fatigue.

In contrast to observations during gait (DeVita & Hortobagyi, 2000), older adults produced larger APF preparatory and ascending peak and average NJM at all time points during the STS in this investigation. At instant of seat-off, Chen, Chang, and Chou (2013) also observed that older adults, with a history of falling, produced significantly larger APF torques during the sit-to-walk task than the younger and age-matched healthy participants. Schultz et al. (1992) found that at seat-off, older adults had more anterior center of pressure (COP) positions which was suggested to be a stabilization strategy to compensate for age-related declines in postural stability; however, this would also cause a longer moment arms from the ankle joint center, and may be responsible for the larger APF NJM produced by the older participants in the current investigation (See Appendix Table B7) (Doorenbosche et al., 1994; Flanagan & Salem, 2008). Anterior shifting in COP has also been observed within the first half of prolonged STS exercise in young adults in our previous investigation (Bryanton & Bilodeau, 2016; *Chapter 4*) and was related to impairments in their ability to control COP deviations during the STS, as well as at postural limits of stability. This is consistent with our observed increase in APF NJM values during the first quarter of the repetitive STS protocol in both age groups, as a means in order to improve postural stability at fatigue onset. Therefore, increased average ascending NJM values, and greater mechanical work performed by the APF observed from 0-25% total time was not a result of compensatory shifting of loading demands; whereas anterior shifting of COP about the foot to stabilize oneself in the face of postural instability was more likely responsible for this (See Appendix Table B7). Together, these results reveal a distinct role of the kinetics expressed at the ankle in controlling COP positions about the BOS while executing the STS task.

Despite similar average ascending KE NJM values, KE % contributions of older adults for both measuers were signficantly lower in comparison to younger participants. This can be attributed to the larger average ascending HE and APF moments produced in older participants regardless of fatigue time, which would result in a greater total summed lower extremity support moment (Figure 6). Alternatively, declining KE NJM and work measures, when repeatedly ascending from a seated position, appear to be solely responsible for reduced KE and increased HE and APF % contributions, since no fatigue-related increases in HE or APF loading occurred throughout the exercise protocol in either age group.

Calculation of net joint mechanical work not only revealed the different type of muscle actions performed at each joint during the preparatory versus ascending phases of the STS task with fatigue and aging, but also the ability to produce sufficient energies in preparation for vertical ascent. Specifically, reductions in preparatory KE NJM and concentric mechanical work were observed with exercise progression; whereas no main fatigue effects were observed at the hip or ankle. This further suggests that impaired ability to generate sufficient KE energies prior to seat off may have been a precursor to STS failure. Also during the preparatory phase, age group main effects were observed at the hip in that work absorption (eccentric) was performed at the hip in older adults; whereas positive work was performed in young adults in preparation for seat-off (Figure 7). For the STS task, the energy absorption at the hip would be achieved through eccentric loading of the HE since an average HE NJM was being produced as the upper body rotated forward in preparation for seat-off. Greater work absorption at the hip with aging has also been previously found during gait (McGibbon & Krebs, 2001; McGibbon & Krebs, 2004; McGibbon, Krebs, & Puniello, 2001; McGibbon, Puniello, & Krebs, 2001). These investigations suggested that increased eccentric actions of the HE aid in stabilizing the trunk and pelvis during the dynamic transfer task. Alternatively, eccentric preloading of the HE may also allow the hip musculature to be in a more active state and it increased their ability to perform hip extension after contact is lost with the seat (Walshe et al., 1998). Together, it is apparent that an alternative preparatory strategy of muscle actions at the hip was associated with aging in this investigation that was not influenced by exercise.

During the ascending phase of the STS, net concentric mechanical work was performed at the ankle, knee, and hip, where KE joint work values were again the greatest of the three joints. In young adults, KE work declined from 0.78 J/kg to 0.62 J/kg by the end of the STS exercise protocol. Although slightly lower in older adults, ascending KE work was again not statistically different from young adults at all times points, declining from 0.64 J/kg to 0.53 J/kg in older participants with exercise progression. Alternatively, ascending APF and HE mechanical work performed did not differ between age groups despite higher ankle and hip NJM loading. Mechanical work was derived as the area under the joint power versus time curve with respect to STS phase, and can also be represented through integrating the NJM angular displacement curve

(DeVita, Helseth, & Hortobagyi, 2007; Flanagan & Salem, 2008; Moolyk et al., 2013; Purkiss & Robertson, 2003; Robertson et al., 2004; Winter, 2009). Considering this, comparable work energies observed at the ankle and hip between young and older participants may be attributable to age-differences in joint excursions during the ascending phase. In this investigation, seat height was controlled to ensure that both young and older participants were required to elevate their COM to the same extent for each STS repetition. Any age differences in joint excursions with respect to STS phase would be a result of either greater preparatory flexion prior to seat-off, as well as earlier or delayed extension onsets (Fogelman & Smith, 1995; Sparto et al., 2007; Yoshioka et al., 2007). A change in movement strategy with fatigue would also reflect a change in coordinative strategy, possibly as a result of impaired force generating capabilities of the KE musculature due to repetitive STS exercise.

In this investigation, the joint that contributed to the most ascending mechanical work in young adults at the start of the protocol was the KE (~60%), followed by the HE (~35%) and the APF (%5). This agrees with data from Wretenberg and Arboreoulious' (1994) study of healthy young adult men. In older adults, the KE contributed to a significantly lesser extent (~ 50%), which was compensated for by higher HE and APF contributions (~ 43% and 7%, respectively) in comparison to young adults (Figure 10). Sparto et al. (2007a) found that despite declines in absolute knee and hip work performed during repetitive lifting exercise, changes in relative joint loading were small. These researchers suggested the CNS may keep the amount of load sharing amongst the joints invariant, despite significant changes in the inter-joint coordination patterns during the repetitive lifting task. This relationship was, however, not observed in the current investigation; STS exercise caused a significant reduction in KE contribution and increased predominately at the hip. In older adults, HE contributions slightly surpassed that of the KE by the end of the exercise (~ 58% and 56% respectively). Since total lower extremity work performance did not change with STS exercise progression, alteration in joint contributions would be attributable to lessened absolute KE work performed and NJM outputs.

At the knee, no significant age differences or changes in the amount of joint excursions with fatigue were found during either preparatory or ascending STS phases. Declines in mechanical work performed by the KE observed in this investigation with repetitive STS exercise were therefore a result of reduced resistive torques at the knee. In addition to producing positive work energies for knee extension, the KE control the motion of the lower leg (Moolyk et al., 2013; Winter & Eng, 1995). Allowing greater forward inclination of the lower leg would in turn increase the amount of dorsiflexion achieved at the ankle and knee forward travel in a closed-chain movement such as the STS (Chiu et al., 2016; Fry et al., 2003; Sibella et al., 2003). Although increased dorsiflexion range of motion was observed prior to seat-off in both young and older adult participants, indicating that they shifted their bodies forward more prior to a rapid reduction in support surface, a reduction in ankle plantarflexion range of motion was also observed during the ascending phase despite achieving fully extended lower extremity joint positions at the end of each reptition; therefore the ankle, and consequently the shank, was in a more extended position when contact was lost with the seat (See Appendix Table B6). A less forward knee position would in turn reduce the moment arm length between the segment COM and the vertical joint reaction forces at the knee, and thus reduce KE NJMs. For example, during squatting, when the knee is allowed to move anteriorly over the toes, larger KE NJM are produced in comparison to restricted squats (Chiu et al., 2016; Fry et al., 2003). Therefore, changes in kinematics observed in this investigation may reflect a strategy to lessen knee loading requirements during the STS task; a more vertical leg position when transitioning to the concentric ascending phase with fatigue progression may be a compensatory movement strategy to aid in lessening KE loading requirements.

Interestingly, although young and older adults had similar amounts of hip forward flexion prior to seat-off (Figure 4); it was revealed that older adults performed less hip extension during the subsequent ascending phase as seen in Figure 3. Gross et al. (1998) also noted that at moment of seat-off, older adults in their investigation had less flexed hip positons compared to younger participants; the limited hip range of motion of the older adults in this current investigation was similarly due to initiating the STS movement in an already more extended hip position, achievable by having a more posteriorly tilted pelvis (see Appendix B, Figure 4B). Similarly, Bouchouras et al. (2015) showed that in addition to declines in KE strengths, older women with osteoarthritis had less hip range of motion during the STS in comparison to age-matched controls, which was associated with increased hamstring activity. Persons with osteoarthritis also have been shown to have greater HE torques and trunk flexion when ascending from a chair to compensate for lower KE torques when compared to age-mathced controls (Pai et al., 1994; Patsika et al., 2011). Therefore, redistribution of joint torques to the HE may necessitate increased hamstring activity with aging, and a more extended hip position and limited hip range of motion would lessen HE work values over the ascending phase of the STS repetitions and its biomechanical cost (Purkiss & Roberson, 2003). A more posteriorly tilted pelvic position would be an undesirable kinematic as older adults would require greater lumbar flexion in order to bring the torso over the feet in preparation for seat-off (see Appendix B, Table B6), leading to higher levels of unwanted lumbar shear forces; therefore, in order to bring the torso over the base of support in preparation for seat off, this forward flexion strategy would result in increasingly greater amounts of lumbar flexion in older individuals in comparison to their younger counterparts, and an increased risk of lower back injury due to higher levels of unfavorable shear forces in the lower back with repetitive STS exercise (List et al., 2013; Sparto et al., 2007; Toussaint et al., 1995; van Dieen, Hoozemans, & Toussaint, 1999).

A limitation of calculating net joint kinetic in traditional inverse dynamics techniques, is that they represent the sum of all agonist and antagonist muscle forces acting upon a single joint, and therefore one cannot infer the extent to which all associated musculature contribute to joint loadings (Bryanton et al., 2012; Bryanton et al., 2015; Nigg & Herzog, 2007; Toussaint et al., 1992; Winter & Eng, 1995). For example, Bryanton et al. (2015) showed that through modeling co-contraction of the hamstrings at the knee during squatting, the quadriceps moment generated at the knee was substantially underestimated and increased to near maximal relative muscular efforts as barbell load increased. Consequently, the true loading of agonist KE musculature may be underestimated by antagonist activity and this raises concerns when comparing joint efforts between tasks that involve differing levels of co-contraction (Jacobs et al., 1996; Toussaint et al., 1992). This limitation extends further with aging research, as higher hamstring co-activity is commonly observed in older adults for a given task compared to their younger counterparts, and may be responsible for lower torques when the physiological cross sectional area of the thigh musculature is accounted for (Hortobagyi et al., 2003; Maculuso et al., 2002). Considering this, it is unclear whether declines in KE NJM performed with fatiguing STS exercise observed in the current investigation were due to: a) lessened high muscle efforts to improve movement efficiency, b) reduced force generating capabilities due greater accumulation of fatigue, or c) increased hamstring contributions and resulting higher antagonist co-activities at the knee.

In summary, aging was associated with a redistribution of joint loading demands when ascending from a seated position; however the way in which multi-joint STS exercise influenced joint kinetics was invariant with aging. Moreover, KE NJM loading and work performed progressively declined throughout the exercise protocol and was suggested to be responsible for limiting STS capacities in both young and older adults, as a compensatory shifting of loading demands to the HE was not observed. Consequently, this research is beneficial for rehabilitative professionals by increasing our understanding of the role of limiting factor muscles such as the KE. Specifically, it indicates that older adults may benefit from strengthening of the quadriceps to elevate or maintain higher levels of strength reserves in order to improve their ability to repeatedly perform multi-joint tasks that require large resistive torques about the knee, such as standing from a seated position.

Acknowledgments: We would like to thank Dr. Heidi Sveistrup and the Motor Control Laboratory at the University of Ottawa for their assistance and provding the equipment for the data collection project.

References

Akram, S.B., & McIlroy, W.E. (2011). Challenging horizontal movement of the body during sit-to-stand: Impact on stability in the young and elderly. *Journal of Motor Behavior, 43*(2), 147-153.

Alexander, N. B., Schultz, A. B., & Warwick, D. N. (1991). Rising from a chair: effects of age and functional ability on performance biomechanics. *Journal of Gerontology*, *46*(3), M91-M98.

Barbieri, F. A., dos Santos, P. C. R., Vitório, R., van Dieën, J. H., & Gobbi, L. T. B. (2013). Effect of muscle fatigue and physical activity level in motor control of the gait of young adults. *Gait & Posture*, *38*(4), 702-707.

Bieryla, K. A., Anderson, D. E., & Madigan, M. L. (2009). Estimations of relative effort during sit-to-stand increase when accounting for variations in maximum voluntary torque with joint angle and angular velocity. *Journal of Electromyography and Kinesiology*, *19*(1), 139-144.

Borg, G. A. V. (1982). Psychological bases of perceived exertion. *Medicine and Science in Sports and Exercise*, *14*(5), 377-381.

Bouchouras, G., Patsika, G., Hatzitaki, V., & Kellis, E. (2015). Kinematics and knee muscle activation during sit-to-stand movement in women with knee osteoarthritis. *Clinical Biomechanics*, *30*(6), 599-607.

Bryanton, M. A., Carey, J. P., Kennedy, M. D., & Chiu, L. Z. (2015). Quadriceps effort during squat exercise depends on hip extensor muscle strategy. *Sports Biomechanics*, *14*(1), 122-138.

Bryanton, M. A., Kennedy, M. D., Carey, J. P., & Chiu, L. Z. (2012). Effect of squat depth and barbell load on relative muscular effort in squatting. *The Journal of Strength & Conditioning Research*, *26*(10), 2820-2828.

Buatois, S., Miljkovic, D., Manckoundia, P., Gueguen, R., Miget, P., Vançon, G., ... & Benetos, A. (2008). Five times sit to stand test is a predictor of recurrent falls in healthy community-living subjects aged 65 and older. *Journal of the American Geriatrics Society*, *56*(8), 1575-1577.

Carter, N.D., Khan, K.M., Mallinson, A., Janssen, P.A., Heinonen, A., Petit, M.A., & McKay, H.A. (2002). Knee extensor strength is a significant determinant of static and dynamic balance as well as quality of life in older community-dwelling women with osteoporosis. *Gerontology, 48*(6), 360-368.

Chen, T., Chang, C. C., & Chou, L. S. (2013). Sagittal plane center of mass movement strategy and joint kinetics during sit-to-walk in elderly fallers. *Clinical Biomechanics*, *28*(7), 807-812.

Chiu, L. Z., Bryanton, M. A., & Moolyk, A. N. (2014). Proximal-to-distal sequencing in vertical jumping with and without arm swing. *The Journal of Strength & Conditioning Research*, *28*(5), 1195-1202.

Chiu, L. Z., vonGaza, G. L., & Jean, L. M. (2016). Net joint moments and muscle activation in barbell squats without and with restricted anterior leg rotation. *Journal of Sports Sciences*, 1-9.

Denton, F. T., & Spencer, B. G. (1998). *Economic costs of an aging population*. IESOPResearch Paper no. 32. Hamilton, ON: McMaster University.

DeVita, P., Helseth, J., & Hortobagyi, T. (2007). Muscles do more positive than negative work in human locomotion. *Journal of Experimental Biology*, *210*(19), 3361-3373.

DeVita, P., & Hortobagyi, T. (2000). Age causes a redistribution of joint torques and powers during gait. *Journal of Applied Physiology*, *88*(5), 1804-1811.

Doorenbosch, C.A.M., Harlaar, J., Roenbroeck, M.E.,& Lankhorst, G.J. (1994). Two strategies of transferring from sit-to-stand: The activation of monoarticular and biarticular muscles. *Journal of Biomechanics*, 27(11), 1299-1307.

Flanagan, S. P., & Salem, G. J. (2008). Lower extremity joint kinetic responses to external resistance variations. *Journal of Applied Biomechanics*, *24*(1), 58.

Fogleman, M., & Smith, J.L (1995). The use of biomechanical measures in the investigation of changes in lifting strategies over extended periods. *International Journal of Industrial Ergonomics, 16*, 57-71.

Fry, A. C., Smith, J. C., & Schilling, B. K. (2003). Effect of knee position on hip and knee torques during the barbell squat. *The Journal of Strength & Conditioning Research*, *17*(4), 629-633.

Godin, G., & Shepard, R.J. (1997). Godin and Leisure-Time Exercise Questionnaire. *Medicine and Science in Sports and Exercise. 29 (June Supplements)*, S36-S38.

Greve, C., Zijlstra, W., Hortobágyi, T., & Bongers, R. M. (2013). Not all is lost: old adults retain flexibility in motor behaviour during sit-to-stand. *PloS one*, *8*(10), e77760.

Gross, M. M., Stevenson, P. J., Charette, S. L., Pyka, G., & Marcus, R. (1998). Effect of muscle strength and movement speed on the biomechanics of rising from a chair in healthy elderly and young women. *Gait & Posture*, *8*(3), 175-185.

Hortobágyi, T., Mizelle, C., Beam, S., & DeVita, P. (2003). Old adults perform activities of daily living near their maximal capabilities. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *58*(5), M453-M460.

Hughes, M. A., Weiner, D. K., Schenkman, M. L., Long, R. M., & Studenski, S. A. (1994). Chair rise strategies in the elderly. *Clinical Biomechanics*, *9*(3), 187-192.

Hughes, M. A., Myers, B. S., & Schenkman, M. L. (1996). The role of strength in rising from a chair in the functionally impaired elderly. *Journal of Biomechanics*, *29*(12), 1509-1513.

Hughes, M. A., & Schenkman, M. L. (1996). Chair rise strategy in the functionally impaired elderly. *Journal of Rehabilitation Research and Development*, *33*(4), 409.

Hurley, M.V., Rees, I., & Newham, D.J. (1998). Quadriceps function, proprioceptive acuity and functional performance in healthy young, middle aged and elderly subjects. *Age and Aging, 27,* 155-162.

Ikezoe, T., Mori, N., Nakamura, M., & Ichihashi, N. (2011). Age-related muscle atrophy in the lower extremities and daily physical activity in elderly women. *Archives of Gerontology and Geriatrics*, *53*(2), e153-e157.

Ikezoe, T., Mori, N., Nakamura, M., & Ichihashi, N. (2011). Atrophy of the lower limbs in elderly women: Is it related to walking ability? *European Journal of Applied Physiology*, *111*, 989-995.

Jacobs, R., Bobbert, M. F., & van Ingen Schenau, G. J. (1996). Mechanical output from individual muscles during explosive leg extensions: the role of biarticular muscles. *Journal of Biomechanics*, *29*(4), 513-523.

Janssen, W. G., Bussmann, H. B., & Stam, H. J. (2002). Determinants of the sit-to-stand movement: a review. *Physical Therapy*, *82*(9), 866-879.

Jones, C. J., Rikli, R. E., & Beam, W. C. (1999). A 30-s chair-stand test as a measure of lower body strength in community-residing older adults. *Research Quarterly for Exercise and Sport*, *70*(2), 113-119.

Kepple, T. M., Siegel, K. L., & Stanhope, S. J. (1997). Relative contributions of the lower extremity joint moments to forward progression and support during gait. *Gait & Posture*, *6*(1), 1-8.

List, R., Gülay, T., Stoop, M., & Lorenzetti, S. (2013). Kinematics of the trunk and the lower extremities during restricted and unrestricted squats. *The Journal of Strength & Conditioning Research*, *27*(6), 1529-1538.

Macaluso, A., Nimmo, M. A., Foster, J. E., Cockburn, M., McMillan, N. C., & De Vito, G. (2002). Contractile muscle volume and agonist-antagonist coactivation account for differences in torque between young and older women. *Muscle & Nerve*, *25*(6), 858-863.

Manini, T., Visser, M., Won-Park, S., Patel, K.V., Stratmeyer, E.S., Chen, H., Goodpaster, B., DeRekeneire, N., Newman, A.B., Simonsick, E.M., Kritchevsky, S.B., Ryder, K., Schwarts, A.V., & Harris, T.B. (2007). Knee extension strength cutpoints for maintaining mobility. *JAGS, 55,* 451-457.

Mathiyakom, W., McNitt-Gray, J. L., Requejo, P., & Costa, K. (2005). Modifying center of mass trajectory during sit-to-stand tasks redistributes the mechanical demand across the lower extremity joints. *Clinical Biomechanics*, *20*(1), 105-111.

McGibbon, C. A., & Krebs, D. E. (2001). Age-related changes in lower trunk coordination and energy transfer during gait. *Journal of Neurophysiology*, *85*(5), 1923-1931.

McGibbon, C. A., & Krebs, D. E. (2004). Discriminating age and disability effects in locomotion: neuromuscular adaptations in musculoskeletal pathology. *Journal of Applied Physiology*, *96*(1), 149-160.

McGibbon, C. A., Krebs, D. E., & Puniello, M. S. (2001). Mechanical energy analysis identifies compensatory strategies in disabled elders' gait. *Journal of Biomechanics*, *34*(4), 481-490.

McGibbon, C. A., Puniello, M. S., & Krebs, D. E. (2001). Mechanical energy transfer during gait in relation to strength impairment and pathology in elderly women. *Clinical Biomechanics*, *16*(4), 324-333.

Moolyk, A. N., Carey, J. P., & Chiu, L. Z. (2013). Characteristics of lower extremity work during the impact phase of jumping and weightlifting. *The Journal of Strength & Conditioning Research*, *27*(12), 3225-3232.

Nigg, B. M., & Herzog, W. (2007). *Biomechanics of the musculo-skeletal system*. John Wiley & Sons.

Pai, Y. C., Chang, H. J., Chang, R. W., Sinacore, J. M., & Lewis, J. L. (1994). Alteration in multijoint dynamics in patients with bilateral knee osteoarthritis. *Arthritis & Rheumatism*, *37*(9), 1297-1304.

Patsika, G., Kellis, E., & Amiridis, I. G. (2011). Neuromuscular efficiency during sit to stand movement in women with knee osteoarthritis. *Journal of Electromyography and Kinesiology*, *21*(5), 689-694.

Petrella, J. K., Kim, J. S., Tuggle, S. C., Hall, S. R., & Bamman, M. M. (2005). Age differences in knee extension power, contractile velocity, and fatigability. *Journal of Applied Physiology*, *98*(1), 211-220.

Puniello, M. S., McGibbon, C. A., & Krebs, D. E. (2001). Lifting strategy and stability in strength-impaired elders. *Spine*, *26*(7), 731-737.

Purkiss, S. B., & Robertson, D. G. E. (2003). Methods for calculating internal mechanical work: comparison using elite runners. *Gait & Posture*, *18*(3), 143-149.

Riley, P. O., Krebs, D. E., & Popat, R. A. (1997). Biomechanical analysis of failed sit-to-stand. *Rehabilitation Engineering, IEEE Transactions on*, *5*(4), 353-359.

Robertson, G., Caldwell, G., Hamill, J., Kamen, G., & Whittlesey, S. (2004). *Research methods in biomechanics*. Human Kinetics.

Savelberg, H. H. C. M., Fastenau, A., Willems, P. J. B., & Meijer, K. (2007). The load/capacity ratio affects the sit-to-stand movement strategy. *Clinical Biomechanics*, *22*(7), 805-812.

Scarborough, D. M., McGibbon, C. A., & Krebs, D. E. (2007). Chair rise strategies in older adults with functional limitations. *Journal of Rehabilitation Research and Development*, *44*(1), 33.

Schultz, A.B., Alexander, N.B., & Ashton-Miller, J.A. (1992). Biomechanical analysis of rising from a chair. *Journal of Biomechanics, 25*(12), 1383-1391.

Sheppard, R.J. (2002). *Gender, physical activity, and aging*. New York, NY: CRC Press.

Sibella, F., Galli, M., Romei, M., Montesano, A., & Crivellini, M. (2003). Biomechanical analysis of sit-to-stand movement in normal and obese subjects. *Clinical Biomechanics*, *18*(8), 745-750.

Sparto, P.J., Parnianpour, M., Reinsel, T.E., & Simon, S. (1997a). The effect of fatigue on multijoint kinematics and load sharing during a repetitive lifting test. *Spine, 22*, 2647-2654.

Sparto, P.J., Parnianpour, M., Reinsel, T.E., & Simon, S. (1997b). The effect of fatigue on multi-joint kinematics, coordination, and postural stability during a repetitive lifting test. *Journal of Orthopaedic and Sports Physical Therapy Association*, *25(*1), 3-12.

Special Senate Committee on Aging (SSCA). (2009). *Canada's aging population: Seizing the opportunity* [online] – [Cited December 3rd, 2011] - - Retrieved from http://www.parl.gc.ca/Content/SEN/Committee/402/agei/rep/AgingFinalReport-e.pdf

Tiedmann, A., Shimada, H., Sherrington, C., Murray, S., & Lord, S. (2008). The comparative ability of eight functional mobility tests for predicting falls in community-dwelling older people. *Age and Ageing, 37*, 430-435.

Toussaint, H. M., de Winter, A. F., de Haas, Y., de Looze, M. P., Van Dieën, J. H., & Kingma, I. (1995). Flexion relaxation during lifting: implications for torque production by muscle activity and tissue strain at the lumbo-sacral joint. *Journal of Biomechanics*, *28*(2), 199-210.

Toussaint, H. M., Van Baar, C. E., Van Langen, P. P., De Looze, M. P., & Van Dieen, J. H. (1992). Coordination of the leg muscles in backlift and leglift. *Journal of Biomechanics*, *25*(11), 1279-1289.

Van der Heijden, M. M., Meijer, K., Willems, P. J., & Savelberg, H. H. (2009). Muscles limiting the sit-to-stand movement: an experimental simulation of muscle weakness. *Gait & posture*, *30*(1), 110-114.

van Dieën, J. H., Hoozemans, M. J., & Toussaint, H. M. (1999). Stoop or squat: a review of biomechanical studies on lifting technique. *Clinical Biomechanics*, *14*(10), 685-696.

Walshe, A. D., Wilson, G. J., & Ettema, G. J. (1998). Stretch-shorten cycle compared with isometric preload: contributions to enhanced muscular performance. *Journal of Applied Physiology*, *84*(1), 97-106.

Winter, D. A. (1980). Overall principle of lower limb support during stance phase of gait. *Journal of Biomechanics*, *13*(11), 923-927.

Winter, D. A. (2009). *Biomechanics and motor control of human movement*. John Wiley & Sons.

Winter, D. A., & Eng, P. (1995). Kinetics: our window into the goals and strategies of the central nervous system. *Behavioural Brain Research*, *67*(2), 111-120.

Wretenberg, P., & Arborelius, U. P. (1994). Power and work produced in different leg muscle groups when rising from a chair. *European Journal of Applied Physiology and Occupational Physiology*, *68*(5), 413-417.

Yoshioka, S., Nagano, A., Himeno, R., & Fukashiro, S. (2007). Computation of the kinematics and the minimum peak joint moments of sit-to-stand movements. *Biomed Eng Online*, *6*(1), 26.

CHAPTER 6

MANUSCRIPT 3:

The Role of Thigh Muscular Efforts in Limiting Sit-to-Stand Capacity in Healthy Young and Older Adults

Megan Bryanton, Martin Bilodeau

The Role of Thigh Muscular Efforts in Limiting Sit-to-Stand Capacity in Healthy Young and Older Adults

[1,3] Megan Bryanton, [2,3] Martin Bilodeau

[1]School of Human Kinetics, University of Ottawa, ON, CA
[2]School of Rehabilitation Sciences, University of Ottawa, ON, CA
[3]Aging and Movement Laboratory, Bruyère Research Institute, ON, CA

Submission Type: Original Article 13

Disclosure of Funding: This research was partially funded by the Canada Foundation for Innovation (M. Bilodeau) and a Faculty of Health Sciences Admission's scholarship to M. Bryanton

Abstract

Aging is associated with an unavoidable decline in muscle mass, known as sarcopenia, leading to reduced muscular strength, power, and force control. One particular measure utilized by rehabilitative professionals in predicting disability with aging is sit-to-stand (STS) capacity. The purpose of this investigation was to determine the role of thigh musculature and associated activation intensities in limiting STS capacity (i.e., a multi-joint endurance task). To do so, muscular efforts of the quadriceps and hamstrings and their co-activation ratios were collected using surface electromyography, as young (18-35 years; n=12) and older (60-75 years; n=12) adult participants performed a repetitive STS exercise protocol. Regression analyses revealed that quadriceps (QF) relative muscular effort (%MVIC) was a strong predictor of STS capacity, as those who required the highest quadriceps efforts had the shortest task times. This group consisted of the older adult participants who had significantly higher starting QF %MVIC, in comparison to the younger age group, and reached maximal efforts at the end of the multi-joint fatigue protocol. In contrast, the ratio of hamstring activation relative to that of the QF was not a significant predictor of STS capacities, nor did it differ between age groups or with STS exercise in young and older adult participants. The findings of this investigation indicate that strengthening of the quadriceps to elevate or maintain higher levels of strength reserve levels would improve older adults ability to perform multi-joint tasks repetitively throughout the day and reduce their inherent risk of injury.

Keywords: sit-to-stand, muscle endurance, quadriceps, hamstrings, aging, co-contraction

Introduction

Aging is associated with an unavoidable decline in muscle mass, known as sarcopenia, and it has been previously used as a predictor of disability and loss of functional autonomy in older adults. This is attributable to declines in muscular strength, power, and force control (Bassey et al., 1992; Ikezoe et al., 2011; LeRoche et al., 2010; Muhlberg & Sieber, 2004; Petrella et al., 2005). Evidence suggests that neural remodeling may precede muscle loss with aging, and larger type II muscle fibers are more vulnerable to attrition (Avin & Law, 2011; Deschenes et al., 2010; Doherty, 2003; Doherty et al., 1993; Kent-Braun & Ng, 1999; Lynch et al., 1999). It is therefore understandable that muscle groups with higher proportions of type II fibers such as the Quadriceps femoris are impacted by sarcopenia to a greater extent in comparison to those with slower fiber proportions such as the Soleus or upper extremities (Ikeda et al., 2005; Ikezoe et al., 2011; Lynch et al., 1999). The influence of this motor unit loss on muscle contractile strength is demonstrated by the relationship found between maximal voluntary torque and the estimated number of motor units in older subjects (Doherty et al., 1993).

Aging has also been previously associated with an improved ability to resist fatigue when older persons are subjected to similar relative loads as their younger counterparts during isometric contraction fatigue protocols (Bilodeau et al., 2001; Hunter et al., 2005; Kent-Braun, 2009), but this appears to be negligible with dynamic contractions (Avin & Law, 2011). Activities of daily living involve the contribution of multiple muscle groups and joint rotations that require varying contraction types (isometric, concentric, eccentric) and varying intensities to execute (Burnfield et al., 2012; DeVita, Helseth & Hortobagyi, 2007; Hortobagyi et al., 2003; Winter & Eng, 1995; Wretenberg & Arborelius, 1994); therefore it is unclear how aging may differently affect the ability to repeatedly perform a multi-joint task.

One particular measure utilized by rehabilitation professionals in predicting disability with aging is sit-to-stand (STS) capacity (i.e., the ability to perform the task repeatedly) (Bohanon, 1995; Buatois et al., 2008; Jones et al., 1999; Petrella et al., 2005). The STS is a complex weight-bearing multi-joint movement involved in numerous activities of daily living. It involves forceful contractions of the ankle plantar flexor, knee extensor, and hip extensor musculature of which efforts are not evenly distributed, with substantially higher knee extensor muscular efforts (Bieryla et al., 2007; Burnfield et al., 2012; Shultz, Alexander, & Ashton-Miller, 1992). Moreover, near maximal knee extensor efforts have been observed in older populations (Hughes et al., 1996), leading to the consensus that their strengths are a limiting factor in STS performance and other functional tasks of daily living (Bassey et al., 1992; Bohanon, 2009; Corrigan & Bohannon, 2001; Eriksrud & Bohannon, 2003; Hurley et al., 1998; Ikezoe et al., 2011; Manini et al., 2007; Puniello et al., 2001; Savelberg et al., 2007; van der Heijden et al., 2006). In turn, it is expected that higher activation intensities required by the associated quadriceps muscles, would cause them to accumulate fatigue more readily with repetitive actions, and to a greater extent in older persons (Boyas & Geuvel, 2011a).

Higher levels of antagonist co-contraction are commonly exhibited in older individuals for a given task compared to younger persons to increase joint stiffness and compensate for reduced force control steadiness, muscle coordination, and somatosensory acuity with aging (Fujita et al., 2011; Hajkinnen et al., 1998; Horak et al., 1989; Hortobagyi et al., 2003; Kallio et al., 2012; Laidlaw et al., 2000; Nagai et al., 2013; Shaffer & Harrison, 2007; Winter et al., 2001). However, during a multi-joint task such as the STS, elevated co-activity of the hamstrings and associated flexor effect at the knee would be an inefficient control strategy since it would further increase quadriceps force generation requirements to sustain the required joint kinetics to ascend from a seated position (Bryanton et al., 2015; Doorenbosche et al., 1994; Fujita et al., 2011; Patsika et al., 2011). Therefore, in addition to declining strength reserves, higher levels of hamstring co-activity at the knee during repetitive multi-joint exercise may also limit STS capacity with aging.

The purpose of this investigation was to evaluate the role of thigh musculature and associated activation intensities in limiting STS capacity (i.e., a multi-joint endurance task). To do so, muscular efforts of the quadriceps and hamstrings, and their co-activation ratios were collected using surface electromyography (EMG), as young and older adult participants performed a repetitive STS exercise protocol. Secondly, unfatigued EMG values were used in a subsequent regression to determine the ability to predict total task times. It was hypothesized that higher quadriceps efforts and antagonist co-activation at the knee, as well as shorter task times would be found in older participants, and muscular effort requirements would predict one's ability to sustain repetitive STS exercise.

Methods

Participants

Twenty four healthy adult men and women between the ages of 18-35 (i.e., young, n=12; 6 females) and 60-85 (i.e., older, n=12; 6 females) were recruited from the community as a convenience sample. Exclusion criteria for participants included previous lower extremity or lower back orthopedic and musculoskeletal injuries that prevented the exercise from being performed safely, as well as taking any medications that may affect balance. Participants were instructed to refrain from any strenuous lower extremity activities prior to visiting the laboratory. A Godin-Leisure time questionnaire (Godin & Sheppard, 1997) was administered to account for physical activity levels in both age groups. Ethics approval was obtained from the University of

Ottawa and Bruyere Research Institute research ethics boards, and informed consent was obtained prior to testing.

Procedures

STS Fatigue Protocol: Subjects were seated on an armless and backless bench adjusted to a height of 80% of the participants' lower leg lengths as described in Bryanton and Bilodeau (Chapter 4). Prior to standing, subjects were instructed to sit in a comfortable erect posture with their arms folded across their chest and feet positioned shoulder width apart. Initial foot placement was marked on the force platform to prevent shifting of feet during the course of the fatigue protocol. STS repetitions were performed continuously at a pace of 30 beats per minutes in which an audible metronome signal when to ascend and descend until: a) they could no longer maintain the given pace for 5 consecutive beats, b) volitional exhaustion occurred, or c) a 30 minute cut-off time was reached. Strong verbal encouragement was provided during the later stages of the fatigue protocol and a modified 10-point Borg scale (0 = no effort and 10 = maximal effort) (Borg, 1982) was administered every minute in order to monitor perceived exertion levels.

EMG Recordings: Surfuace electromyography (EMG) signals of the rectus femoris (RF), vastus lateralis (VL), and biceps femoris (BF) were recorded during STS testing procedures with bipolar surface electrodes of 1 mm in width, and 10 mm in length, with a 10mm center-to-center interelectrode distance (DE-2.1, Delsys Inc., Boston, USA). All electrodes were placed in a direction parallel to the muscle fibers for a given muscle. A reference electrode was positioned approximately 6 cm distal to the inferior pole of the patella, over the bony surface of the tibia. EMG signals were recorded using the Bagnoli 16 EMG system (Delsys Inc., Boston, USA) at a sampling rate of 2,000 Hz and amplification between 100X and 10000X. A 20-450 Hz band-pass filter was applied to all EMG signals before they were rectified and smoothed using root mean square (RMS) with a 50 ms window. Average RMS amplitudes were then calculated over the concentric phase of the quadriceps for each sit-to-stand repetition analyzed, and was then normalized with respect to standardized maximal isometric RMS amplitudes (% of Maximal Voluntary Isometric Conctraction (MVIC)) of a 100ms window from a maximal isometric knee extension and flexion trial obtained prior to STS testing. Standardized isometric trials as well as electrode placements were performed in accordance to SENIAM recommendations. Lastly, since the properties of the surface EMG signal are a result of the biochemical and physiological properties of the underlying skeletal muscle, fatiguing exercise causes a shift in the signal's power spectrum towards lower frequencies and increased single amplitudes (Cifrek et al., 2009; DeLuca, 1984). To address this issue, standardized normalization extension and flexion contractions were also performed immediately after the cessation of STS exercise in order to renormalize fatigued musculature activation with respect to the altered maximal amplitude.

Data Analysis

Concentric phase RF, VL and BF %MVICs were averaged over 5 STS repetitions using BioProct3 software, at the start and end of the STS fatigue protocol. It is difficult to discern whether increased amplitudes relative to normalized actions are attributable to muscle fatigue or compensatory action between muscles (Hug, 2011). For example, prolonged KE fatiguing exercise has been shown to cause not only increased synergistic activity of the vasti, but also increased contribution of the biarticular RF, which in an unfatigued state generally plays less of a contribution role to KE (Akima et al., 2002; Akima et al., 2004). To reduce the possibility of misinterpretation, an average RF and VL activation was used to represent a general quadriceps femoris (QF) activation intensity to account for mean contributions of both the monoarticular and biarticular knee extensors (Fujita et al., 2011). This would also solve problems of cross talk for the RF with underlying vastus intermedius action potential being detected inadvertently. Lastly, knee co-activation levels were quantified using H:Q ratios calculated using normalized (start) and renormalized (end) BF activation levels with respect to that of the QF.

Statistical Analysis

To compare changes in thigh muscle activation intensities and co-activation at the knee in young and older participants with fatiguing STS exercise, separate mixed model ANOVAs with one between subjects (age; Young vs. Old) and one repeated measures (time; 0 vs. 100% total time) factors were performed for QF %MVIC, BF %MVIC and H:Q data. Where appropriate, Tukey HSD for post-hoc comparisons was performed, and Cohen's d effect sizes were calculated to determine magnitudes of differences.

Secondly, stepwise linear regression analyses were performed using non-fatigued initial QF and BF effort levels (%MVIC at the start of the STS protocol) in order to test for a significant predicting relationship to total STS task time. Three different regression analyses were performed based on the grouping of data: a) separately for young and older participants, 2) using all participants who had total STS times of less than 30 minutes (i.e., did not reach the 30 minute cut-off time) and 3) combining age groups regardless of task times. The alpha level was set *a priori* at $\alpha=0.05$.

Results

EMG and Co-contraction Ratios

With exhaustive STS exercise, QF and BF %MVCs significantly increased in both young (n=12) and older adults (n=12) ($p<0.001$, $d=1.10$ and $p=0.002$, $d=0.820$, respectively). At either time point (0% vs. 100% total time), older adults had significantly greater % MVIC efforts for both QF and BF activity, with no interactions (Figure 1). No significant time ($p=0.999$, $d=0.000$) or age ($p=0.317$, $d=0.124$) effects were found for H:Q co-activation ratios (Table 2).

When the entire sample was considered, stepwise regression analyses revealed that QF %MVIC levels at the start of the STS exercise protocol was the only variable able to significantly predict total STS capacity durations amongst individuals (ß= -0.679, $t(23)= -4.338$, $p<0.001$) (Figure 2), and not BF(ß= -0.096, $t(23)= -0.561$, $p=0.581$)(Figure 3) or H:Q ratio (ß= -0.070, $t(23)= -0.435$, $p=0.668$) (Figure 4). QF effort levels explained a significant proportion of the variance in total STS task times ($R^2=0.461$, $F(1,22)=18.819$, $p<0.001$). This relationship was expressed as:

$$\textit{Total STS time} = 36.667-(0.251 \times \textit{QF\%MVIC}) \qquad (1)$$

When only participants who did not make it to the 30 minute cut-off were used (n=16; 6 young, 10 old), stepwise regression analyses revealed that QF %MVIC levels at the start of the STS exercise protocol was the only variable able to significantly predict total STS capacity durations amongst individuals (ß= -0.550, $t(14)= -2.375$, $p<0.034$), and not BF(ß= -0.016, $t(14)= -0.067$, $p=0.941$) or H:Q ratio (ß= -0.075, $t(14)= -0.289$, $p=0.778$). QF effort levels explained a significant proportion of the variance in total STS exercise times ($R^2=0.303$, $F(1,13)=5.639$, $p<0.034$). This relationship was expressed as:

$$\textit{Total STS time} = 29.268-(0.183 \times \textit{QF\%MVIC}) \qquad (2)$$

Lastly, no significant relationships were found when the stepwise-regression was performed for the young group only. In contrast, when only the older adult sample was considered, stepwise regression analyses revealed that QF %MVIC levels at the start of the STS exercise protocol was the only muscle activity variable able to significantly predict total STS capacity durations amongst individuals (ß= -0.682, *t*(11)= -2.945, $p<0.015$) and not BF(ß= 0.105, *t*(11)= 0.430, p=0.677) or H:Q ratio (ß= 0.117, *t*(11)= 0.460, p=0.657). QF effort levels explained a significant proportion of the variance in total STS exercise times ($R^2=0.464$, *F*(1,10)=8.673, p=0.015). This relationship was expressed as:

$$\text{Total STS time} = 33.897-(0.255 \times QF\%MVC) \tag{3}$$

Table 1. Subject Characteristics (± *SDs*)

Group	Age (yrs)	Body mass (kg)	Height (cm)	GLTQ
Young (n= 12)	25.0 (*5.0*)	72.0 (*16.6*)	171.7 (*11.9*)	50.3 (*21.9*)
Old (n=12)	66.8 (4.9)	73.8 (*14.0*)	171.2 (11.2)	46.4 (33.8)

Table 2. Group Average Total Task Times and Co-contraction Ratios (H:Q) (±SD) at the Beginning (0%) and End (100%) of the Repetitive STS Exercise Protocol in Young and Older Adults.

	H:Q-0%	H:Q-100%	Total Time (min)
Young	0.20 (0.08)	0.25 (0.15)	27.2 (*3.8*)
Old	0.32 (0.27)	0.27 (0.17)	16.8 (*9.7*)*

** denotes significant age group difference from young*

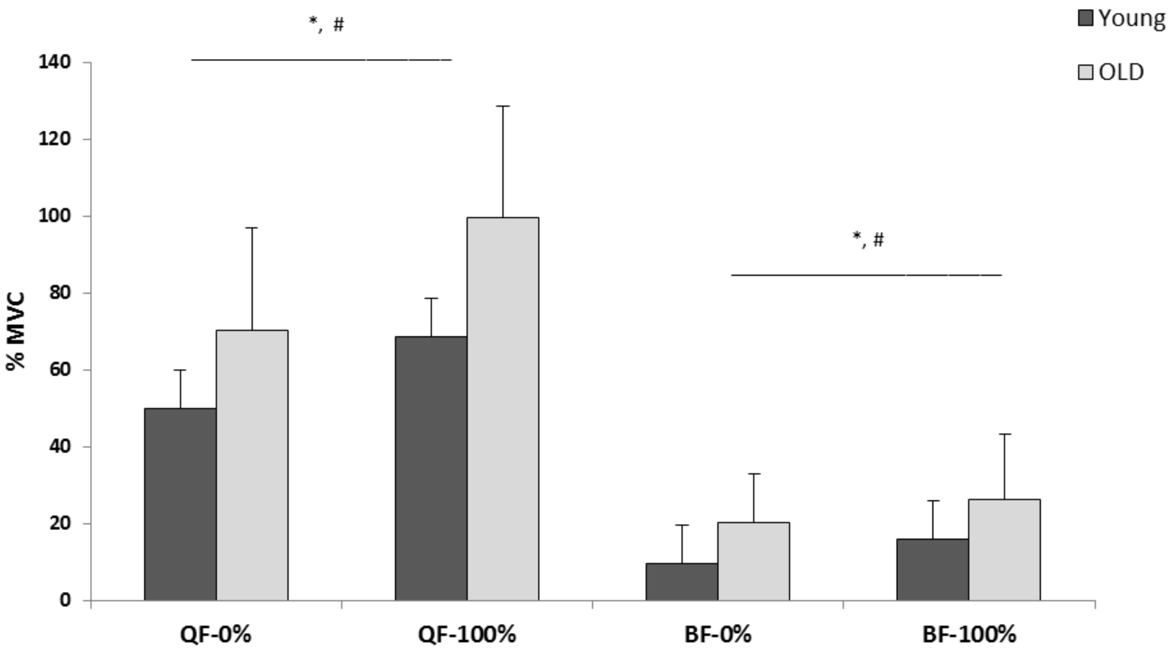


Figure 1. Quadriceps femoris (QF) and Biceps femoris (BF) EMG activation intensities (%MVIC) at the start (0%) and end (100%) of the repetitive sit-to-stand exercise protocol of young and older adult participants. Error bars denote standard deviations. * *denotes a significant age main effect. # indicates a significant time main effect*.

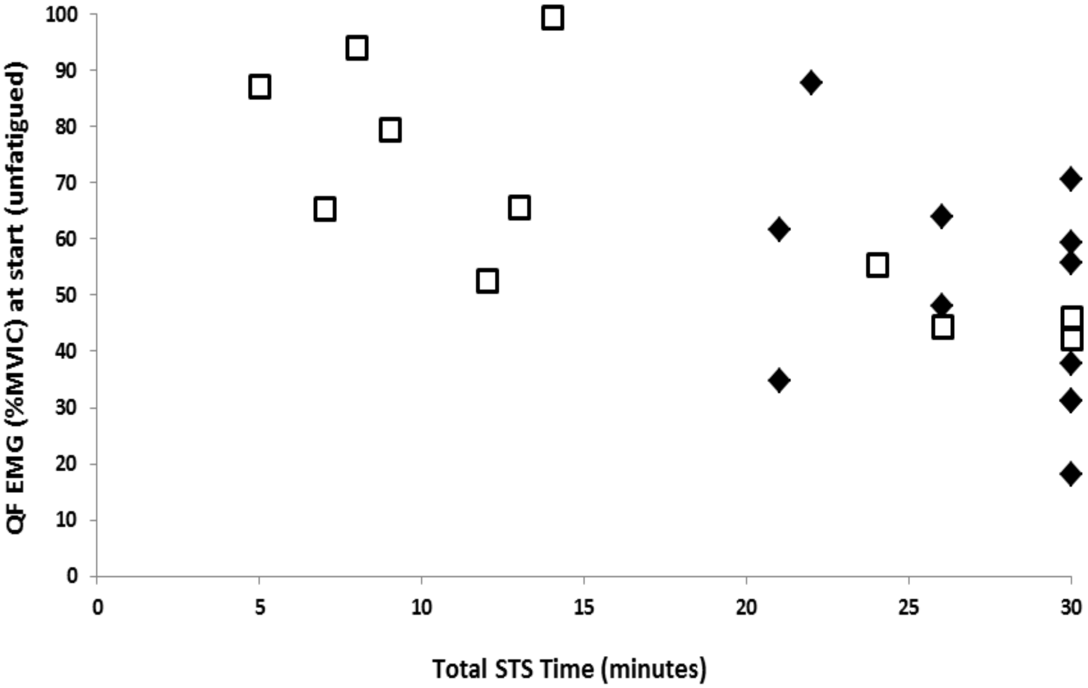


Figure 2. QF %MVIC at start vs. STS total task time in young (solid) and older (open) participants.

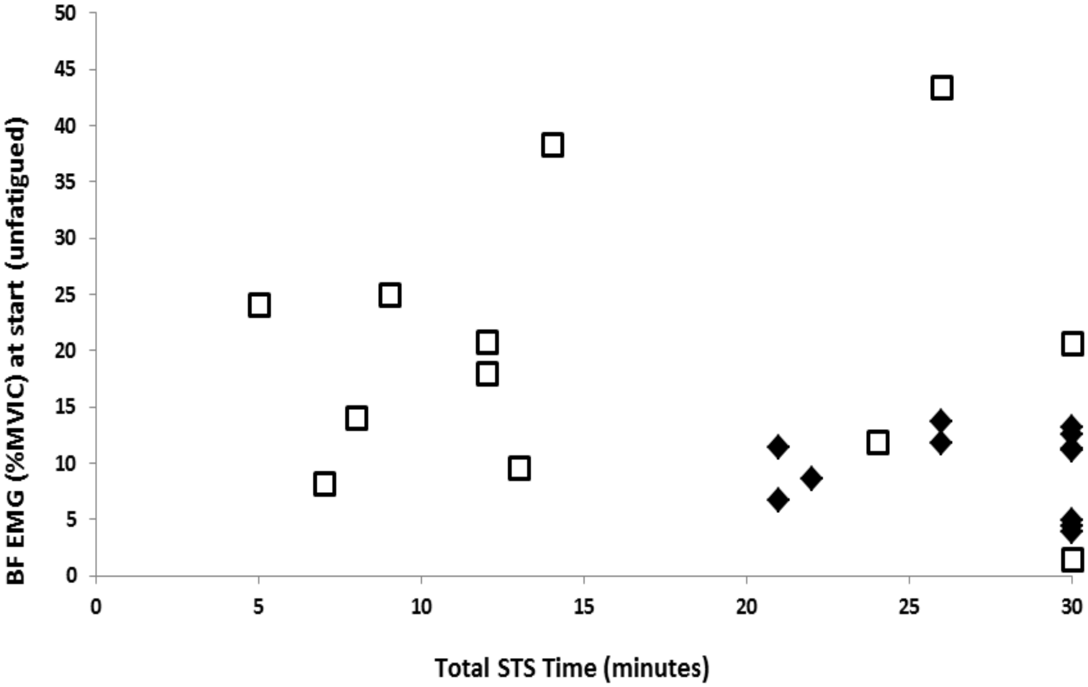


Figure 3. BF %MVIC at start vs. STS total task time in young (solid) and older (open) participants.

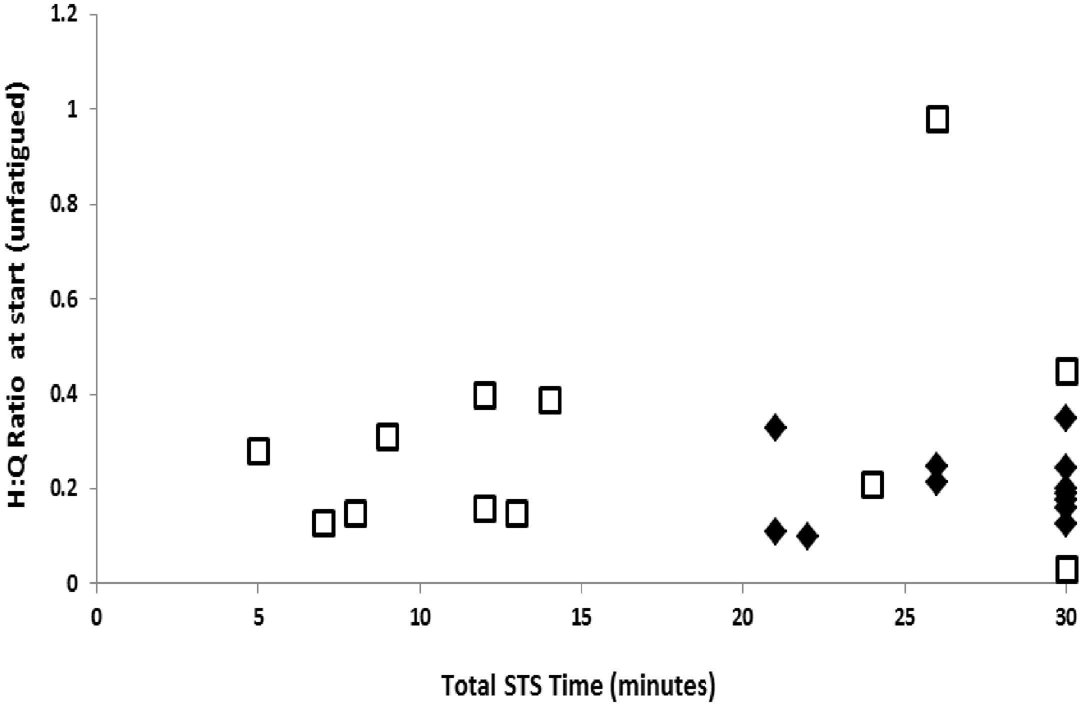


Figure 4. H:Q activation ratio at start vs. STS total task time in young (solid) and older (open) participants.

Discussion

The purpose of this investigation was to determine how muscular effort requirements of the thigh may limit the ability to perform a repetitive multi-joint fatigue task, the STS. As previous research has suggested that lower knee extensor strength reserves are predictive of STS performance with aging (Hughes et al., 1996; Ikeda et al., 2005; Petrella et al., 2005; Puniello et al., 2001; Scarborough, McGibbon & Krebs, 2007), we hypothesized that higher quadriceps effort required to stand up from a seated position, as well as the amount of antagonist co-activation levels at the knee by the hamstrings, would also result in shorter STS capacities and be a strong predictor of respective endurance times, particularly in older adult participants. The findings of our investigation partially confirmed this hypothesis as QF %MVIC was a strong predictor of prolonged STS exercise capacities. Moreover, those who required the highest quadriceps efforts had the shortest task times. This represented the older adult participants who had significantly higher starting QF intensities in comparison to the younger age group, and reached maximal efforts at the end of the multi-joint fatigue protocol. In contrast, H:Q ratios of hamstring activation relative to that of the QF was not a significant predictor of STS capacities, nor did it differ between age groups or with STS exercise in young and older adult participants.

The ability to perform activities of daily living has a significant impact on one’s quality of life, especially in regards to older persons with reduced mobility skills (Muhlberg & Sieber, 2004; Roos et al., 1997; van Roie et al., 2011). Particularly, muscle weakness of the knee extensors has an undeniable association with loss of functional independence as higher muscular efforts relative to maximal strength reserves are required for a given body weight bearing activity in comparison to younger counterparts (Hortobaygi et al., 2003; Hughes et al., 1996; Puniello et al., 2001). For example, during the STS, Hughes et al. (1996) observed that when ascending from a chair, older participants (78 ± 8.1 years) required knee extensor relative muscular efforts of approximately 80% of their strength reserves. In our current investigation, starting QF and BF %MVCs levels over the concentric phase were also significantly higher in older participants (70 (+/- 27) and 20 (+/- 13) %MVIC, respectively) in comparison to younger participants (50 (+/- 20) and 9 (+/- 4) %MVIC, respectively). Although higher starting co-activation ratios were also seen in older participants, they did not differ statistically (Table 2). Regardless, from this we can infer that older participants were required to perform the STS task at higher relative muscular efforts of the quadriceps in comparison to their younger participants. As a consequence, fatigue would develop more readily and limit an older person’s ability to perform daily repetitive actions that involve standing up from a seated position.

At the end of the multi-joint fatiguing task, QF levels reached 100 (+/- 29) %MVIC in the older age group, indicating that many of the participants were working at their maximal activation capabilities at the end of the STS exercise protocol. In contrast, QF levels of the younger participants finished at approximately 69 (+/- 21) %MVIC, which may be attributable to that not all of them reached full exhaustion; half of the young participants made it to the 30 minute exercise cut-off time, whereas only 2 of the 12 older adults were capable of this. Godin Leisure time questionnaire scores did not differ statistically between the two age groups; therefore lifestyle differences (sedentary versus physically active) may not be a factor responsible for differences in endurance times between young and older participants (D’Antona et al., 2007). This was also reflected in the regression analyses; when performed on young adult data only, no significant relationship was found between starting QF %MVIC and total STS task times. In contrast, when data from the younger and older participants that had task time less than 30 minutes were combined, a significant predicting relationship was observed. Regardless, the

Godin Leisure- time questionnaire is self reported data and caution should be raised when interpreted in this manner.

Clustering of younger participants at the 30 minute time point, as seen in Figure 2, show that starting QF %MVICs ranged from 20% MVIC to 70% MVIC. If our regression equations were used, an individual working at 70% MVIC would not be able to last for 30 minutes of exercise, which is apparent in the distribution of the older participants' data. It is possible that if the cut-off time was extended beyond 30 minutes in this investigation, the distribution of the younger participant data may have shown a similar linear trend with a shifting to the right due to relative muscular effort requirements being significantly lower in the young age group. Although this may be a limitation of this investigation, regardless, the predictive capabilities of QF effort requirements was still apparent in older adults for whom the findings of this investigation are most applicable. Therefore, we conclude that strength reserves of the knee extensors are still a predominant limiting factor in the ability to perform prolonged STS exercise, and that quadriceps effort requirements is the best indicator of one's STS capacity.

A muscle's endurance capabilities will be dependent on its inherent muscle characteristics and associated recruitment strategies employed by the central nervous system (Bilodeau et al., 2003; DeLuca et al., 1982; Enoka et al., 2011; Enoka & Stuart, 1992; Lieber, 2002). Increased type I fiber proportions and associated alterations in motor unit recruitment strategies have been previously thought to be responsible for documented greater fatigue resistance in older persons during prolonged, submaximal isometric activities (Bilodeau et al., 2001; Enoka et al., 2003; Hunter et al., 2005; Kent-Braum et al, 2002; Watanabe et al., 2011). However, these force levels may not be reflective of real-life situations in which older persons must work at a higher level of their strength reserves. Additionally, age differences in fatigue resistance have been suggested to be negligible during dynamic tasks, regardless of the intensity of the contraction subjected to (Avin & Law, 2011). Our findings corroborate this since, despite the potential that age-related differences in thigh muscle properties may have existed between our young and older participants, any age-related advantage to resist fatigue was negligible during STS exercise in older persons, as their knee extensors were required to work at higher relative effort intensities in comparison to their younger counterparts. In addition, when only the older participants were considered in regression analyses, a stronger predictive relationship was observed compared to those participants who had total task times of less than 30 minutes.

In our previous investigation (Bryanton & Bilodeau, *Chapter 5*), repetitive STS exercise resulted in a progressive decline in net joint moments produced and mechanical work performed by the knee extensors. In the current investigation, surface EMG of the associated musculature, the quadriceps, demonstrates that declines in KE kinetics would not be a result of reduced knee muscular efforts, but rather may have been due to fatigue-related impairments in force generation capabilities of the quadriceps. Quadriceps contribution to knee extension would also be underestimated if there was disproportionately increased flexor effort at the knee due to greater antagonist hamstring co-contraction, either as a strategy to increase joint rigidity, or a result of increased hamstring contribution to hip extension (Bryanton et al., 2015). As previously mentioned, although increases in BF %MVIC was seen with STS exercise in all participants, the H:Q ratio of BF activation relative to the QF did not change. Since the BF had substantially lower activation intensities at the start of the exercise regardless of age (≤ 20%MVIC), it is unlikely that a substantial amount of fatigue was accumulated, where this would be expected to have occurred in the QF. If so, elevated normalized signal amplitudes of the QF would be due to increased motor unit requirement and firing frequencies to sustain force output by the end of the protocol; whereas increases in the BF would more likely be associated with increased force output to assist in hip extension when ascending from the seat. Consequently, although no change in muscle EMG co-activation intensities were observed in this investigation, we cannot conclude that the actual amount of opposing flexor forces at the knee did not increase, and may be responsible for the progressive decline in the net knee extensors joint moments in Bryanton & Bilodeau, (*Chapter 5*) since force output levels cannot be directly inferred from EMG data when subjected to fatigue (Hug, 2011).

Alternately, elevated co-activity and rigidity about a joint has been shown to compensate for declines in somatosensation and force control steadiness (Nagai et al., 2013; Winter et al., 2001); however as previously mentioned, this would be a very inefficient control strategy with prolonged repetitive exercise, as it would necessitate an even greater agonist effort (Bryanton et al., 2015; Doorenbosche et al., 1994; Winter & Eng, 1995). This is reflected in the older adult group where both higher levels of QF and BF muscular activations were observed in comparison to younger participants. Since neither BF %MVIC or H:Q ratios showed a predictive or correlational relationship to STS total task times in either group, this suggests that if higher antagonistic activity of the hamstring does play a limiting role in STS capacity, it is less likely that a direct causal relationship exists. Regardless, it does however suggest that young and older adults had similar motor strategies when subjected to repetitive STS exercise as STS efforts increased. Hortobaygi et al. (2003) found that increased task effort when performing an activity of daily living was associated with higher hamstring activation in older persons, while Van Zandwijk et al. (2000) observed increased VL, RF, and BF recruitment between submaximal and maximal vertical jump efforts. Therefore, higher task efforts may necessitate greater hamstring antagonist activity, regardless of fatigue or age.

A limitation of EMG normalization techniques is that maximal isometric contractions are not always an indicator of full activation potential of a muscle during a dynamic task. For example, EMG amplitudes have been shown to exceed 100% MVIC during dynamic task (Hug, 2011). Gross et al. (1998) also found this to be true for quadriceps musculature during the sit-to-walk task, as VL and RF activation levels peaked at 1.280 (± 0.821) and 1.307 (± 0.705) relative to maximal standardized isometric contractions, respectively. Instead of peak activation intensity, which only provides an instantaneous quantification of muscle contribution, our current analyses measured average RMS amplitudes of the thigh over the entire concentric phase when repeatedly ascending from a seated position. We suspected that this would provide a more robust indication of effort muscle involvement requirements over time, and would explain why our values were significantly lower in comparison to Gross et al. (1998).

In conclusion, the results of this investigation implicate that age-related declines in KE strength increases the amount of quadriceps effort an older person must exert to perform a given task in comparison to their younger counterparts. In turn, higher intensities of efforts required to be performed in succession would lead to quicker fatigue onset. Together, knee extensor strength may play an important limiting role in STS capacity in older adults, which can be attributed to their significantly higher QF %MVIC required to successfully stand up from a seated position. Although greater hamstring co-activity at the knee may also contribute to further limiting STS performance, a significant relationship to total repetitive STS exercise times was not found. The results of this investigation have important applications to preventative and restorative rehabilitative measures for functional mobility and disability with aging. They suggest that strengthening of the quadriceps to elevate or maintain higher levels of strength reserve would lower the level of effort required to perform a given task. This would also improve the ability to perform multi-joint tasks that require large resistive torques about the knee, repetitively throughout the day without concern of fatigue and inherent risk of injury.

Acknowledgments: We would like to thank Dr. Heidi Sveistrup and the Motor Control Laboratory at the University of Ottawa for their assistance and provding the equipment for the data collection project.

References

Akima, H., Foley, J. M., Prior, B. M., Dudley, G. A., & Meyer, R. A. (2002). Vastus lateralis fatigue alters recruitment of musculus quadriceps femoris in humans. *Journal of Applied Physiology*, *92*(2), 679-684.

Akima, H., Takahashi, H., Kuno, S. Y., & Katsuta, S. (2004). Coactivation pattern in human quadriceps during isokinetic knee-extension by muscle functional MRI. *European Journal of Applied Physiology*, *91*(1), 7-14.

Avin, K. G., & Law, L. A. F. (2011). Age-related differences in muscle fatigue vary by contraction type: a meta-analysis. *Physical Therapy*, *91*(8), 1153-1165.

Bassey, E.J., Fiatrone, M.A., O'Neill, E.F., Kelly, M., Evans, W.J., & Lipsitz, L.A. (1992). Leg extensor power and functional performance in very old men and women. *Clinical Science, 82,* 321-327.

Bieryla, K. A., Anderson, D. E., & Madigan, M. L. (2009). Estimations of relative effort during sit-to-stand increase when accounting for variations in maximum voluntary torque with joint angle and angular velocity. *Journal of Electromyography and Kinesiology*, *19*(1), 139-144.

Bilodeau, M., Henderson, T.K., Nolta, B.E., Purslet, P.J, & Sandfort, G.L. (2001). Effect of aging on Fatigue characteristics of elbow flexor muscles during sustained submaximal contraction. *Journal of Applied Physiology, 91*(6), 2654-2665.

Bilodeau, M., Schindler-Ivens, S., Williams, D.M., Chandran, R., & Sharma, S.S. (2003). EMG frequency content changes with increasing force and during fatigue in the quadriceps femoris muscle of men and women. *Journal of Electromyography and Kinesiology*, *13*, 83-92.

Bohannon, R. W. (1995). Sit-to-stand test for measuring performance of lower extremity muscles. *Perceptual and Motor Skills*, *80*(1), 163-166.

Bohannon, R. W. (2009). Body weight-normalized knee extension strength explains sit-to-stand independence: a validation study. *The Journal of Strength & Conditioning Research*, *23*(1), 309-311.

Borg, G. A. V. (1982). Psychological bases of perceived exertion. *Medicine and Science in Sports and Exercise*, *14*(5), 377-381.

Boyas, S., & Guével, A. (2011). Influence of exercise intensity and joint angle on endurance time prediction of sustained submaximal isometric knee extensions. *European Journal of Applied Physiology*, *111*(6), 1187-1196.

Bryanton, M. A., Carey, J. P., Kennedy, M. D., & Chiu, L. Z. (2015). Quadriceps effort during squat exercise depends on hip extensor muscle strategy. *Sports Biomechanics*, *14*(1), 122-138.

Buatois, S., Miljkovic, D., Manckoundia, P., Gueguen, R., Miget, P., Vançon, G., ... & Benetos, A. (2008). Five times sit to stand test is a predictor of recurrent falls in healthy community-living subjects aged 65 and older. *Journal of the American Geriatrics Society*, *56*(8), 1575-1577.

Burnfield, J.M., Shu, Y., Buster, T.W., Taylor, A.P., McBride, M.M., & Krause, M.E. (2012).Kinematic and electromyographic analyses of normal and device-assisted sit-to-stand transfers. *Gait and Posture*, *36*(3), 516-522.

Corrigan, D., & Bohannon, R. W. (2001). Relationship between knee extension force and stand-up performance in community-dwelling elderly women. *Archives of Physical Medicine and Rehabilitation*, *82*(12), 1666-1672.

D'Antona, G., Pellegrino, M.A., Carlizzi, C.N., & Bottinelli, R. (2007). Deterioration of contractile properties of muscles fibers in elderly subjects is modulated by the level of physical activity. *European Journal of Applied Physiology*, *100*, 603-611.

DeLuca, C.J., LeForer, R.S., Mcute, M.P., & Xenakis, A.P. (1982). Behavior and human motor-units in different muscles during linearly varying contractions. *Journal of Physiology*, *392*, 113-128.

Deschenes, M. R., Roby, M. A., Eason, M. K., & Harris, M. B. (2010). Remodeling of the neuromuscular junction precedes sarcopenia related alterations in myofibers. *Experimental Gerontology*, *45*(5), 389-393.

DeVita, P., Helseth, J., & Hortobagyi, T. (2007). Muscles do more positive than negative work in human locomotion. *Journal of Experimental Biology*, *210*(19), 3361-3373.

Doherty, T. J. (2003). Invited review: aging and sarcopenia. *Journal of Applied Physiology*, *95*(4), 1717-1727.

Doherty, T.J., Vandervoort, A.A., Taylor, A.W., & Brown, W.F. (1993). Effects of motor unit losses on strength in older men and women. *Journal of Applied Physiology, 74*(2), 868-874.

Doorenbosch, C.A.M., Harlaar, J., Roenbroeck, M.E., & Lankhorst, G.J. (1994). Two strategies of transferring from sit-to-stand: The activation of monoarticular and biarticular muscles. *Journal of Biomechanics*, 27(11), 1299-1307.

Enoka, R. M., Baudry, S., Rudroff, T., Farina, D., Klass, M., & Duchateau, J. (2011). Unraveling the neurophysiology of muscle fatigue. *Journal of Electromyography and Kinesiology*, *21*(2), 208-219.

Enoka, R. M., Christou, E. A., Hunter, S. K., Kornatz, K. W., Semmler, J. G., Taylor, A. M., & Tracy, B. L. (2003). Mechanisms that contribute to differences in motor performance between young and old adults. *Journal of Electromyography and Kinesiology, 13*(1), 1-12.

Enoka, R.M, & Stuart, D.G. (1992). Neurobiology of muscle fatigue. *Journal of Applied Physiology*, *72*(*5*), 1631-1648.

Eriksrud, O., & Bohannon, R. W. (2003). Relationship of knee extension force to independence in sit-to-stand performance in patients receiving acute rehabilitation. *Physical Therapy, 83*(6), 544-551.

Fujita, E., Kanehisa, H., Yoshitake, Y. A. S. U. H. I. D. E., Fukunaga, T., & Nishizono, H. (2011). Association between knee extensor strength and EMG activities during squat movement. *Med Sci Sports Exerc*, *43*(12), 2328-2334.

Godin, G., & Shepard, R.J. (1997). Godin and Leisure-Time Exercise Questionnaire. *Medicine and Science in Sports and Exercise. 29 (June Supplements),* S36-S38.

Hakkinen, K., Kallinen, M., Izquierdo, M., Jokelainen, K., Lassila, H., Malikia, E., Kraemer, W.J., Newton, R.U., & Alen, M. (1998). Changes in agonist-antagonist EMG, muscle CSA, and force during strength training in middle-aged and older people. *Journal of Applied Physiology, 84*(4), 1341-1349.

Horak, F. B., Shupert, C. L., & Mirka, A. (1989). Components of postural dyscontrol in the elderly: a review. *Neurobiology of Aging*, *10*(6), 727-738.

Hortobágyi, T., Mizelle, C., Beam, S., & DeVita, P. (2003). Old adults perform activities of daily living near their maximal capabilities. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *58*(5), M453-M460.

Hug, F. (2011). Can muscle coordination be precisely studied by surface electromyography?. *Journal of Electromyography and Kinesiology*, *21*(1), 1-12.

Hunter, S.K., Critchlow, A., & Enoka, R.M. (2005) Muscle endurance is greater for old men compared with strength-matched young men. *Journal of Applied Physiology, 99*, 890-897.

Hurley, M.V., Rees, I., & Newham, D.J. (1998). Quadriceps function, proprioceptive acuity and functional performance in healthy young, middle aged and elderly subjects. *Age and Aging, 27*, 155-162.

Ikeda, S., Tsumura, H., & Torisu, T. (2005). Age-related quadriceps-dominant muscle atrophy and incident radiographic knee osteoarthritis. *Journal of Orthopaedic Science*, *10,* 121-126.

Ikezoe, T., Mori, N., Nakamura, M., & Ichihashi, N. (2011). Age-related muscle atrophy in the lower extremities and daily physical activity in elderly women. *Archives of Gerontology and Geriatrics*, *53*(2), e153-e157.

Jones, C. J., Rikli, R. E., & Beam, W. C. (1999). A 30-s chair-stand test as a measure of lower body strength in community-residing older adults. *Research Quarterly for Exercise and Sport*, *70*(2), 113-119.

Kallio, J., Sogaard, K., Avela, J., Komi, P., Selanne, H., & Linnamo, V. (2012). Age-related decreases in motor unit discharge rate and force control during isometric plantar flexion. *Journal of Electromyography and Kinesiology*, *22*(6), 983-989.

Kent-Braun, J.A., & Ng, A.V. (1999). Specific strength and voluntary muscle activation in young and elderly women and men. *Journal of Applied Physiology, 87*, 22-29.

Kent-Braun, J.A., Ng, A.V., Doyle, J.W., & Towse, T. (2002). Human skeletal muscle responses vary with age and gender during fatigue due to incremental isometric exercise. *Journal of Applied Physiology, 93*, 1813-1823.

Laidlaw, D. H., Bilodeau, M., & Enoka, R. M. (2000). Steadiness is reduced and motor unit discharge is more variable in old adults. *Muscle & Nerve*, *23*(4), 600-612.

Lieber, R. L. (2002). *Skeletal muscle structure, function, and plasticity*. Lippincott Williams & Wilkins.

Lynch, N.A., Metler, E.J., & Lindle, R.S. (1999). Muscle quality. I. Age-associated differences between arm and leg muscle group. *Journal of Applied Physiology, 86(*1), 188-194.

Manini, T., Visser, M., Won-Park, S., Patel, K.V., Stratmeyer, E.S., Chen, H., Goodpaster, B., DeRekeneire, N., Newman, A.B., Simonsick, E.M., Kritchevsky, S.B., Ryder, K., Schwarts, A.V., & Harris, T.B. (2007). Knee extension strength cutpoints for maintaining mobility. *JAGS, 55*, 451-457.

Muhlberg, W., & Sieber, C. (2004). Sarcopenia and frailty in geriatric patients: Implications or training and prevention. *Z Gerontol Geriat*, 37, 2-8.

Nagai, K., Yamada, M., Mori, S., Tanaka, B., Yemura, K., Aoyama, T., Ichihashi, N., & Tsuboyama, T. (2013). Effect of the muscle coactivation during quiet standing on dynamic postural control in older adults. *Arch Gerontol Geriatr, 56*(1), 129-133.

Patsika, G., Kellis, E., & Amiridis, I. G. (2011). Neuromuscular efficiency during sit to stand movement in women with knee osteoarthritis. *Journal of Electromyography and Kinesiology*, *21*(5), 689-694.

Petrella, J. K., Kim, J. S., Tuggle, S. C., Hall, S. R., & Bamman, M. M. (2005). Age differences in knee extension power, contractile velocity, and fatigability. *Journal of Applied Physiology*, *98*(1), 211-220.

Puniello, M. S., McGibbon, C. A., & Krebs, D. E. (2001). Lifting strategy and stability in strength-impaired elders. *Spine*, *26*(7), 731-737.

Renshaw, D., Bice, M. R., Cassidy, C., & Eldridge, J. A. (2010). A Comparison of Three Computer-based Methods Used to Determine EMG Signal Amplitude. *International Journal of Exercise Science, 3*(1).

Roos, M.R., Rice, C.L., & Vandervoort, A.A. (1997). Age-related changes in motor unit function. M*uscle and Nerve, 20*, 679-690.

Savelberg, H. H. C. M., Fastenau, A., Willems, P. J. B., & Meijer, K. (2007). The load/capacity ratio affects the sit-to-stand movement strategy. *Clinical Biomechanics, 22*(7), 805-812.

Scarborough, D. M., McGibbon, C. A., & Krebs, D. E. (2007). Chair rise strategies in older adults with functional limitations. *Journal of Rehabilitation Research and Development*, *44*(1), 33.

Schultz, A.B., Alexander, N.B., & Ashton-Miller, J.A. (1992). Biomechanical analysis of rising from a chair. *Journal of Biomechanics, 25*(12), 1383-1391.

Shaffer, S. W., & Harrison, A. L. (2007). Aging of the somatosensory system: a translational perspective. *Physical therapy, 87*(2), 193-207.

Van der Heijden, M. M., Meijer, K., Willems, P. J., & Savelberg, H. H. (2009). Muscles limiting the sit-to-stand movement: an experimental simulation of muscle weakness. *Gait & Posture, 30*(1), 110-114.

Van Roie, E., Verschueren, S. M., Boonen, S., Bogaerts, A., Kennis, E., Coudyzer, W., & Delecluse, C. (2011). Force-velocity characteristics of the knee extensors: an indication of the risk for physical frailty in elderly women. *Archives of Physical Medicine and Rehabilitation, 92*(11), 1827-1832.

Van Zandwijk, J. P., Bobbert, M. F., Munneke, M. A. R. T. E. N., & Pas, P. I. E. T. E. R. (2000). Control of maximal and submaximal vertical jumps. *Medicine and Science in Sports and Exercise*, *32*(2), 477-485.

Vigotsky, A. D., Harper, E. N., Ryan, D. R., & Contreras, B. (2015). Effects of load on good morning kinematics and EMG activity. *PeerJ, 3*, e708.

Watanabe, K., Kouzaki, M., Merletti, R., Fujibayashi, M., & Maritan, T. (2011). Spatial EMG potential distribution pattern of vastus lateralis muscle during isometric knee extension in young and elderly men. *Journal of Electromyography and Kinesiology*.

Winter, D. A., & Eng, P. (1995). Kinetics: our window into the goals and strategies of the central nervous system. *Behavioural brain research*, *67*(2), 111-120.

Winter, D. A., Patla, A. E., Rietdyk, S., & Ishac, M. G. (2001). Ankle muscle stiffness in the control of balance during quiet standing. *Journal of Neurophysiology*, *85*(6), 2630-2633.

Wretenberg, P., & Arborelius, U. P. (1994). Power and work produced in different leg muscle groups when rising from a chair. *European Journal of Applied Physiology and Occupational physiology*, *68*(5), 413-417.

CHAPTER 7

MANUSCRIPT 4:

Age- and Intensity-dependent Alterations in Muscular Control of Chair Rise Strategies with Dynamic Knee Extensor Fatiguing Exercise

Megan Bryanton, Martin Bilodeau

Age- and Intensity-dependent Alterations in Muscular Control of Chair Rise Strategies with Dynamic Knee Extensor Fatiguing Exercise

[1,3] Megan Bryanton, [2,3] Martin Bilodeau

[1]School of Human Kinetics, University of Ottawa, ON, CA
[2]School of Rehabilitation Sciences, University of Ottawa, ON, CA
[3]Aging and Movement Laboratory, Bruyère Research Institute, ON, CA

Submission Type: Original Article 13

Disclosure of Funding: This research was partially funded by the Canada Foundation for Innovation (M. Bilodeau) and a Faculty of Health Sciences Admission’s scholarship to M. Bryanton

Abstract

Reduced knee extensor (KE) performance with aging has been shown to be a predictor of sit-to-stand (STS) capabilities with aging as near maximal efforts have been shown in older populations. In addition, strength limitations due to declining muscle reserves with aging have the potential to impact the muscle control strategies utilized when rising from a seated position. The purpose of this investigation was to evaluate the effects of reduced KE force output due to isolated fatiguing exercise, on STS muscular compensatory strategies in young and older adult participants. Twenty-two young and older adults were asked to perform STS repetitions before and after dynamic KE fatiguing contractions (60 °/sec) at two intensities (80% and 50% MVC) until they could no longer maintain the desired force output. Surface electromyography was used to measure muscular efforts (%MVIC) and temporal characteristics (time of onset and peak activity relative to seat-off) of the Tibialis anterior (TA), Soleus (SOL), medial gastrocnemius (GAS), Vastus lateralis (VL), Rectus femoris (RF), Bicep femoris long head (BF) and Gluteus maximus (GMax) muscles. Results showed increased SOL, GAS, RF and GMax efforts after KE fatigue during STS ascent in both age groups, however RF increased to a greater extent in older adults with lower KE strengths. Older participants also had higher TA, VL, RF and BF %MVIC regardless of STS condition. These results indicate that isolated KE fatiguing exercise caused compensatory muscle strategies when ascending from a chair via increased reliance of unfatigued muscles at the ankle and hip as well as increased activity of synergist muscles. Older adults may therefore benefit from strength training of KE musculature to prevent further loss of muscle reserves in order to prolong functional independence.

Keywords: Knee extensors, Aging, Sit-to-stand, Electromyography, Muscular effort, MVC

Introduction

Aging is associated with an unavoidable decline in muscle mass and strength, known as sarcopenia, which been shown to be a predictor of disability and loss of functional autonomy in older persons (Ikezoe et al., 2011; Muhlberg & Sieber, 2004; Petrella et al., 2005). Although the etiology of sarcopenia still remains unclear, loss of muscle mass, selective loss of high threshold motor unit populations, and subsequent increased innervation ratios may be responsible for impaired strength and control force output experienced with aging (Bazzucchi et al., 2004; Carville et al., 2007; Doherty et al., 2003; Laidlaw et al., 2000; Petrella et al., 2005). It is therefore understandable why mixed muscle groups containing larger proportions of type II muscle fibers, such as the knee extensor (KE) musculature, have been found to be impacted by sarcopenia to a greater extent in comparison to other lower extremity musculature, with slower fiber type profiles, or in the upper extremities (Bazzucchi et al., 2004; Enoka et al., 2003; Ikeda et al., 2005; Lynch et al., 1999).

Reduced maximal strength and motor performance of the knee extensors has deleterious effects on mobility for numerous transfer tasks of daily living that involve large muscular demands, particularly when standing up from a seated position (Bohannon, 2009; Brech et al., 2013; Carville et al., 2007; Corrigan & Bohannon, 2001; Eriksrud & Bohannon, 2003; Hortobagyi et al., 2003; Hughes et al., 1996; Kallio et al., 2012; Muhlberg & Sieber, 2004; Roos et al., 1997; van Roie et al., 2011). The sit-to-stand (STS) is a multi-articular movement and a basic skill required for independent living, that involves an uneven distribution of muscular efforts across the lower extremity (Bieryla et al., 2007; Burnfield et al., 2012). For example, Burnfield et al. (2012) noted that during the ascending phase of the STS, Vastus lateralis EMG values peaked at 63% of their MVC in healthy adults; whereas hamstring and gluteus maximus peaked at 14% and 21%, respectively. Moreover, biomechanical investigations have indicated KE strength as a primary limiting factor of STS performance in elderly populations, as near maximal efforts (80-100%MVC) have been observed in older adults (Hortobaygi et al., 2003; Hughes et al., 1996; Savelberg et al., 2007); however contributions of other lower extremity muscle groups were not evaluated. Regardless, considering disproportionately greater declines in KE strength compared to other lower extremity musculature experienced with aging, fatigue may develop more readily in older persons compared with younger individuals during repetitive actions if a primary agonist is working at an intensity of 80% MVC or greater. Additionally, a lesser extent of force declines would be sufficient to impair STS performance if KE efforts are already near maximal due to reduced muscle reserved in older adults.

Strength limitations and reduced force generating capabilities have been suggested to result in compensatory strategies through shifting of muscular demands to more evenly distribute efforts to sustain STS movement performance (Hortobagyi et al., 2003; Puniello et al., 2001; Savelberg et al., 2007; van der Heijden et al., 2009; Yoshioka et al., 2007). This may occur within a muscle group synergy such as through earlier pre-activation and increased co-activation of specific muscle pairs, as well as across joints (Akima et al., 2002; Akima et al., 2004; Bonnard et al., 1994). For example, Akima et al. (2002) found that high intensity fatigue of the KE musculature (≥70% MVC) caused a reduction in vastus lateralis contributions and increased use of the other quadriceps muscles to sustain force output during repetitive KE contractions. In turn, Bonnard et al. (1994) found that with repetitive hopping, fatigue accumulated in the ankle plantar flexor musculature resulted in increased activity of the Rectus femoris, as well as earlier pre-activation of the Gastrocnemius. Lastly, temporal shifting in muscular contributions to the activity may also occur to improve movement efficiency by limiting simultaneous peak activities of agonist- antagonist muscle pairs (Chiu, Bryanton, & Moolyk, 2012; Gregoire et al., 1984). Considering all this, there may be several degrees of freedom that one may take advantage of in the face of reduced KE performance; however age-dependent compensatory actions due to fatigue have not been thoroughly investigated for a demanding multi-joint task such as the STS.

In summary, previous research has generally provided correlational evidence of the role of impaired force generating capabilities of a primary agonist muscle on the performance of ADL such as the STS task. In turn, it is unclear whether characteristics of muscle compensatory strategies during a multi-joint task that requires considerable strength reserves such as the STS, may change with aging. Alterations in muscular coordination responsible for successful execution of the STS task can be determined by evaluating the distribution of activation intensities and temporal patterns with or between muscle synergies (Hug, 2011). Surface electromyography (EMG) may therefore provide valuable information regarding age-dependent muscular control strategies when performing the STS through indication of their activation intensities and temporal characteristics in order to compensate for reduced KE performance. The purpose of this investigation was to evaluate the age-related effects of reduced force output and fatigue of the KE on muscular compensatory strategies when rising from a chair in young and older adult participants. It was expected that the extent of force declines would determine the extent of the compensatory action; if compensatory strategies are due to lack of strength reserves of the KE, they would be more apparent in older adults in comparison to their younger counterparts.

Methods

Participants

Twenty two healthy adult men and women between the ages of 18-35 years (i.e., young adult, n=11; 5 females) and 60-85 years (i.e., older adult, n=11; 5 females) recruited from the community as a convenience sample participated in this investigation. Exclusion criteria for participants included having previous lower extremity or lower back orthopedic and musculoskeletal injuries that prevented the exercise from being performed safely, as well as taking any medications that may have affected balance. This sample size allows detection of within and between subject effect size differences of 0.2 standard deviations (small difference) while minimizing type I error to 5% and type II error to 17% (Power= 83%). Participants were instructed to refrain from any strenuous lower extremity activities prior to visiting the laboratory. Ethics approval was obtained from the University of Ottawa and Bruyere Research Institute research ethics board, and informed consent was obtained prior to testing. In addition to individual anthropometrics of height and body weight, the Godin-Leisure time questionnaire (Godin & Sheppard, 1997) was asked to be filled out by participants and scores were calculated as an indication of the type and frequency of physical activity levels in young and older participants.

Procedures

EMG Recordings: Electromyographic (EMG) signals of the lower extremity musculature were collected on the dominant limb, which was deemed as the leg that the participants would kick a soccer ball with. EMG signals from the Rectus femoris (RF), Vastus lateralis (VL), Biceps femoris long head (BF), Soleus (SOL), medial head of the Gastrocnemius (GAS), Tibialis anterior (TA), and the Gluteus maximus (GMax) were recorded during STS and fatigue testing procedures with bipolar surface electrodes of 1 mm in width, 10 mm in length, with a 10mm center-to-center interelectrode distance (DE-2.1, Delsys Inc., Boston, USA). All electrodes were placed in a direction parallel to the general direction of muscle fibers for a given muscle in accordance to SENIAM recommendations. A reference electrode was positioned approximately 6 cm distal to the inferior pole of the patella, over the bony surface of the tibia. EMG signals were recorded using the Bagnoli 16 EMG system (Delsys Inc., Boston, USA) at a sampling rate of 2,000 Hz and amplification between 100X and 10000X, and bandpass between 20-450 Hz using Spike2 software (Cambridge Electronic Design Limited, Cambridge, ENG). EMG signals were then rectified and smoothed using root mean square (RMS) with a 50 ms window. All RMS signal amplitudes were then normalized to peak mean values of a 50 ms window from a maximal voluntary isometric contraction (%MVIC) obtained prior to the STS testing for each respective muscle group using SENIAM recommendations. Post-fatigue normalization of the quadriceps was also conducted by having the participants perform a single MVIC once volitional exhaustion occurred after each fatigue protocol. This was performed in order to determine activation intensities of the investigated muscles in both un-fatigued and fatigued states as absolute amplitude of the surface EMG signal provides a poor index of neural drive to the muscle and is also not appropriate for comparisons between conditions and persons (Dimitrova & Dimitroc, 2003; Farina et al., 2010; Keenan et al., 2005; Yang & Winter, 1984).

Isokinetic Dynamometry and Fatigue Protocol: Previous investigations reported intensities of 80% MVC of KE relative muscular effort in healthy older adults during STS in an unfatigued state and intensities of approximately 40-60% MVCs in younger adults (Bieryla et al., 2009; Burnfeild et al., 2012; Hortobagyi et al., 2003; Hughes et al., 1996). Therefore, both young and older adults were asked to perform repetitive bi-lateral dynamic knee extension contractions on an isokinetic dynamometer (Biodex System 3 ProH, Biodex Medical Systems, Shirley, USA) at both 80% and 50% of their predetermined KE MVC peak torque output that was collected prior to the fatiguing contractions, at 60 degrees per second (º/s) (i.e., approximate time it takes to perform a STS repetition) for a 90 to 0 degrees ROM at the knee. Before maximal KE strength attempts, participants performed a dynamic warm up which consisted of three sets of isokinetic leg extensions with approximately 60 seconds rest in between: set 1) 10 repetitions at 180 º/s at an estimated perceived effort of 25% MVC, set 2) 6 repetitions at 120 º/s at an estimated perceived effort of 50% MVC, and lastly, set 3) 3 repetitions at 90 º/s at an estimated perceived effort of 75% MVC. Participants were then allowed to familiarize themselves with the KE strength testing speed of 60º/s. After a brief rest period, participants were asked to perform a minimum of three maximal KE, with 60 seconds rest between attempts. If the participant's values continued to increase by the third set, a fourth attempt was performed. From this the participant's highest attempt was used for setting 80% and 50% MVC threshold for the fatigue protocol.

For the isolated fatigue of the KE, consecutive repetitions were performed at the desired intensity (80% or 50% MVC) until the participant was no longer able to achieve the desired force output, of which visual feedback of this level was provided on a computer monitor in front of them during the fatigue tasks. The end of the fatigue set was determined by the researcher when the participant was no longer able to achieve the desired force output intensity for 3 consecutive KE repetitions. Immediately after, a maximal isometric knee extension attempt of 3 seconds was performed for EMG re-normalization following fatigue. This was then followed immediately by STS measures. Two rounds of fatigue were performed at each intensity and later averaged in order to increase validity of measurements: starting at the highest 80% intensity, followed by 50% intensity fatigue protocols (For example: 1) 80%, 2) 80%, 3) 50%, 4) 50%) as the aim was to reduce force generating capabilities by first 20% MVC and then 50% MVC, and that this number of fatigue protocols in one setting would effect each set incrementally. Finally, strong verbal encouragements were provided to ensure maximal efforts.

STS Protocol: Participants were instructed to sit on an armless and backless bench with a force plate fixed on top (Bertec Corporation, Columbus, OH) in a comfortable erect posture with arms folded across their chest in order to deter the use of arm movement. Initial foot placement was marked on the force platform to prevent shifting of feet during the course of the fatigue protocol. Seat height was adjusted to 80% of the participant's lower limb length. For each STS repetition, participants were instructed to stand up from the chair to a fully extended erect posture at a self-selected, comfortable speed. Participants were signaled by the researcher when to stand and sit in order to ensure that a brief pause was performed at both start and ending positions before moving onto the subsequent repetition. Reaction forces provided by the seat force platform were synched with EMG acquisitions into Spike2 at a sampling frequency of 100 Hz, which provided an indication of the commencement of forward body movement when initiating the STS, as well as the instant that contact with the buttocks was lost with the seat. Participants were also instructed to relax their muscles once returning to the seated position before the next repetition was initiated. STS testing was performed prior to and after dynamic fatiguing of the knee extensors. Three sets of three STS repetitions were performed during the unfatigued conditions with 1- minute rest intervals between sets, and one set of three repetitions was performed after each fatigue protocol, for a total of two sets after fatiguing intensity of 80% KE MVC and two sets after 50% KE MVC fatigue intensity.

Data Analysis

The primary analyses compared changes in mean EMG muscle activation intensities (% MVIC) during the preparatory (initiation of forward body displacement until loss of contact with the buttocks) and ascending (from seat-off until full upright posture achieved). Previous investigations have utilized peak values during STS trials, and mean activity values were calculated instead, as this would allow for a more robust analyses to movement artifact and time, and a more comprehensive picture of muscle contributions over an entire movement phase (Renshaw et al., 2010; Vigotsky et al., 2015). Secondly, instances of muscle onset and peak activity timings relative to seat-off were also calculated using Spike as indicated by 5 standard deviations above resting signal, and compared between younger and older adults to indicate any alterations in muscle strategies due to isolated fatigue of the KE musculature that may not be apparent through %MVIC analyses.

For each fatigue condition, values were averaged between sets for each participant. With this, a mixed-model ANOVA with one between- subjects (age: Young vs. Older Adults) and one repeated- measure (fatigue intensity; Pre vs. Post-80% vs. Post 50%) was used for significance testing for each muscle intensity (%MVIC), onset time, and time of peak activity. Where appropriate, Tukey HSD was used for post-hoc comparisons. Independent T-test were performed to compare dynamic KE strengths as well as Godin physical activity scores between younger and older adults. The alpha level was set a priori at $\alpha=0.05$. Lastly, Cohen's effect sizes were calculated to determine magnitudes of differences.

Results

Statistical analysis revealed a significant group difference in KE dynamic maximal strengths; older participants had lower max KE torque values compared to young adults, when body weight was accounted for (t (20): 3.70, $p>0.001$) (Table 1). There were no significant group differences for Godin-Leisure time scores (t (20): 0.343, $p=0.185$); both young and older groups were matched for physical activity level (Table 1).

Mauchly's tests of sphericity were found to be significant during the preparatory phase for the RF, BF, GAS and TA, and during the ascending phase for the VL, SOL, and GAS, and GMax ($p<0.05$), and Greenhouse-Geisser corrections were subsequently used. For the preparatory phase of the STS, significant fatigue main effects were observed for %MVICs of the TA ($p=0.012$, $d=0.557$), RF ($p=0.002$, $d=0.689$), BF ($p=0.012$, $d=0.565$) and the GMax ($p=0.011$, $d=0.505$), but not for the SOL ($p=0.495$, $d=0.197$), GAS ($p=0.973$,$d=0.000$) and, or VL ($p=0.170$, $d=0.305$). In turn, significant age main effects were observed for the TA ($p=0.015$, $d=0.596$), RF ($p<0.001$, $d=1.158$), VL ($p<0.001$, $d=1.357$); older adults had higher %MVIC in comparison to younger adults, but this was not found for the SOL ($p=0.729$, $d=0.078$), GAS ($p=0.324$, $d=0.227$), BF ($p=0.094$, $d=0.393$), or GMax ($p=0.512$, $d=0.150$). Lastly, a significant fatigue × age interactions was found for the RF only ($p=0.040$, $d=0.445$), and a trend towards significance for the BF ($p=0.058$, $d=0.427$). For the ankle musculature, KE fatigue of 50% MVC caused a reduction in TA activity but 80%MVC did not (PRE vs POST-50; $p=0.009$, PRE vs. POST-80; $p=0.424$, POST-80 vs. POST-50; $p=0.000$) in both young and older adults, while SOL and GAS %MVIC were unaffected during the preparatory phase for both fatigue conditions (Figure 1). For the KE musculature, although neither fatigue intensity caused a significant change in VL activity, RF activity increased in both groups from PRE values to POST-80 ($p<0.001$). Result also demonstrated that RF %MVIC in older adults increased to a greater extent in comparison to younger particiapnts, as RF activity further increased between POST-80 and POST-50 in older adults only (Figure 2). Lastly, in both age groups, BF activity significantly increased in both groups from PRE to POST-80 and -50 only ($p=0.013$ and $p=0.045$, respectively), but there was a decrease from POST-80 to POST-50 ($p=0.030$), while the

GMax only increased from PRE to POST-80 (p=0.003) but not for the POST-50 measures (PRE vs POST-50; p=0.206, POST-80 vs. POST-50 p=0.070).

For the ascending phase of the STS, significant fatigue main effects were found for the SOL (p=0.003, d=0.699), GAS (p=0.001, d=0.718), RF (p<0.000, d=0.990), and GMax (p<0.001, d=1.12), but not for the TA (p=0.160, d=0.309), VL (p=0.184, d=0.305), or BF (p=0.582,d=0.167). Significant age main effects were then found for the TA (p=0.027, d=0.534), VL (p<0.001, d=1.597), RF (p<0.001, d=1.569), and BF (p=0.002, d=0.775) (SOL; p=0.729, d=0.078, GAS; p=0.207, d=0.291, GMax; p=0.101, d=0.385); again older adults had higher %MVICs compared to young adults, with a fatigue × age interaction again only for the RF (p<0.001, d=0.694), and a trend for the SOL (p=0.053, d=0.445). For the ankle musculature, post hoc analyses showed that SOL and GAS has higher POST-80 (p=0.003 and p=0.002) and POST-50 activities (p=0.005 and p=0.002) compared to PRE but there was no subsequent increase between POST-80 and -50 (p=0.992 and p=0.255 after seat-off. For KE musculature, similar to the preparatory phase, neither fatigue intensity caused a significant change in VL activity, and RF activity increased in both groups from PRE values to POST-80 (p=0.000), and increased to a greater extent in older adults as only increased activity from POST-80 and POST-50 was seen in this group (Figure 2). Lastly BF did not change in either group during the ascending phase; however GMax intensity significantly increased in both groups to the same extent from PRE to POST-80 (p=0.000) but did not increase further beyond this for the POST-50 measures (PRE vs POST-50; p=0.00, POST-80 vs. POST-50 p=0.073).

Statistical analyses for temporal measures of muscle activity showed significance for Mauchly’s test of Sphericity for the onsets of the VL, and peak timings of the BF, and Greenhouse-Geisser corrections were used. Fatigue main effects for onset times of the TA only (p=0.009, d=0.514) which became delayed with KE fatigue, and a trend for the RF was noted (p=0.068, d=0.380) (SOL; p=0.298, d=0.250, GAS; p=0.324, d=0.241, VL; p=0.488, d=0.179, BF; p=0.266, d=0.261, GMax; p=0.239, d=0.272). A significant fatigue × age interactions for the SOL (p=0.008, d=0.520), GAS (p=0.006, d=0.537) and GMax (p=0.036, d=0.425), with no age main effects was also found, only a trend towards significance for the TA (p=0.060, d=0.446) and RF (p=0.086, d=0.403) (SOL; p=0.486, d=0.160, GAS; p=0.533, d=0.143, VL; p=0.187, d=0.304, BF; p=0.528, d=0.143, GMax; p=0.313, d=0.232). KE fatigue caused earlier SOL and GAS activity onsets in older adults only (Figure 4), while earlier GMax onset was only observed in young adults for POST-50 (Figure 5). No significant fatigue main effects were found for relative peak timings (TA; p=0.443, d=0.204, SOL; p=0.510, d=0.185, GAS; p=0.806, d=0.105, VL; p=0.150, d=0.314, RF; p=0.232, d=0.274, BF; p=0.681, d=0.123, GMax; p=0.411, d=0.215), however age main effects were found for the RF (p=0.026, d=0.536), SOL (p=0.010, d=0.636) and GAS (p=0.031, d=0.519) (TA; p=0.422, d=0.182, VL; p=0.592, d=0.123, BF; p=0.730, d=0.078, GMax; p=0.872, d=0.032), with no interactions (p>0.10 for all) (Table 2). RF peak activity occured earlier closer to seat-off in older adults compared to the younger age group, while peak SOL and GAS activity occurred later at the end of the STS ascending phase in older adults (Table 2).

Table 1. Subject Characteristics (± *SDs*)

Group	Age (yrs)	Body mass (kg)	Height (cm)	GLTQ	KE MVC (60°/s) (Nm/kg)
Young (n= 11; 5 females)	27.4 (*4.5*)	74.4 (*16.7*)	168.6 (*10.8*)	39.2 (*12.5*)	**4.4 (*0.7*)**
Old (n=11; 5 females)	68.4 (*4.1*)	70.7 (*15.1*)	172.0 (11.0)	54.0 (*34.1*)	**3.1 (*0.8*)***

** denotes significant age group difference from young*

Table 2. Group Mean (± *SDs*) Peak Muscle Activity Timing Relative to Seat-off (seconds) in Young (Y) and Older (O) Adults.

Muscle	PRE		POST-80%		POST-50%	
	Y	**O**	**Y**	**O**	**Y**	**O**
TA	0.06 *(0.05)*	0.03 *(0.10)*	0.06 *(0.05)*	0.02 *(0.13)*	0.07 *(0.05)*	0.04 *(0.14)*
SOL	0.24 *(0.23)*	0.47 *(0.18)**	0.29 *(0.20)*	0.49 *(0.14)* *****	0.26 *(0.25)*	0.44 *(0.14)******
GAS	0.25 *(0.22)*	0.51 *(0.30)**	0.32 *(0.23)*	0.48 *(0.23)* *****	0.25 *(0.22)*	0.49 *(0.27) **
VL	0.08 *(0.04)*	0.11 *(0.19)*	0.06 *(0.04)*	0.08 *(0.17)*	0.05 *(0.03)*	0.06 *(0.08)*
RF	0.07 *(0.05)*	0.02 *(0.04)**	0.08 *(0.06)*	0.03 *(0.06)* *****	0.09 *(0.05)*	0.04 *(0.08) **
BF	0.23 *(0.11)*	0.32 *(0.24)*	0.31 *(0.23)*	0.30 *(0.25)*	0.28 *(0.20)*	0.29 *(0.27)*
GMax	0.30 *(0.22)*	0.33 *(0.14)*	0.33 *(0.23)*	0.28 *(0.12)*	0.35 *(0.23)*	0.34 *(0.25)*

** denotes significant age group difference from young*

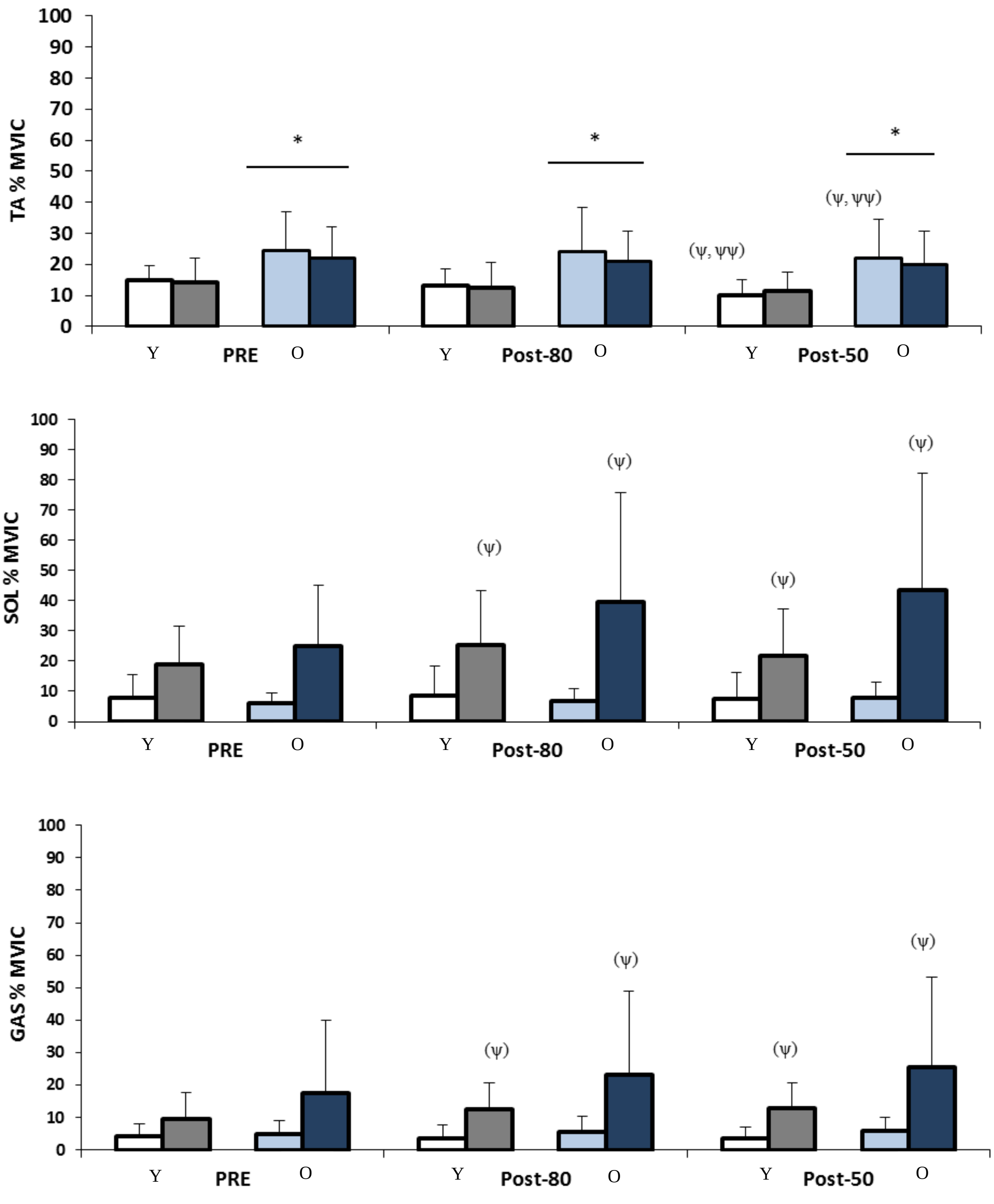


Figure 1. Tibialis anterior (TA), Soleus (SOL) and medial gastrocnemius (GAS) %MVIC average activity with respect to preparatory (light) and ascending (dark) phases of the STS in young (Y; greyscale) and older (O; blue) adults. Error bars denote SDs. ψ denotes a significant difference from PRE, ψψ denotes a significant difference from previous condition. * denotes significant difference from young adults.

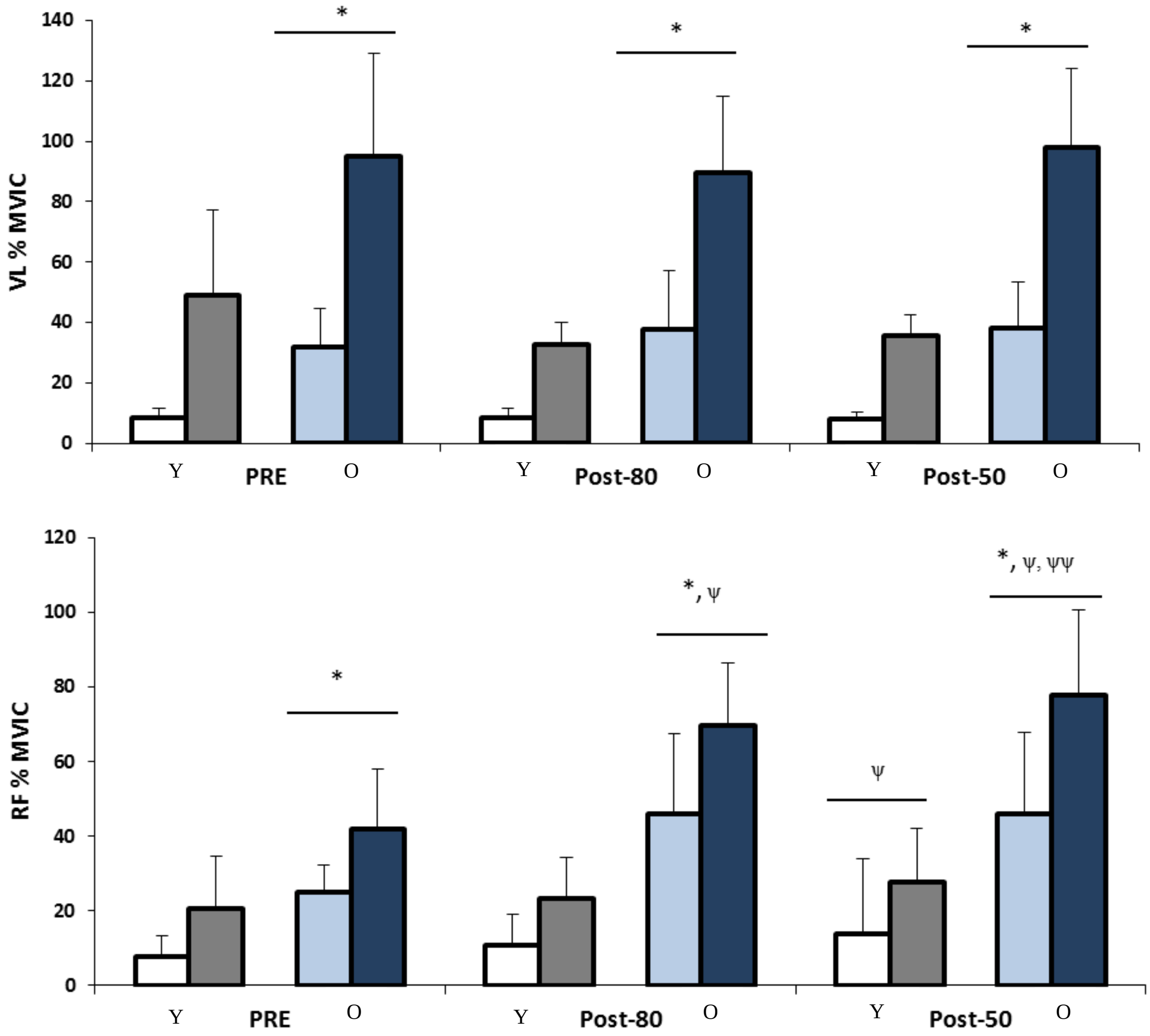


Figure 2. Vastus lateralis (VL) and rectus femoris (RF) %MVIC average activity with respect to preparatory (light) and ascending (dark) phases of the STS in young (Y;greyscale) and older (O; blue) adults. Error bars denote SDs. ψ denotes a significant difference from PRE, ψψ denotes a significant difference from previous condition. * denotes significant difference from young adults.

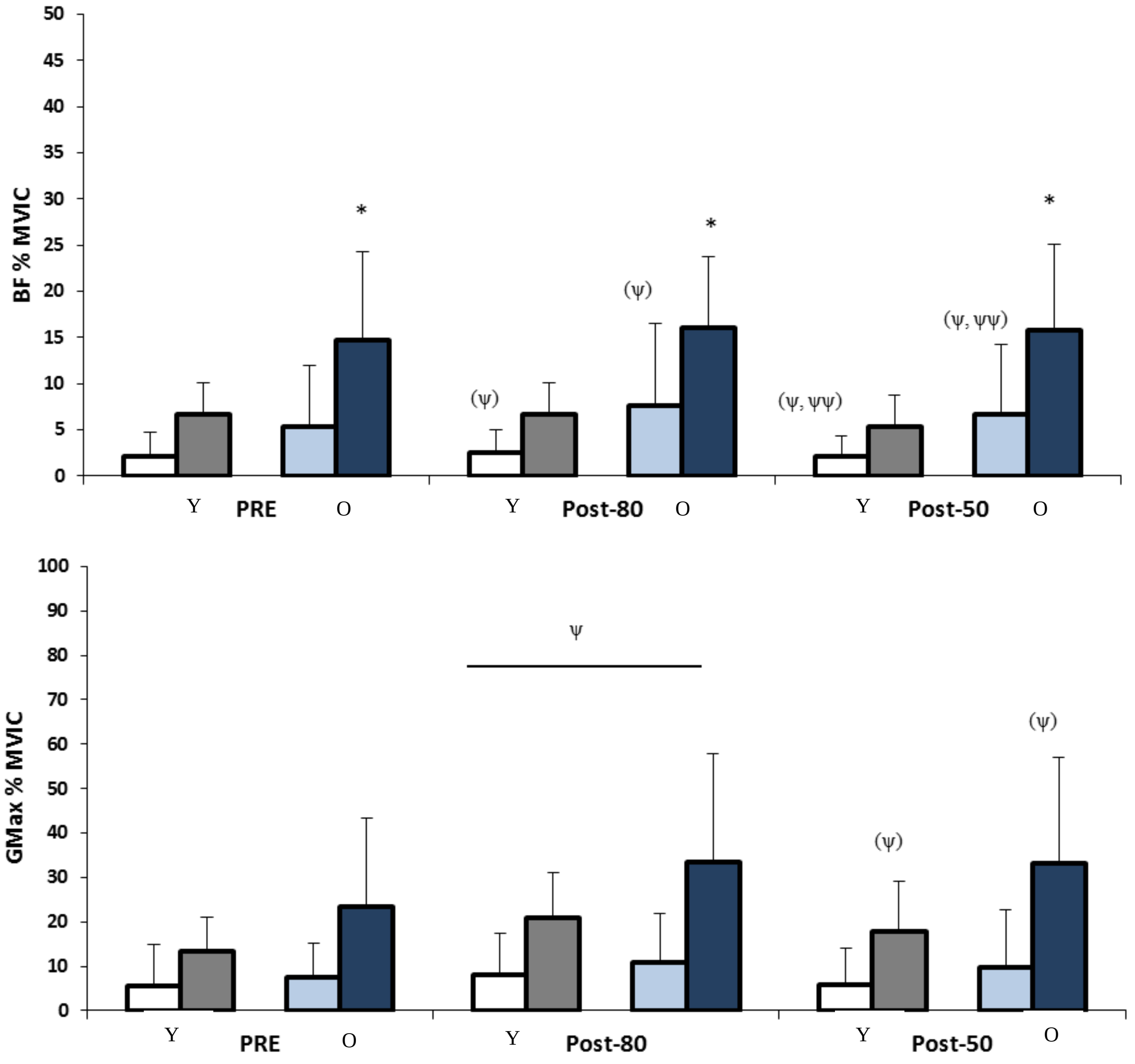


Figure 3. Biceps femoris long head (BF) and gluteus maximus (GMax) %MVIC average activity with respect to preparatory (light) and ascending (dark) phases of the STS in young (Y; greyscale) and older (O; blue) adults. Error bars denote SDs. ψ denotes a significant difference from PRE. * denotes significant difference from young adults.

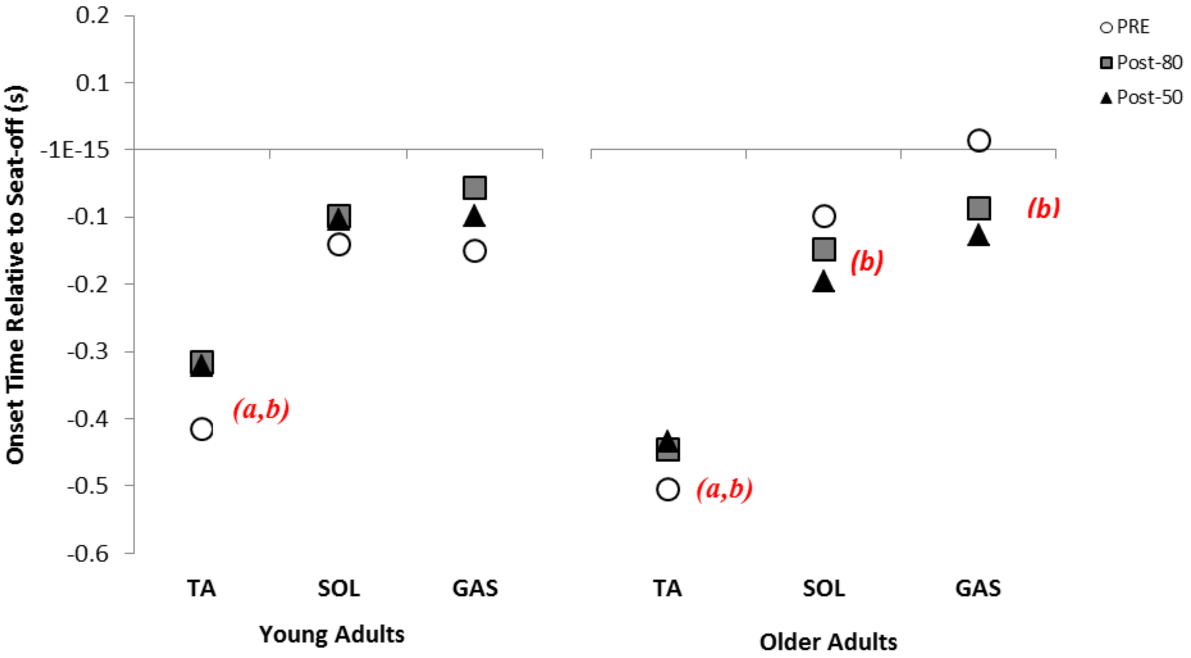


Figure 4. Ankle musculature onset times relative to seat-off (seconds) in young and older adults with respect to knee fatigue condition. *a indicated significant difference between PRE and POST-80%, b indicates a significant difference between PRE and POST-50%, and c denotes a significant difference between POST-80% and POST-50%*

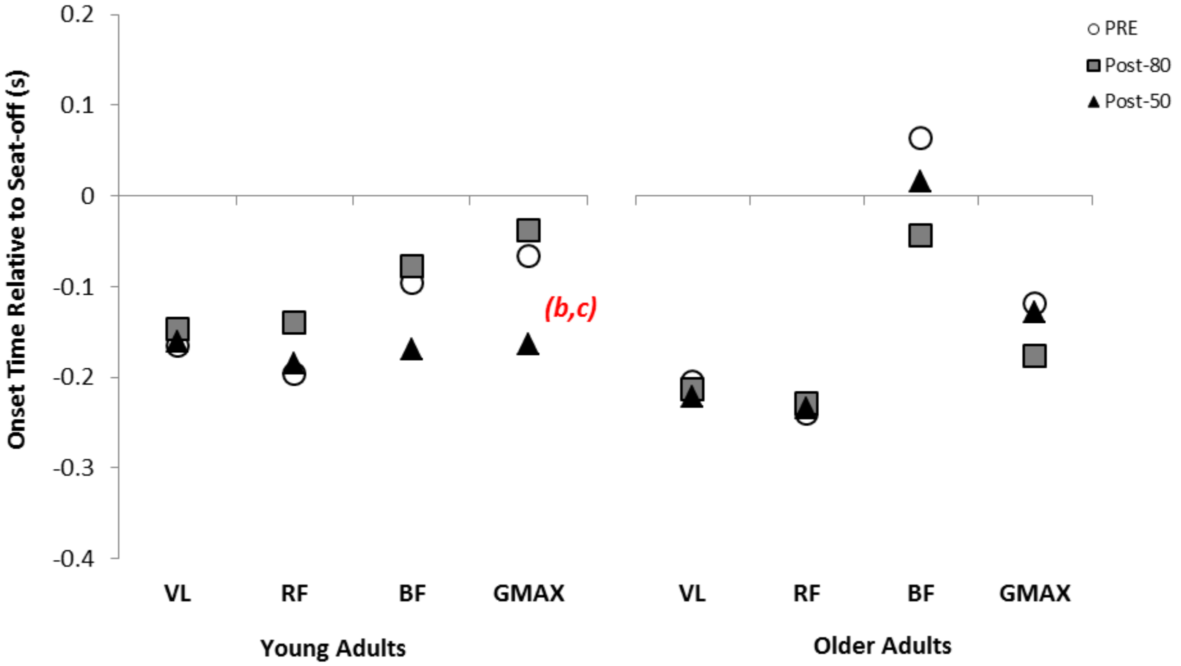


Figure 5. Thigh musculature onset times relative to seat-off (seconds) in young and older adults with respect to knee fatigue condition. *a indicates a significant difference between PRE and POST-80%, b indicates a significant difference between PRE and POST-50%, and c denotes a significant difference between POST-80% and POST-50%*

Discussion

The purpose of this investigation was to evaluate the age-related effects of reduced force output and fatigue of the KE on muscular compensatory strategies when rising from a chair. The STS is a complex multi-articular body weight movement that requires the coordinated control of several muscle groups whereas activities are controlled by the central nervous system (Alexander et al., 1991; Dehail et al., 2007; Gross et al., 1998; Roebroeck et al., 1994; Winter & Eng, 1995). The movement is initiated with horizontal displacement of one's center of mass by anteriorly flexing the torso and hip in preparation for when contact is lost with the seat (i.e., the preparatory phase). Next, vertical displacement occurs during the ascending phase and ends once a full upright extended posture is achieved (Roebroeck et al., 1994). This investigation determined the average muscular activity over these two distinct phases of the STS. Gross et al. (1998) found that peak quadriceps muscle activation during the STS task surpassed levels of standardized maximal isometric contractions. Supra-maximal peak relative activation values have also been commonly observed during dynamic running and ballistic movements (Hug, 2011); therefore analyses based solely on peak activities may be misleading due to difficulty selecting proper standardization techniques, especially for dynamic movements during which muscle lengthening occurs. By averaging amplitudes over a particular movement phase, the analyses of this current investigation provided a more robust analysis relative to movement artifact and temporal characteristics, in comparison to peak values that only provide instantaneous measures of muscle activation (Renshaw et al., 2010; Vigostky et al., 2015).

In this investigation, significantly higher average preparatory and ascending VL and RF efforts were observed in older adults for both non-fatigued and fatigued STS conditions and may reflect the lower KE strength reserves in our older participants (Figure 2 and Table 1). During

PRE STS conditions, average ascending activations of the VL and RF were ~50% MVIC and ~20% MVC respectively in young adults and 90% and 40% MVIC in older adults. Interestingly, KE fatiguing contractions caused increased %MVIC of the biarticular RF, while those of the monoarticular VL were unchanged. Although this occurred in both age groups, RF activation was more apparent in older adults; when force generating capabilities were reduced by 20% (Post-80), increased preparatory and ascending RF efforts occurred only in older adults, and further increased when reduced by 50% (Post-50). In contrast, RF activities of younger participants were seen to increase only for the Post-50 STS condition. Previous investigations have found that during repetitive KE contractions, the vasti (lateralis, medialis, and intermedius) are initially more synergistically active, while the biarticular RF increase its’ contribution to KE torque output as fatigue progresses (Akima et al., 2002; Ebenbichler et al., 1998; Kouzaki et al., 1999; Kellis, 1999). Considering this, the increased activation intensities of the RF observed in this investigation occurred to prevent excessive declines in KE torque output. Since similar fatigue intensity conditions relative to maximal KE torques were performed by both young and older adult age groups, these findings reflect the role of KE strength reserves on STS muscular control strategies. KE torque output declines of 20% were sufficient to see increased RF %MVICs in older participants with lower KE strengths, while declines of 50% were required for this to occur in the stronger, young participants. Unfortunately, force output cannot be directly inferred from EMG signals (Hug, 2011); therefore we cannot conclude if increased RF STS intensities are a result of a) fatigue accumulated when compensating for the vasti during the latter stage of the KE fatigue protocol itself or b) increased role in contributing to KE during the STS after fatiguing exercise.

It is understandable why VL relative muscular efforts did not change in older adults after KE fatigue since they were already near maximally active (~90% MVIC); however it is unclear why this was also observed in the younger participants who had substantially lower activation intensities while standing from a chair. Although it is possible that reduced neural drive to the vastii may have resulted as a protective mechanism to prevent excessive contractile failure and tissue injuries (Boyas & Guevel, 2011b; Enoka et al., 2011; Gonzalez-Izal et al., 2012), VL %MVIC in the fatigued STS condition were still well below post-fatigue re-normalization levels in young adults and remained stable regardless of the induced force declines in the fatigued condition. Regardless, at this time we are unable to determine the mechanism behind these findings; however they may further support the notion that increased RF contributions occurred during the fatigue protocol itself, allowing the vastii to work at similar levels of intensity during the subsequent STS repetitions.

Evaluations for quadriceps temporal characteristics relative to seat-off after KE fatigue showed no significant change in VL or RF onsets or peak burst activity time in either age group. Although older adult participants had slightly earlier VL and RF onset times compared to young adults, these differences were not statistically significant. Older adult participants did however have earlier peak activity timings of RF for all STS conditions. Together, these findings suggest that the quadriceps have a set motor strategy in producing sufficient resistive torques to ascend from a seated position that is not altered by the accumulation of fatigue (Goulart & Valls-Sole, 1999), but seem to differ slightly with aging to compensate for impaired force generating capabilities.

The BF is a constituent of the biarticular hamstring muscle group that assists the GMax in hip extension, as well as causing opposing knee flexor forces at the knee (Bryanton et al, 2015).

Therefore, lower levels of hamstrings activity would represent a more efficient STS muscular control strategy. With KE fatigue, a reduction in BF normalized amplitudes was seen during preparatory phases in both young and older adults; whereas ascending intensities remained unchanged. Declines were also proportional to the extent to which KE force generation was impaired in both age groups, as lower %MVICs were observed in the Post-50 compared to the Post-80 STS condition. Since no significant fatigue or age main effects were found for BF onsets and peak activity timings, reduced %MVIC preparatory activities in the absence of temporal shifting in its activation curve may have been a neural control strategy to reduce the amount of co-activity at the knee occurring prior to seat-off.

Older adults in this investigation had similar preparatory but statistically higher ascending phase BF average %MVIC values than young adults for all STS conditions. Therefore, in addition to higher muscular efforts required to perform common tasks of daily living, older adults demonstrate greater coactivity at the knee (Hortobagyi et al., 2003; Larsen et al., 2008). Larsen et al. (2008) concluded that the age dependent differences in neural strategy during stair climbing through elevated EMG normalized activity and greater thigh antagonist activity, was attributable to smaller reserve capacity with aging. Elevated co-contraction levels have been suggested to be a compensatory control strategy to increase joint stiffness in the face of impaired neuromuscular function with aging in order to enhance movement control accuracy and postural stability (DeVita & Hortobagyi, 2000; Horak et al., 1989; Kallio et al., 2012; Larsen et al., 2008; Nagai et al., 2013; Shaffer & Harrison, 2007) and may have contributed to our age group differences.

No age differences were, however, found for activation levels of the primary hip extensor muscle, the GMax in all STS conditions. Fatigue-related findings in turn showed that the Post-80 had increased average GMax %MVICs during both preparatory and ascending phases; whereas increased GMax relative efforts occurred only for ascending values in the Post-50 STS condition. These findings demonstrate the compensatory involvement of the GMax as a result of KE fatigue; however this may not be directly related to available KE force outputs since levels did not differ between young and older participants. Regardless, these results do indicate that a similar shift in movement strategy occurred as a result of KE fatigue in both age groups.

Analyses of GMax onset times showed that young adults had earlier activation onsets during the Post-50 STS condition in comparison to PRE and Post-80 conditions. Since this was not associated with any change in peak activity burst time when KE strengths of young adults were reduced by 50%, they may have adopted a different control strategy than older adults by allowing the hip extensors to be in a more active state in preparation for seat-off (Walshe et al., 1998; Van Zandwijk et al., 2000). Similarly, Van Zandwijk et al. (2000) observed that in addition to increased activation intensity, earlier onset of the GMax occurred with maximal vertical jumping compared to sub-maximal jumping efforts in their young adult participants. Since increased preparatory GMax %MVICs during this Post-50 condition was lower than those of the Post-80 but comparable to PRE STS activities, earlier pre-activity of the GMax exhibited by young adults may have been adopted to improve movement efficiency thus negating the need to increase its activation intensity in preparation for seat-off when KE force generating capabilities were further impaired.

At the ankle, young and older adults had similar average preparatory and ascending ankle plantar-flexor efforts regardless of STS condition. With fatigue, SOL and GAS %MVIC values increased in both age groups, but did not differ between Post-80 and Post-50 STS conditions. Similar to the GMax, increased ankle plantar flexor contribution to STS performance was not directly dependent on the extent of force declines induced. In older adults, earlier SOL and GAS onset times occurred once KE strength was reduced by 50% (Post-50 STS condition). The role of the ankle plantar-flexors in contributing to STS performance is to promote ankle extension to ascend the body vertically, as well as to slow down body forward displacement and stabilize center of pressure positions about the feet (Dehail et al., 2007; Flanagan & Salem, 2008). An earlier activation time of the ankle plantar flexor musculature is suggested by Gross et al. (1998) to represent the older participants attempting to begin generating ankle torques required to reduce horizontal momentum. Since this was not exhibited in the older participants in the current investigation until the Post-50 STS condition, this postural strategy was only required once large amounts of fatigue was accumulated and force quality was greatly impaired. In addition to reduced force output, peripheral fatigue has also been shown to impair the accuracy of somatosensory input obtained and integrated by the associated musculature, leading to declines in postural stability (Paillard, 2012). Although postural analyses were not performed in this investigation, impaired balance capabilities in older adults with KE fatigue may have led to alterations in the ankle musculature control strategy to better regulate body sway. Furthermore, the older adult group’s timings of peak GAS and SOL burst activities also occurred significantly later in the STS ascending phase due to larger compensatory corrective responses in order to break forward body momentum and prevent their center of pressures from deviating outside of their base of support (Dehail et al., 2007; Kanekar & Aruin, 2014; Tucker et al., 2008). Together, age-dependent corrective postural responses observed in this investigation would be attributed to age-related declines in postural control capabilities.

Lastly, older participants were found to have higher TA %MVIC during both preparatory and ascending phases of the STS in comparison to their younger counterparts for all fatigue conditions. In turn, Post -50 conditions showed a significant reduction in TA activity during the preparatory phase only, in both age groups. Dynamic fatiguing exercise of the KE at both 80% and 50% MVC conditions also caused a significant delay in TA onset timings in both young and older adults despite no changes in its peak burst times relative to seat-off. Dehail et al. (2007), Gross et al. (1998), and Khemlani et al (1999) all observed that during the STS, the TA is activated first in healthy young and older adults due to its role in anticipatory postural adjustments that pre-emptively assist in controlling balance during a dynamic motor task (Stapley et al., 1998). Pre-activity of the dorsi-flexor would cause a pre-emptive posterior shift in center of pressure prior to voluntary forward torso leaning during the preparatory phase of the STS. Consequently, our results suggest that the anticipatory action of the TA in controlling posture was attenuated after KE fatigue in both young and older adult participants. Goulart and Valls-Sole (1999) also noted that this diminished TA anticipatory activity in more challenging STS task postural conditions. Considering this, reduced pre-emptive activity of the TA prior to a rapid reduction in support surface may indicate that a stabilization strategy was adopted due to fatigue-related impairments in postural stability, through restricting center of pressure deviations (Alexander et al., 1991; Hernandez et al., 2012; Prado et al., 2011).

Although this investigation was the first to evaluate average EMG activations over two distinct phases of the STS task, the general temporal and activation characteristics we observed is supported by previous STS literature (Dehail et al., 2007; Gross et al., 1998): after earlier anticipatory onset of the TA, all other lower extremity muscles involved in the execution of the STS movement become active immediately prior to seat-off in order to sufficiently prepare to elevate the body. During the subsequent ascending phase, when simultaneous ankle plantar-flexion, knee and hip extensions are performed, activation intensities peak after contact if lost with the seat in the associated musculature. This general sequence of muscular control events also appears to be preserved with aging. Although increased activation intensities and alterations in their onsets were observed in this investigation, the general temporal sequence of events was preserved after fatiguing exercise was performed in a primary agonist muscle group, the KE.

Surface EMG is a feasible and non-intrusive method to study neural control of movement; however many factors can influence signal components and lead to misinterpretation of results (Farina, Merletti & Enoka, 2004; Hug, 2011). Specifically, fatiguing exercise results in a shift in the muscle signal's power spectrum towards lower frequencies and increased signal amplitudes (Cifrek et al., 2009; DeLuca et al., 1984). Normalization of muscle activity relative to post-fatigue standardized maximal contraction amplitudes were performed in order to reduce such possible errors allowing indirect measures of neural drive to a muscle to be made and compared between persons and STS conditions (Gross et al., 1998; Hug, 2011). Other limitations include cross-talk on muscle, which occurs when the EMG signal is contaminated by nearby muscles' electrical activity (Farina, Merletti & Enoka, 2004; Hug, 2011). Cross-talk is also a potential problem with measurements of RF activity as the vastus intermedius lies beneath it, and increases the likelihood of RF measures being skewed and misinterpreted. Similar to our results, Isear et al. (1997) also noted unique and significantly lower muscle activity of the RF compared to the vastii throughout the concentric phase of the unloaded body weight squat. Therefore, it was concluded that the fatigue-related findings of increased RF activity observed in this current investigation, as well as the results of Isear et al. (1997) are true representations of the distinctly different activity of the biarticular RF during a multi-articular task involving simultaneous ankle, knee, and hip extension (Voronov, 2004).

In summary, isolated KE fatiguing exercise resulted in compensatory muscle strategies through increased contribution of unfatigued muscles and originally less active ankle and hip musculature. In addition to higher thigh muscular efforts, age differences existed in temporal characteristics of the ankle plantarflexors with and without the presence of KE fatigue. Reduced force generating capabilities of the KE musculature appear to influence neural movement control strategy when rising from a chair. This was particularly apparent in older adults who had significantly lower KE strength and compensated for near maximal VL effort levels required to stand up from a seated position. Additionally, alterations in temporal characteristics of the ankle musculature to regulate balance presented in this investigation suggest that fatiguing exercise of the KE impairs control of body posture during a dynamic multi-articular task of daily living, especially in older persons. Considering this, older adults may benefit from strength training involving closed-chain functional exercises that target KE musculature while challenging postural stability, as a means to prevent further loss of muscle reserves and prolong living independently.

References

Akima, H., Foley, J. M., Prior, B. M., Dudley, G. A., & Meyer, R. A. (2002). Vastus lateralis fatigue alters recruitment of musculus quadriceps femoris in humans. *Journal of Applied Physiology*, *92*(2), 679-684.

Akima, H., Takahashi, H., Kuno, S. Y., & Katsuta, S. (2004). Coactivation pattern in human quadriceps during isokinetic knee-extension by muscle functional MRI. *European Journal of Applied Physiology*, *91*(1), 7-14.

Alexander, N. B., Schultz, A. B., & Warwick, D. N. (1991). Rising from a chair: effects of age and functional ability on performance biomechanics. *Journal of Gerontology*, *46*(3), M91-M98.

Bazzucchi, I., Felici, F., Macaluso, A., & De Vito, G. (2004). Differences between young and older women in maximal force, force fluctuations, and surface EMG during isometric knee extension and elbow flexion. *Muscle & Nerve*, *30*(5), 626-635.

Bieryla, K. A., Anderson, D. E., & Madigan, M. L. (2009). Estimations of relative effort during sit-to-stand increase when accounting for variations in maximum voluntary torque with joint angle and angular velocity. *Journal of Electromyography and Kinesiology*, *19*(1), 139-144.

Bohannon, R. W. (2009). Body weight-normalized knee extension strength explains sit-to-stand independence: a validation study. *The Journal of Strength & Conditioning Research*, *23*(1), 309-311.

Bonnard, M., Sirin, A. V., Oddsson, L., & Thorstensson, A. (1994). Different strategies to compensate for the effects of fatigue revealed by neuromuscular adaptation processes in humans. *Neuroscience Letters*, *166*(1), 101-105.

Boyas, S., & Guével, A. (2011). Neuromuscular fatigue in healthy muscle: underlying factors and adaptation mechanisms. *Annals of Physical and Rehabilitation Medicine*, *54*(2), 88-108.

Brech, G. C., Alonso, A. C., Luna, N. M. S., & Greve, J. M. (2013). Correlation of postural balance and knee muscle strength in the sit-to-stand test among women with and without postmenopausal osteoporosis. *Osteoporosis International*, *24*(7), 2007-2013.

Bryanton, M. A., Carey, J. P., Kennedy, M. D., & Chiu, L. Z. (2015). Quadriceps effort during squat exercise depends on hip extensor muscle strategy. *Sports Biomechanics*, *14*(1), 122-138.

Burnfield, J.M., Shu, Y., Buster, T.W., Taylor, A.P., McBride, M.M., & Krause, M.E. (2012).Kinematic and electromyographic analyses of normal and device-assisted sit-to-stand transfers. *Gait and Posture*, *36*(3), 516-522.

Carville, S.F., Perry, M.C., Rutherford, O.M., Smith, I.C.H., & Newham, D.J. (2007). Steadiness of quadriceps contractions in young and older adults with and without history of falling. *European Journal of Applied Physiology, 100,* 527-533.

Chiu, L. Z., Bryanton, M. A., & Moolyk, A. N. (2014). Proximal-to-distal sequencing in vertical jumping with and without arm swing. *The Journal of Strength & Conditioning Research*, *28*(5), 1195-1202.

Cifrek, M., Medved, V., Tonković, S., & Ostojić, S. (2009). Surface EMG based muscle fatigue evaluation in biomechanics. *Clinical Biomechanics*, *24*(4), 327-340.

Corrigan, D., & Bohannon, R. W. (2001). Relationship between knee extension force and stand-up performance in community-dwelling elderly women. *Archives of Physical Medicine and Rehabilitation*, *82*(12), 1666-1672.

Dehail, P., Bestaven, E., Muller, F., Mallet, A., Robert, B., Bourdel-Marchasson, I., & Petit, J. (2007). Kinematic and electromyographic analysis of rising from a chair during a "Sit-to-Walk" task in elderly subjects: role of strength. *Clinical Biomechanics*, *22*(10), 1096-1103.

DeLuca, C.J., LeForer, R.S., Mcute, M.P., & Xenakis, A.P. (1982). Behavior and human motor-units in different muscles during linearly varying contractions. *Journal of Physiology*, *392*, 113-128.

DeVita, P., & Hortobagyi, T. (2000). Age causes a redistribution of joint torques and powers during gait. *Journal of Applied Physiology*, *88*(5), 1804-1811.

Dimitrova, N. A., & Dimitrov, G. V. (2003). Interpretation of EMG changes with fatigue: facts, pitfalls, and fallacies. *Journal of Electromyography and Kinesiology*, *13*(1), 13-36.

Doherty, T.J., Vandervoort, A.A., Taylor, A.W., & Brown, W.F. (1993). Effects of motor unit losses on strength in older men and women. *Journal of Applied Physiology*, *74*(2), 868-874.

Ebenbichler, G., Kollmitzer, J., Quittan, M., Uhl, F., Kirtley, C., & Fialka, V. (1998). EMG fatigue patterns accompanying isometric fatiguing knee-extensions are different in mono-and bi-articular muscles. *Electroencephalography and Clinical Neurophysiology/Electromyography and Motor Control*, *109*(3), 256-262.

Enoka, R. M., Baudry, S., Rudroff, T., Farina, D., Klass, M., & Duchateau, J. (2011). Unraveling the neurophysiology of muscle fatigue. *Journal of Electromyography and Kinesiology*, *21*(2), 208-219.

Eriksrud, O., & Bohannon, R. W. (2003). Relationship of knee extension force to independence in sit-to-stand performance in patients receiving acute rehabilitation. *Physical Therapy*, *83*(6), 544-551.

Farina, D., Holobar, A., Merletti, R., & Enoka, R. M. (2010). Decoding the neural drive to muscles from the surface electromyogram. *Clinical Neurophysiology*, *121*(10), 1616-1623.

Flanagan, S. P., & Salem, G. J. (2008). Lower extremity joint kinetic responses to external resistance variations. *Journal of Applied Biomechanics*, *24*(1), 58.

Gregoire, L., Veeger, H. E., Huijing, P. A., & van Ingen, S. G. (1984). Role of mono-and biarticular muscles in explosive movements. *International Journal of Sports Medicine*, *5*(6), 301-305.

Godin, G., & Shepard, R.J. (1997). Godin and Leisure-Time Exercise Questionnaire. *Medicine and Science in Sports and Exercise. 29 (June Supplements)*, S36-S38.

González-Izal, M., Malanda, A., Gorostiaga, E., & Izquierdo, M. (2012). Electromyographic models to assess muscle fatigue. *Journal of Electromyography and Kinesiology*, *22*(4), 501-512.

Goulart, F. R. D. P., & Valls-Solé, J. (1999). Patterned electromyographic activity in the sit-to-stand movement. *Clinical Neurophysiology*, *110*(9), 1634-1640.

Hernandez, M.E., Ashton-Miller, J.A., & Alexander, N.B. (2012). Age-related changes in speed and accuracy during rapid targeted center of pressure movements near the posterior limits of base of support. *Clinical Biomechanics*, *27*, 910-916.

Horak, F. B., Shupert, C. L., & Mirka, A. (1989). Components of postural dyscontrol in the elderly: a review. *Neurobiology of Aging*, *10*(6), 727-738.

Hortobágyi, T., Mizelle, C., Beam, S., & DeVita, P. (2003). Old adults perform activities of daily living near their maximal capabilities. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *58*(5), M453-M460.

Hug, F. (2011). Can muscle coordination be precisely studied by surface electromyography?. *Journal of Electromyography and Kinesiology*, *21*(1), 1-12.

Hughes, M. A., Myers, B. S., & Schenkman, M. L. (1996). The role of strength in rising from a chair in the functionally impaired elderly. *Journal of Biomechanics*, *29*(12), 1509-1513.

Ikeda, S., Tsumura, H., & Torisu, T. (2005). Age-related quadriceps-dominant muscle atrophy and incident radiographic knee osteoarthritis. *Journal of Orthopaedic Science*, *10,* 121-126.

Ikezoe, T., Mori, N., Nakamura, M., & Ichihashi, N. (2011). Age-related muscle atrophy in the lower extremities and daily physical activity in elderly women. *Archives of Gerontology and Geriatrics*, *53*(2), e153-e157.

Ikezoe, T., Mori, N., Nakamura, M., & Ichihashi, N. (2011). Atrophy of the lower limbs in elderly women: Is it related to walking ability? *European Journal of Applied Physiology*, *111,* 989-995.

Isear Jr, J. A., Erickson, J. C., & Worrell, T. W. (1997). EMG analysis of lower extremity muscle recruitment patterns during an unloaded squat. *Medicine and Science in Sports and Exercise, 29*(4), 532-539.

Kallio, J., Sogaard, K., Avela, J., Komi, P., Selanne, H., & Linnamo, V. (2012). Age-related decreases in motor unit discharge rate and force control during isometric plantar flexion. *Journal of Electromyography and Kinesiology*, *22*(6), 983-989.

Kanekar, N., & Aruin, A. S. (2014). Aging and balance control in response to external perturbations: role of anticipatory and compensatory postural mechanisms. *Age*, *36*(3), 1067-1077.

Keenan, K. G., Farina, D., Maluf, K. S., Merletti, R., & Enoka, R. M. (2005). Influence of amplitude cancellation on the simulated surface electromyogram. *Journal of Applied Physiology*, *98*(1), 120-131.

Kellis, E. (1999). The effects of fatigue on the resultant joint moment, agonist and antagonist electromyographic activity at different angles during dynamic knee extension efforts. *Journal of Electromyography and Kinesiology*, *9*(3), 191-199.

Khemlani, M. M., Carr, J. H., & Crosbie, W. J. (1999). Muscle synergies and joint linkages in sit-to-stand under two initial foot positions. *Clinical Biomechanics*, *14*(4), 236-246.

Kouzaki, M., Shinohara, M., & Fukunaga, T. (1999). Non-uniform mechanical activity of quadriceps muscle during fatigue by repeated maximal voluntary contraction in humans. *European Journal of Applied Physiology and Occupational Physiology*, *80*(1), 9-15.

Laidlaw, D. H., Bilodeau, M., & Enoka, R. M. (2000). Steadiness is reduced and motor unit discharge is more variable in old adults. *Muscle & Nerve*, *23*(4), 600-612.

Larsen, A. H., Puggaard, L., Hämäläinen, U., & Aagaard, P. (2008). Comparison of ground reaction forces and antagonist muscle coactivation during stair walking with ageing. *Journal of Electromyography and Kinesiology*, *18*(4), 568-580.

Lynch, N.A., Metler, E.J., & Lindle, R.S. (1999). Muscle quality. I. Age-associated differences between arm and leg muscle group. *Journal of Applied Physiology, 86(*1), 188-194.

Muhlberg, W., & Sieber, C. (2004). Sarcopenia and frailty in geriatric patients: Implications or training and prevention. *Z Gerontol Geriat*, 37, 2-8.

Nagai, K., Yamada, M., Mori, S., Tanaka, B., Yemura, K., Aoyama, T., Ichihashi, N., & Tsuboyama, T. (2013). Effect of the muscle coactivation during quiet standing on dynamic postural control in older adults. *Arch Gerontol Geriatr*, *56*(1), 129-133.

Paillard, T. (2012). Effects of general and local fatigue on postural control: a review. *Neuroscience & Biobehavioral Reviews*, *36*(1), 162-176.

Petrella, J. K., Kim, J. S., Tuggle, S. C., Hall, S. R., & Bamman, M. M. (2005). Age differences in knee extension power, contractile velocity, and fatigability. *Journal of Applied Physiology*, *98*(1), 211-220.

Prado, J.M., Mauro, C.M., & Duarte, M. (2011). Age-related difference on weight transfer during unconstrained standing. *Gait and Posture, 33*(1), 93-97.

Puniello, M. S., McGibbon, C. A., & Krebs, D. E. (2001). Lifting strategy and stability in strength-impaired elders. *Spine*, *26*(7), 731-737.

Renshaw, D., Bice, M. R., Cassidy, C., & Eldridge, J. A. (2010). A Comparison of Three Computer-based Methods Used to Determine EMG Signal Amplitude. *International Journal of Exercise Science*, *3*(1).

Roebroeck, M. E., Doorenbosch, C. A. M., Harlaar, J., Jacobs, R., & Lankhorst, G. J. (1994). Biomechanics and muscular activity during sit-to-stand transfer. *Clinical Biomechanics*, *9*(4), 235-244.

Roos, M.R., Rice, C.L., & Vandervoort, A.A. (1997). Age-related changes in motor unit function. M*uscle and Nerve, 20,* 679-690.

Savelberg, H. H. C. M., Fastenau, A., Willems, P. J. B., & Meijer, K. (2007). The load/capacity ratio affects the sit-to-stand movement strategy. *Clinical Biomechanics*, *22*(7), 805-812.

Shaffer, S. W., & Harrison, A. L. (2007). Aging of the somatosensory system: a translational perspective. *Physical Therapy*, *87*(2), 193-207.

Stapley, P., Pozzo, T., & Grishin, A. (1998). The role of anticipatory postural adjustments during whole body forward reaching movements. *Neuroreport*, *9*(3), 395-401.

Tucker, M.G., Kavanagh, J.J., Barrett, R.S., & Morrison, S. (2008). Age-related differences in postural reaction time and coordination during voluntary sway movements. *Human Movement Science, 27*(5), 728-737.

Van der Heijden, M. M., Meijer, K., Willems, P. J., & Savelberg, H. H. (2009). Muscles limiting the sit-to-stand movement: an experimental simulation of muscle weakness. *Gait & Posture, 30*(1), 110-114.

Van Roie, E., Verschueren, S. M., Boonen, S., Bogaerts, A., Kennis, E., Coudyzer, W., & Delecluse, C. (2011). Force-velocity characteristics of the knee extensors: an indication of the risk for physical frailty in elderly women. *Archives of Physical Medicine and Rehabilitation*, *92*(11), 1827-1832.

Van Zandwijk, J. P., Bobbert, M. F., Munneke, M. A. R. T. E. N., & Pas, P. I. E. T. E. R. (2000). Control of maximal and submaximal vertical jumps. *Medicine and Science in Sports and Exercise*, *32*(2), 477-485.

Vigotsky, A. D., Harper, E. N., Ryan, D. R., & Contreras, B. (2015). Effects of load on good morning kinematics and EMG activity. *PeerJ*, *3*, e708.

Voronov, A.V. (2004). The roles of monoarticular and biarticular muscles of the lower limbs in terrestrial locomotion. *Human Physiology, 30,*476-484.

Walshe, A. D., Wilson, G. J., & Ettema, G. J. (1998). Stretch-shorten cycle compared with isometric preload: contributions to enhanced muscular performance. *Journal of Applied Physiology*, *84*(1), 97-106.

Winter, D. A., & Eng, P. (1995). Kinetics: our window into the goals and strategies of the central nervous system. *Behavioural Brain Besearch*, *67*(2), 111-120.

Yang, J. F., & Winter, D. A. (1984). Electromyographic amplitude normalization methods: improving their sensitivity as diagnostic tools in gait analysis. *Arch Phys Med Rehabil*, *65*(9), 517-521.

Yoshioka, S., Nagano, A., Himeno, R., & Fukashiro, S. (2007). Computation of the kinematics and the minimum peak joint moments of sit-to-stand movements. *Biomed Eng Online*, *6*(1), 26.

CHAPTER 8

GENERAL DISCUSSION

Summary

The main finding of this research compilation was that it demonstrated a determining relationship between knee extensor (KE) performance and sit-to-stand (STS) strategy in young and older adults with fatiguing exercise. In Manuscript 2 (*Chapter 5)*, during repetitive multi-articular STS exercise, both young and older adults experienced progressive declines in KE net joint moments and mechanical work that was unaccompanied by compensatory shifting of loading demands to the ankle plantar-flexors nor hip extensors. Interestingly, surface electromyography (EMG) in Manuscript 3 (*Chapter 6)* revealed that this was associated with an increase in quadriceps activation intensities relative to maximal amplitudes (%MVIC). Together, this exemplifies that although joint kinetic analyses provide a picture of net joint loading demands during a multi-articular task, they do not reflect the extent to which the associated musculature are working relative to their maximal strength reserves. Moreover, increased activity of the bi-articular, antagonist hamstrings may also influence measures of knee kinetics. Traditional inverse dynamic analyses of net joint moment calculations represent the sum of all agonist and antagonist muscle forces acting upon a joint, and increased co-activity of the hamstring can underestimate contributions of the quadriceps in generating an extensor moment at the knee (Bryanton et al., 2015). Since higher levels of hamstring activity were observed at the end of the repetitive STS exercise protocol, increased opposing knee flexor forces may have also contributed to declines in KE kinetic measures despite increased quadriceps efforts; however this was not reflected by their activation ratios (i.e., H:Q ratios).

It was also found that the extent to which the quadriceps were active (i.e., relative efforts) was a significant predictor of STS capacity, particularly in older adult participants who had significantly shorter total task times and higher quadriceps %MVIC at the beginning of the exercise protocol (*Chapter 6*). Aging was found to cause a redistribution of joint torques and work through increased ankle plantar-flexor and hip extensor contributions to ascending from a seated position. Although muscle activity was not investigated during the prolonged STS protocol, lower KE strength reserves may be responsible for this compensatory loading strategy as older adults would be required to work at higher levels of KE efforts for the STS task in comparison to their younger counterparts. This relationship has also been previously documented in the investigations of Doorenbosche et al. (1994), Hortobagyi et al. (2003), and Hughes et al. (1996). In turn, higher effort requirements would lead to substantially greater accumulation of fatigue in the quadriceps muscles of older adults in comparison to the younger participants, and would limit their ability to perform repeated STS actions for an extended period of time.

Through analyses of muscular coordination and activation intensities, it was also revealed that reduced force-generating capabilities due to isolated dynamic fatiguing exercise of the KE caused compensatory muscle strategies when ascending from a chair via increased reliance of unfatigued muscles at the ankle and hip, as well as increased activity of synergist muscles. In turn, the extent to which these alterations occurred was dependent on the extent to which force declines were induced. In Manuscript 4 (*Chapter 7),* higher thigh (Vastus lateralis, Rectus femoris, Bicep femoris) muscular efforts were again observed in older participants in both non-fatigued and fatigued STS conditions; however ankle plantar-flexor and gluteus maximus %MVICs were similar between age groups. In Manuscript 2 (*Chapter 5*), peak HE net joint moments and mechanical work performed were similar between young and older participants;

however the average HE net joint moment output during the ascending phase of the STS was larger in older adults. Therefore, although gluteus maximus intensity may be similar, greater hamstring activity and limited hip range of motion in older adults may explain this relationship.

Temporal characteristics of the ankle plantar-flexors did, however, differ with aging regardless of the presence of KE fatigue. Impaired force control and torque generating capabilities of the KE musculature also influenced the postural control strategies of ankle musculature when rising from a chair differently with respect to age: KE fatigue may impair control of body posture during a dynamic multi-articular task of daily living, especially in older persons experiencing unavoidable neuromuscular declines. Moreover, in Manuscript 1 (*Chapter 4*), results showed that repetitive STS exercise was also associated with stabilization strategies through repositioning of center of pressure more anteriorly towards the mid-foot and away from postural limits of stability when contact is lost with the seat. Together, the association of KE strength and risk of falling in older populations experiencing functional declines previously documented in the literature (Carter et al., 2001; Carville et al., 2007; Ikezoe et al., 2011a; Ikezoe et al., 2011b; Manini et al., 2007; Puniello et al., 2001) may be explained by greater accumulation of fatigue in the quadriceps due to an uneven distribution of muscular efforts across the lower extremity musculature that is exacerbated with aging.

Research Conclusions

This research compilation is the first work to investigate the net joint moments, mechanical work, and muscle EMG activities of the lower extremity in young and older adults with respect to preparatory and ascending phases of the STS, during either repetitive multi-joint or isolated single joint fatigue. Previous research has generally ignored the potential influence of fatigue in primary agonist muscle such as the KE on limiting dynamic movement capabilities in young and older adults. Therefore, information gained from this research provides valuable information regarding the role of KE strength in functional mobility capabilities in senescence. In doing so, we have determined four major conclusions:

1. The ability to perform repetitive actions of a multi-joint task that requires large resistive torques about the ankle, knee, and hip is determined by the extent to which the limiting muscle group is active.
2. Age-related declines in available KE strength reserves will influence the distribution of joint torques and mechanical work across the lower extremities, as well as muscular coordination strategies of associated musculature, regardless of available muscle reserves.
3. Aging does not appear to influence the way in which repetitive STS exercise will impact lower extremity joint kinetics
4. The accumulation of fatigue in KE musculature impairs the ability to control body posture, where associated stabilization strategies are apparent in ankle kinetics and temporal characteristics of muscle activations, in order to regulate center of pressure positions about the feet when faced with a rapidly reducing support surface at seat-off.

Practical Applications

This research was intended to elucidate how age-related declines in muscle performance affect the ability to perform common daily tasks, such as standing from a chair and getting out of the bed. Through understanding a muscle’s ability to contribute during such movements and why unfavorable compensation strategies manifest, this and subsequent research will not only enhance the ability for early detection of functional impairments in those with reduced mobility, but also will ultimately add to the establishment of effective health intervention programs that support elderly individuals’ ability to maintain independent living. It will benefit rehabilitative professionals by increasing our understanding of the role of limiting muscle groups responsible for difficulty in executing multi-joint movements, as well as in the prevention of chronic overuse injuries due to improper movement kinematics, and will enhance our understanding of risk factors that have been previously associated with fall risk and the incidence of mortality in older adults over the age of 60 years.

Limitations and Future Research Directions

Although this research identified the importance of KE force generating capabilities in limiting the ability to repetitively rise from a seated position, as well as the associated muscular control strategies in young and older adults, the exact mechanisms of fatigue and their consequences on movement and postural strategies was beyond the scope of the aims of this thesis compilation. Future research should consider evaluating the physiological mechanisms (central versus peripheral) between the two forms of fatiguing perturbances employed in this research (dynamic multi-articular versus single-joint exercise) and how this may differ with aging. Consequently, it is expected that different relative contributions of central versus peripheral fatigue impairements would impact the STS strategies adopted differently. For instance, a greater susceptibility to central fatigue mechanisms in older populations may have lead to more globally pronounced reductions in their ability to voluntary activate lower extremity musculature. In contrast, peripheral fatigue mechanisms may have had a more local affect on reduced contractile performance of the fatigued musculature (i.e., the KE). This characterization would be possible through comparisons of maximal voluntary contractions and superimposed electrical stimulation on KE torque outputs before and after the fatiguing exercise. However, since no age x fatigue interactions were noted in compensatory STS actions during either multi-joint STS or dynamic KE exercise (indicating that young and older adults were impacted by fatigue in similar fashion regardless of KE strength reserves), possible age-dependant differences in the form of fatigue accumulated are not expected to substantially impact the findings of this research compilation and the associated interpretations.

Secondly, based on previous research regardling the effect of seat height on KE demands when ascending from a seated position, as well as similar multi-joint movements (Bryanton et al., 2012; 2015; Hughes et al., 1996; Janssen et al., 2002), the standardizing technique of chair heights relative to lower limb length was essential to ensuring that similar subject specific STS conditions to either a) induce fatigue (*Manuscripts 1-3*), or to b) observe its effects on STS performance (*Manuscript 4*). Moreoever, a seat height selected of 80% total limb length ensured that it was low enough to require adequate muscular efforts, yet high enough that all participants, young and old, were able ascend successfully, and do so repeatedly. However, this low seat height may have limited the extent of compensatory actions of the HE since participants had no choice but to produce sufficient KE torques based on the standardized segment geometric of a parallel thigh position and anteriorly rotated shank, and associated moment arm lengths (Bryanton et al., 2012; Chiu et al., 2016; Fry et al., 2003). Therefore, although a higher seat position would have most likely fatigued the KE musculature to a lesser extent, as initial lower efforts would have been required by both young and older participants, compensatory shifting of loading demands to the HE may have been observed as initially hypothesized and as suggested in previous literature (Savelberg et al., 2007; Yoshioka et al., 2007).

The use of normalized EMG measures is an acceptable means of quantifying activity levels of a muscle. This however, requires the assumption that maximal EMG amplitudes collected are truly maximal in rested (or fatigued) conditions. This is particularly important when using a single standardized isometric maximal contraction to interpret relative muscular efforts during a dynamic task, as it is uncertain whether the muscle has been truly maximally activated. Therefore, performing one MVIC in order to normalize (and re-normalize) signal characteristics, before or after fatigue, may not have been sufficient to establish an optimal reference value and should be considered a limitation of *Manuscripts 3 and 4.* Moreover, the assumption that muscle activities were similar between both limbs was also required in these investigations due to equipment availability: EMG signals were only collected for the dominant limb during STS testing. Therefore, the potential for limb asymmetries in %MVIC, as well as other kinematic and kinetic measures used in our analyses, was not accounted for in this thesis and should be considered in future investigations.

Lastly, it could be argued that a limitation of this research in comparing age-dependant STS strategies with and without faitugue is that the older adult particpants were inherently in the younger age-range, and may not be reflective of those experiencing substantial functional declines; this minimized potentially large differences between groups. However, in order to successfully complete the repetitive STS tasks, both young and older particpants needed to be in good physical health. Moreover, since age main effects were infact observed for muscular activities and joint loadings during the STS, we can confidently conclude that group differences were a consequence of healthy aging in older adults without any observable physical impairment. This age group would have also minimized other confounding effects associated with health issues and impairments that are more prevalent in much older individuals (≥80 years of age). Regardless, future research endeavors should consider the evaluations of much older populations to further reveal the role of KE strength reserves in limiting STS performance, as well as how improving such reserves through means of intervention may or may not improve STS capacities.

CHAPTER 9

RESEARCH CONTRIBUTIONS

Manuscript 1 - *Postural Stability with Exhaustive Repetitive Sit-To-Stand Exercise in Young Adults.* M. Bryanton conceptualized the study, carried out the data collection, statistical analyses, and wrote and edited the manuscript. M. Bilodeau participated in the conception and design of the study, provided advice and content expertise, and revised the manuscript. All authors read and approved the final manuscript.

Manuscript 2 – *Compensatory Alterations in Joint Kinetics during Repetitive Sit-to-Stand Exercise in Young and Older Adults* M. Bryanton conceptualized the study, carried out the data collection, statistical analyses, and wrote and edited the manuscript. M. Bilodeau participated in the conception and design of the study, provided advice and content expertise, and revised the manuscript. All authors read and approved the final manuscript.

Manuscript 3 – *The Role of Thigh Muscular Efforts in Limiting Sit-to-Stand Capacity in Healthy Young and Older Adults during Repetitive Multi-Joint Exercise*. M. Bryanton conceptualized the study, carried out the data collection, statistical analyses, and wrote and edited the manuscript. M. Bilodeau participated in the conception and design of the study, provided advice and content expertise, and revised the manuscript. All authors read and approved the final manuscript.

Manuscript 4 *Age- and Intensity- Dependent Alterations in Muscular Control of Chair Rise Strategt with Dynamic Knee Extensor Fatiguing Exercise*. M. Bryanton conceptualized the study, carried out the data collection, statistical analyses, and wrote and edited the manuscript. M. Bilodeau participated in the conception and design of the study, provided advice and content expertise, and revised the manuscript. All authors read and approved the final manuscript.

CHAPTER 10

REFERENCES

Akima, H., Foley, J. M., Prior, B. M., Dudley, G. A., & Meyer, R. A. (2002). Vastus lateralis fatigue alters recruitment of musculus quadriceps femoris in humans. *Journal of Applied Physiology*, *92*(2), 679-684.

Akima, H., Takahashi, H., Kuno, S. Y., & Katsuta, S. (2004). Coactivation pattern in human quadriceps during isokinetic knee-extension by muscle functional MRI. *European Journal of Applied Physiology, 91*(1), 7-14.

Akram, S.B., & McIlroy, W.E. (2011). Challenging horizontal movement of the body during sit-to-stand: Impact on stability in the young and elderly. *Journal of Motor Behavior, 43*(2), 147-153.

Alexander, N. B., Gross, M. M., Medell, J. L., & Hofmeyer, M. R. (2001). Effects of functional ability and training on chair-rise biomechanics in older adults. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *56*(9), M538-M547.

Alexander, N. B., Schultz, A. B., & Warwick, D. N. (1991). Rising from a chair: effects of age and functional ability on performance biomechanics. *Journal of Gerontology*, *46*(3), M91-M98.

Allen, D. G., & Westerblad, H. (2001). Role of phosphate and calcium stores in muscle fatigue. *The Journal of Physiology*, *536*(3), 657-665.

Allman, B. L., & Rice, C. L. (2002). Neuromuscular fatigue and aging: central and peripheral factors. *Muscle & Nerve*, *25*(6), 785-796.

Allum, J.H. (2002). Age-dependant variations in the directional sensitivity of balance corrections and compensatory arm movements in man. *Journal of Physiology, 542,* 643-663.

Avin, K. G., & Law, L. A. F. (2011). Age-related differences in muscle fatigue vary by contraction type: a meta-analysis. *Physical Therapy*, *91*(8), 1153-1165.

Balsom, P. D., Gaitanos, G. C., Söderlund, K., & Ekblom, B. (1999). High-intensity exercise and muscle glycogen availability in humans. *Acta Physiologica Scandinavica, 165*, 337-346.

Barbieri, F. A., dos Santos, P. C. R., Vitório, R., van Dieën, J. H., & Gobbi, L. T. B. (2013). Effect of muscle fatigue and physical activity level in motor control of the gait of young adults. *Gait & Posture*, *38*(4), 702-707.

Bassey, E.J., Fiatrone, M.A., O'Neill, E.F., Kelly, M., Evans, W.J., & Lipsitz, L.A. (1992). Leg extensor power and functional performance in very old men and women. *Clinical Science, 82,* 321-327.

Bazzucchi, I., Felici, F., Macaluso, A., & De Vito, G. (2004). Differences between young and older women in maximal force, force fluctuations, and surface EMG during isometric knee extension and elbow flexion. *Muscle & Nerve, 30*(5), 626-635.

Bellew, J.W., & Fender, P.C. (2006). Control of balance differes after knee or ankle fatigue in older women. *Archives of Physical Medicine and Rehabilitation, 87*(11), 1486-1489.

Bernardi, M., Rosponi, A., Castellano, V., Rodio, A., Traballesi, M., Delussu, A. S., & Marchetti, M. (2004). Determinants of sit-to-stand capability in the motor impaired elderly. *Journal of Electromyography and Kinesiology, 14*(3), 401-410.

Bieryla, K. A., Anderson, D. E., & Madigan, M. L. (2009). Estimations of relative effort during sit-to-stand increase when accounting for variations in maximum voluntary torque with joint angle and angular velocity. *Journal of Electromyography and Kinesiology, 19*(1), 139-144.

Bigland-Ritchie, B. (1981). EMG and fatigue of human voluntary and stimulated contractions. *Human Muscle Fatigue: Physiological Mechanisms*, 130-156.

Bilodeau, M., Henderson, T.K., Nolta, B.E., Purslet, P.J, & Sandfort, G.L. (2001). Effect of aging on Fatigue characteristics of elbow flexor muscles during sustained submaximal contraction. *Journal of Applied Physiology, 91*(6), 2654-2665.

Bilodeau, M., Schindler-Ivens, S., Williams, D.M., Chandran, R., & Sharma, S.S. (2003). EMG frequency content changes with increasing force and during fatigue in the quadriceps femoris muscle of men and women. *Journal of Electromyography and Kinesiology, 13,* 83-92.

Bisiaux, M., & Moretto, P. (2008). The effects of fatigue on plantar pressure distribution in walking. *Gait and Posture, 28*, 693-698.

Blaszczyk, J.W., Cieslinska-Swider, J., Plewa, M., Zahorska-Markiewicz, & Markiewicz, A. (2009). Effects of excessive bodyweight on postural control. *Journal of Biomechanics, 42,* 1295-1300.

Bohannon, R. W. (1995). Sit-to-stand test for measuring performance of lower extremity muscles. *Perceptual and Motor Skills, 80*(1), 163-166.

Bonnard, M., Sirin, A. V., Oddsson, L., & Thorstensson, A. (1994). Different strategies to compensate for the effects of fatigue revealed by neuromuscular adaptation processes in humans. *Neuroscience letters, 166*(1), 101-105.

Borg, G. A. V. (1982). Psychological bases of perceived exertion. *Medicine and Science in Sports and Exercise*, *14*(5), 377-381.

Bouchouras, G., Patsika, G., Hatzitaki, V., & Kellis, E. (2015). Kinematics and knee muscle activation during sit-to-stand movement in women with knee osteoarthritis. *Clinical Biomechanics, 30*(6), 599-607.

Boyas, S., & Guével, A. (2011a). Influence of exercise intensity and joint angle on endurance time prediction of sustained submaximal isometric knee extensions. *European Journal of Applied Physiology*, *111*(6), 1187-1196.

Boyas, S., & Guével, A. (2011b). Neuromuscular fatigue in healthy muscle: underlying factors and adaptation mechanisms. *Annals of Physical and Rehabilitation Medicine*, *54*(2), 88-108.

Brech, G. C., Alonso, A. C., Luna, N. M. S., & Greve, J. M. (2013). Correlation of postural balance and knee muscle strength in the sit-to-stand test among women with and without postmenopausal osteoporosis. O*steoporosis International, 24*(7), 2007-2013.

Bryanton, M. A., Carey, J. P., Kennedy, M. D., & Chiu, L. Z. (2015). Quadriceps effort during squat exercise depends on hip extensor muscle strategy. *Sports Biomechanics*, *14*(1), 122-138.

Bryanton, M. A., Kennedy, M. D., Carey, J. P., & Chiu, L. Z. (2012). Effect of squat depth and barbell load on relative muscular effort in squatting. *The Journal of Strength & Conditioning Research*, *26*(10), 2820-2828.

Buatois, S., Miljkovic, D., Manckoundia, P., Gueguen, R., Miget, P., Vançon, G. & Benetos, A. (2008). Five times sit to stand test is a predictor of recurrent falls in healthy community-living subjects aged 65 and older. *Journal of the American Geriatrics Society, 56*(8), 1575-1577.

Buckley, T., Pitsikoulis, C., Barthelemy, E., & Hass, C.J. (2009). Age impairs sit to walk motor performance. *Journal of Biomechanics, 42*, 2318-2322.

Buller, A. J., Eccles, J. C., & Eccles, R. M. (1960). Interactions between motoneurones and muscles in respect of the characteristic speeds of their responses. *The Journal of Physiology*, *150*(2), 417.

Bullock-Saxton, J. E., Wong, W. J., & Hogan, N. (2001). The influence of age on weight-bearing joint reposition sense of the knee. *Experimental Brain Research*, *136*(3), 400-406.

Burnfield, J.M., Shu, Y., Buster, T.W., Taylor, A.P., McBride, M.M., & Krause, M.E. (2012).Kinematic and electromyographic analyses of normal and device-assisted sit-to-stand transfers. *Gait and Posture, 36*(3), 516-522.

Callahan, D. M., Foulis, S. A., & Kent-Braun, J. A. (2009). Age-related fatigue resistance in the knee extensor muscles is specific to contraction mode. *Muscle & Nerve*, *39*(5), 692-702.

Caron, O. (2003). Effects of local fatigue of the lower limbs on postural control and postural stability in standing posture. *Neuroscience Letters*, *340*(2), 83-86.

Caron, O. (2004). Is there interaction between vision and local fatigue of the lower limbs on postural control and postural stability in human posture?. *Neuroscience Letters*, *363*(1), 18-21.

Carter, N.D., Khan, K.M., Mallinson, A., Janssen, P.A., Heinonen, A., Petit, M.A., & McKay, H.A. (2002). Knee extensor strength is a significant determinant of static and dynamic balance as well as quality of life in older community-dwelling women with osteoporosis. *Gerontology, 48*(6), 360-368.

Carville, S.F., Perry, M.C., Rutherford, O.M., Smith, I.C.H., & Newham, D.J. (2007). Steadiness of quadriceps contractions in young and older adults with and without history of falling. *European Journal of Applied Physiology, 100*, 527-533.

Chaubet, V., & Paillard, T. (2012). Effects of unilateral knee extension muscle fatigue induced by stimulated and voluntary contraction on postural control during bipedal stance. *Neurophysiologie Clinique/ Clinical Neurophysiology, 42*, 377-383.

Chen, T., Chang, C. C., & Chou, L. S. (2013). Sagittal plane center of mass movement strategy and joint kinetics during sit-to-walk in elderly fallers. *Clinical Biomechanics*, *28*(7), 807-812.

Cheng, P. T., Wu, S. H., Liaw, M. Y., Wong, A. M. K., & Tang, F. T. (2001). Symmetrical body-weight distribution training in stroke patients and its effects on fall prevention. *Archives of Physical Medicine and Rehabilitation, 82*(12), 1650-1654.

Chiu, L. Z., & Salem, G. J. (2006). Comparison of joint kinetics during free weight and flywheel resistance exercise. *The Journal of Strength & Conditioning Research*, *20*(3), 555-562.

Chiu, L. Z., & Salem, G. J. (2012). Potentiation of vertical jump performance during a snatch pull exercise session. *Journal of Applied Biomechanics*, *28*(6), 627-35.

Chiu, L. Z., vonGaza, G. L., & Jean, L. M. (2016). Net joint moments and muscle activation in barbell squats without and with restricted anterior leg rotation. *Journal of Sports Sciences*, 1-9.

Chiu, L.Z.F., Fry, A.C., Schilling, B.K., Johnson, E.J., & Weiss, L.W. (2004). Neuromuscular fatigue and postactivation potentiation following two successive high intensity resistance exercise sessions. *European Journal of Applied Physiology, 92*, 385-392.

Cifrek, M., Medved, V., Tonković, S., & Ostojić, S. (2009). Surface EMG based muscle fatigue evaluation in biomechanics. *Clinical Biomechanics*, *24*(4), 327-340.

Clark, D. J., Patten, C., Reid, K. F., Carabello, R. J., Phillips, E. M., & Fielding, R. A. (2010). Impaired voluntary neuromuscular activation limits muscle power in mobility-limited older adults. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, glq012.

Cappozzo, A., Felici, F., Figura, F. And Gazzani, F. (1985). Lumbar spine loading during the half-squat exercise. *Medicine and Science in Sports and Exercise*, *17*, 613.

Corbeil, P., Blouin, J., Begin, F., Nougier, V., & Teasedale, N. (2003). Perturbation of the postural control system induced by muscular fatigue. *Gait and Posture, 18*, 92-100.

Corbeil, P., Simoneau, M., Rancourt, D., Tremblay, A., & Teasdale, N. (2001). Increased risk for falling associated with obesity: mathematical modeling of postural control. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, *9*(2), 126-136.

Corrigan, D., & Bohannon, R. W. (2001). Relationship between knee extension force and stand-up performance in community-dwelling elderly women. *Archives of Physical Medicine and Rehabilitation*, *82*(12), 1666-1672.

D'Antona, G., Pellegrino, M.A., Carlizzi, C.N., & Bottinelli, R. (2007). Deterioration of contractile properties of muscles fibers in elderly subjects is modulated by the level of physical activity. *European Journal of Applied Physiology, 100*, 603-611.

Dehail, P., Bestaven, E., Muller, F., Mallet, A., Robert, B., Bourdel-Marchasson, I., & Petit, J. (2007). Kinematic and electromyographic analysis of rising from a chair during a "Sit-to-Walk" task in elderly subjects: role of strength. *Clinical Biomechanics*, *22*(10), 1096-1103.

DeLuca, C.J., LeForer, R.S., Mcute, M.P., & Xenakis, A.P. (1982). Behavior and human motor-units in different muscles during linearly varying contractions. *Journal of Physiology, 392*, 113-128.

Demura, S., & Yamada, T. (2007). Height of chair seat and movement characteristics in sit-to-stand by young and elderly adults. *Perceptual and motor skills*, *104*(1), 21-31.

Denton, F. T., & Spencer, B. G. (1998). *Economic costs of an aging population*. IESOPResearch Paper no. 32. Hamilton, ON: McMaster University.

Deschenes, M. R., Roby, M. A., Eason, M. K., & Harris, M. B. (2010). Remodeling of the neuromuscular junction precedes sarcopenia related alterations in myofibers. *Experimental Gerontology*, *45*(5), 389-393.

DeVita, P., & Hortobagyi, T. (2000). Age causes a redistribution of joint torques and powers during gait. *Journal of Applied Physiology*, *88*(5), 1804-1811.

DeVita, P., Helseth, J., & Hortobagyi, T. (2007). Muscles do more positive than negative work in human locomotion. *Journal of Experimental Biology*, *210*(19), 3361-3373.

Dimitrova, N. A., & Dimitrov, G. V. (2003). Interpretation of EMG changes with fatigue: facts, pitfalls, and fallacies. *Journal of Electromyography and Kinesiology*, *13*(1), 13-36.

Doherty, T. J. (2003). Invited review: aging and sarcopenia. *Journal of Applied Physiology*, *95*(4), 1717-1727.

Doherty, T.J., Vandervoort, A.A., Taylor, A.W., & Brown, W.F. (1993). Effects of motor unit losses on strength in older men and women. *Journal of Applied Physiology*, *74*(2), 868-874.

Doorenbosch, C.A.M., Harlaar, J., Roenbroeck, M.E.,& Lankhorst, G.J. (1994). Two strategies of transferring from sit-to-stand: The activation of monoarticular and biarticular muscles. *Journal of Biomechanics*, 27(11), 1299-1307.

Ebenbichler, G., Kollmitzer, J., Quittan, M., Uhl, F., Kirtley, C., & Fialka, V. (1998). EMG fatigue patterns accompanying isometric fatiguing knee-extensions are different in mono-and bi-articular muscles. *Electroencephalography and Clinical Neurophysiology/Electromyography and Motor Control*, *109*(3), 256-262.

Edström, L., & Kugelberg, E. R. I. C. (1968). Histochemical composition, distribution of fibres and fatiguability of single motor units. Anterior tibial muscle of the rat. *Journal of Neurology, Neurosurgery, and Psychiatry*, *31*(5), 424.

Enoka, R. (2002). The neuromechanical basis of human movement.

Enoka, R. M., Baudry, S., Rudroff, T., Farina, D., Klass, M., & Duchateau, J. (2011). Unraveling the neurophysiology of muscle fatigue. *Journal of Electromyography and Kinesiology*, *21*(2), 208-219.

Enoka, R. M., & Duchateau, J. (2008). Muscle fatigue: what, why and how it influences muscle function. *The Journal of Physiology*, *586*(1), 11-23.

Enoka, R. M., Christou, E. A., Hunter, S. K., Kornatz, K. W., Semmler, J. G., Taylor, A. M., & Tracy, B. L. (2003). Mechanisms that contribute to differences in motor performance between young and old adults. *Journal of Electromyography and Kinesiology*, *13*(1), 1-12.

Enoka, R.M, & Stuart, D.G. (1992). Neurobiology of muscle fatigue. *Journal of Applied Physiology*, *72*(*5*), 1631-1648.

Eriksrud, O., & Bohannon, R. W. (2003). Relationship of knee extension force to independence in sit-to-stand performance in patients receiving acute rehabilitation. *Physical Therapy*, *83*(6), 544-551.

Escamilla, R. F. (2001). Knee biomechanics of the dynamic squat exercise. *Medicine and Science in Sports and Exercise*, *33*(1), 127-141.

Farina, D., Holobar, A., Merletti, R., & Enoka, R. M. (2010). Decoding the neural drive to muscles from the surface electromyogram. *Clinical Neurophysiology*, *121*(10), 1616-1623.

Fitts, R. H. (2008). The cross-bridge cycle and skeletal muscle fatigue. *Journal of Applied Physiology*, *104*(2), 551-558.

Flanagan, S. P., & Salem, G. J. (2008). Lower extremity joint kinetic responses to external

Fogleman, M., & Smith, J.L (1995). The use of biomechanical measures in the investigation of changes in lifting strategies over extended periods. *International Journal of Industrial Ergonomics, 16*, 57-71.

Forestier, N., & Nougier, V. (1998). The effects of muscular fatigue on the coordination of a multijoint movement in human. *Neuroscience Letters*, *252*(3), 187-190.

Forestier, N., Teasdale, N., & Nougier, V. (2002). Alteration of the position sense at the ankle induced by muscular fatigue in humans. *Medicine and Science in Sports and Exercise*, *34*(1), 117-122.

Fortier, S., & Basset, F.A. (2012). The effects of exercise on limb proprioceptive signals. *Journal of Electromyography and Kinesiology, 22*, 795-802.

French, B., Thomas, L., Leathley, M., Sutton, C., McAdam, J., Forster, A., & Watkins, C. (2010). Does repetitive task training improve functional activity after stroke? A Cochrane systematic review and meta-analysis. *Journal of Rehabilitation Medicine*, *42*(1), 9-15.

Fry, A. C., Smith, J. C., & Schilling, B. K. (2003). Effect of knee position on hip and knee torques during the barbell squat. *The Journal of Strength & Conditioning Research*, *17*(4), 629-633.

Fuglevand, A. J., Winter, D. A., & Patla, A. E. (1993). Models of recruitment and rate coding organization in motor-unit pools. *Journal of neurophysiology*, *70*(6), 2470-2488.

Fujimoto, M., & Chou, L. S. (2012). Dynamic balance control during sit-to-stand movement: an examination with the center of mass acceleration. *Journal of biomechanics*, *45*(3), 543-548.

Fujita, E., Kanehisa, H., Yoshitake, Y. A. S. U. H. I. D. E., Fukunaga, T., & Nishizono, H. (2011). Association between knee extensor strength and EMG activities during squat movement. *Med Sci Sports Exerc*, *43*(12), 2328-2334.

Fuller, J. R., Lomond, K. V., Fung, J., & Côté, J. N. (2009). Posture-movement changes following repetitive motion-induced shoulder muscle fatigue. *Journal of Electromyography and Kinesiology*, *19*(6), 1043-1052.

Gandevia, S. C. (1992). Some central and peripheral factors affecting human motoneuronal output in neuromuscular fatigue. *Sports Medicine*, *13*(2), 93-98.

Gandevia, S. C., Allen, G. M., Butler, J. E., & Taylor, J. L. (1996). Supraspinal factors in human muscle fatigue: evidence for suboptimal output from the motor cortex. *The Journal of physiology*, *490*(Pt 2), 529.

Gannon, J., Doran, P., Kirwan, A., & Ohlendieck, K. (2009). Drastic increase of myosin light chain MLC-2 in senescent skeletal muscle indicates fast-to-slow fibre transition in sarcopenia of old age. *European Journal of Cell Biology*, *88*(11), 685-700.

Gantchev, G. N., & Dimitrova, D. M. (1996). Anticipatory postural adjustments associated with arm movements during balancing on unstable support surface. *International Journal of Psychophysiology*, *22*(1), 117-122.

Ge, W. (1998). Age-related differences in body segment movement during perturbed stance in humans. *Clinical BiomechanicS, 13*, 300-307.

Gill, J. M., & Mainous III, A. G. (1998). The role of provider continuity in preventing hospitalizations. *Archives of Family Medicine, 7*(4), 352.

Godin, G., & Shepard, R.J. (1997). Godin and Leisure-Time Exercise Questionnaire. *Medicine and Science in Sports and Exercise. 29 (June Supplements)*, S36-S38.

González-Izal, M., Malanda, A., Gorostiaga, E., & Izquierdo, M. (2012). Electromyographic models to assess muscle fatigue. *Journal of Electromyography and Kinesiology*, *22*(4), 501-512.

Goulart, F. R. D. P., & Valls-Solé, J. (1999). Patterned electromyographic activity in the sit-to-stand movement. *Clinical Neurophysiology*, *110*(9), 1634-1640.

Gregoire, L., Veeger, H. E., Huijing, P. A., & van Ingen, S. G. (1984). Role of mono-and biarticular muscles in explosive movements. *International Journal of Sports Medicine*, *5*(6), 301-305.

Greve, C., Zijlstra, W., Hortobágyi, T., & Bongers, R. M. (2013). Not all is lost: old adults retain flexibility in motor behaviour during sit-to-stand. *PloS one*, *8*(10), e77760.

Gribble, P. A., & Hertel, J. (2004). Effect of hip and ankle muscle fatigue on unipedal postural control. *Journal of Electromyography and Kinesiology*, *14*(6), 641-646.

Gribble, P. A., & Hertel, J. (2004). Effect of lower-extremity muscle fatigue on postural control. *Archives of Physical Medicine and Rehabilitation*, *85*(4), 589-592.

Gross, M. M., Stevenson, P. J., Charette, S. L., Pyka, G., & Marcus, R. (1998). Effect of muscle strength and movement speed on the biomechanics of rising from a chair in healthy elderly and young women. *Gait & Posture*, *8*(3), 175-185.

Hakkinen, K., Kallinen, M., Izquierdo, M., Jokelainen, K., Lassila, H., Malikia, E., Kraemer, W.J., Newton, R.U., & Alen, M. (1998). Changes in agonist-antagonist EMG, muscle CSA, and force during strength training in middle-aged and older people. *Journal of Applied Physiology*, *84*(4), 1341-1349.

Helbostad, J.L., Leirfall, S., Moe-Nilssen, R., & Sletvold, O. (2007). Physical fatigue affects gait characteristics in older persons. *Journal of Gerontology: MEDICAL SCIENCES, 62(9),* 1010-1015.

Henneman, E. (1985). The size-principle: a deterministic output emerges from a set of probabilistic connections. *Journal of Experimental Biology*, *115*(1), 105-112.

Hernandez, M.E., Ashton-Miller, J.A., & Alexander, N.B. (2012). Age-related changes in speed and accuracy during rapid targeted center of pressure movements near the posterior limits of base of support. *Clinical Biomechanics, 27*, 910-916.

Horak, F. B., & Nashner, L. M. (1986). Central programming of postural movements: adaptation to altered support-surface configurations. *Journal of Neurophysiology*, *55*(6), 1369-1381.

Horak, F. B., Shupert, C. L., & Mirka, A. (1989). Components of postural dyscontrol in the elderly: a review. *Neurobiology of Aging*, *10*(6), 727-738.

Hortobágyi, T., & DeVita, P. (2000). Muscle pre-and coactivity during downward stepping are associated with leg stiffness in aging. *Journal of Electromyography and Kinesiology*, *10*(2), 117-126.

Hortobágyi, T., Mizelle, C., Beam, S., & DeVita, P. (2003). Old adults perform activities of daily living near their maximal capabilities. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *58*(5), M453-M460.

Hortobagyi, T., Solnbik, S., Rider, P., Steinweg, K., Helseth, J., & DeVita, P. (2009). Interaction between age and gait velocity in the amplitude and timing of antagonist muscle coactivation. *Gait and Posture, 29(*4), 558-564.

Huffenus, A. F., Amarantini, D., & Forestier, N. (2006). Effects of distal and proximal arm muscles fatigue on multi-joint movement organization. *Experimental Brain Research*, *170*(4), 438-447.

Hug, F. (2011). Can muscle coordination be precisely studied by surface electromyography?. *Journal of Electromyography and Kinesiology*, *21*(1), 1-12.

Hughes, M. A., Myers, B. S., & Schenkman, M. L. (1996). The role of strength in rising from a chair in the functionally impaired elderly. *Journal of Biomechanics*, *29*(12), 1509-1513.

Hughes, M. A., Weiner, D. K., Schenkman, M. L., Long, R. M., & Studenski, S. A. (1994). Chair rise strategies in the elderly. *Clinical Biomechanics*, *9*(3), 187-192.

Hunter, S.K., Critchlow, A., & Enoka, R.M. (2005) Muscle endurance is greater for old men compared with strength-matched young men. *Journal of Applied Physiology, 99*, 890-897.

Hurley, M.V., Rees, I., & Newham, D.J. (1998). Quadriceps function, proprioceptive acuity and functional performance in healthy young, middle aged and elderly subjects. *Age and Aging, 27,* 155-162.

Hrysomallis, C., McLaughlin, P., & Goodman, C. (2006). Relationship between static and dynamic balance tests among elite Australian Footballers. *Journal of Science and Medicine in Sport*, *9*(4), 288-291.

Ikeda, S., Tsumura, H., & Torisu, T. (2005). Age-related quadriceps-dominant muscle atrophy and incident radiographic knee osteoarthritis. *Journal of Orthopaedic Science*, *10,* 121-126.

Ikezoe, T., Mori, N., Nakamura, M., & Ichihashi, N. (2011). Age-related muscle atrophy in the lower extremities and daily physical activity in elderly women. *Archives of Gerontology and Geriatrics*, *53*(2), e153-e157.

Ikezoe, T., Mori, N., Nakamura, M., & Ichihashi, N. (2011). Atrophy of the lower limbs in elderly women: Is it related to walking ability? *European Journal of Applied Physiology*, *111*, 989-995.

Isear Jr, J. A., Erickson, J. C., & Worrell, T. W. (1997). EMG analysis of lower extremity muscle recruitment patterns during an unloaded squat. *Medicine and Science in Sports and Exercise*, *29*(4), 532-539.

Jacobs, R., Bobbert, M. F., & van Ingen Schenau, G. J. (1996). Mechanical output from individual muscles during explosive leg extensions: the role of biarticular muscles. *Journal of Biomechanics*, *29*(4), 513-523.

Jakobi, J. M., & Rice, C. L. (2002). Voluntary muscle activation varies with age and muscle group. *Journal of Applied Physiology*, *93*(2), 457-462.

Janssen, W. G., Bussmann, H. B., & Stam, H. J. (2002). Determinants of the sit-to-stand movement: a review. *Physical Therapy*, *82*(9), 866-879.

Jeka, J., Oie, K. S., & Kiemel, T. (2000). Multisensory information for human postural control: integrating touch and vision. *Experimental Brain Research*, *134*(1), 107-125.

Jones, C. J., Rikli, R. E., & Beam, W. C. (1999). A 30-s chair-stand test as a measure of lower body strength in community-residing older adults. *Research Quarterly for Exercise and Sport*, *70*(2), 113-119.

Kallio, J., Sogaard, K., Avela, J., Komi, P., Selanne, H., & Linnamo, V. (2012). Age-related decreases in motor unit discharge rate and force control during isometric plantar flexion. *Journal of Electromyography and Kinesiology, 22*(6), 983-989.

Kanekar, N., & Aruin, A. S. (2014). Aging and balance control in response to external perturbations: role of anticipatory and compensatory postural mechanisms. *Age*, *36*(3), 1067-1077.

Keenan, K. G., Farina, D., Maluf, K. S., Merletti, R., & Enoka, R. M. (2005). Influence of amplitude cancellation on the simulated surface electromyogram. *Journal of Applied Physiology*, *98*(1), 120-131.

Kellis, E. (1999). The effects of fatigue on the resultant joint moment, agonist and antagonist electromyographic activity at different angles during dynamic knee extension efforts. *Journal of Electromyography and Kinesiology*, *9*(3), 191-199.

Kennedy, A., Guevel, A., & Sveistrup, H. (2012). Impact of ankle muscle fatigue and recovery on the anticipatory postural adjustments to externally initiated perturbations in dynamic postural control. *Experimental Brain Research, 223*, 553-562.

Kennedy, A., Hug, F., Bilodeau, M., Sveistrup, H., & Guével, A. (2011). Neuromuscular fatigue induced by alternating isometric contractions of the ankle plantar and dorsiflexors. *Journal of Electromyography and Kinesiology*, *21*(3), 471-477.

Kent-Braun, J.A., & Ng, A.V. (1999). Specific strength and voluntary muscle activation in young and elderly women and men. *Journal of Applied Physiology, 87*, 22-29.

Kent-Braun, J.A., Ng, A.V., Doyle, J.W., & Towse, T. (2002). Human skeletal muscle responses vary with age and gender during fatigue due to incremental isometric exercise. *Journal of Applied Physiology*, *93*, 1813-1823.

Kepple, T. M., Siegel, K. L., & Stanhope, S. J. (1997). Relative contributions of the lower extremity joint moments to forward progression and support during gait. *Gait & Posture*, *6*(1), 1-8.

Kernell, D., Donselaar, Y., & Eerbeek, O. (1987). Effects of physiological amounts of high-and low-rate chronic stimulation on fast-twitch muscle of the cat hindlimb. II. Endurance-related properties. *Journal of Neurophysiology*, *58*(3), 614-627.

Khemlani, M. M., Carr, J. H., & Crosbie, W. J. (1999). Muscle synergies and joint linkages in sit-to-stand under two initial foot positions. *Clinical Biomechanics*, *14*(4), 236-246.

Klitgard, H., Mantoni, M., Schiaffino, S., Ausoni, S., Gorza, L., Laurent-Winter, C., Schnohr, P., & Saltin, B. (1990). Function, morphology and protein expression of ageing skeletal muscle: A cross-sectional study of elderly men with different training backgrounds. *Acta Physiol Scand*, *140*, 41-54.

Kouzaki, M., Shinohara, M., & Fukunaga, T. (1999). Non-uniform mechanical activity of quadriceps muscle during fatigue by repeated maximal voluntary contraction in humans. *European Journal of Applied Physiology and Occupational Physiology*, *80*(1), 9-15.

Laidlaw, D. H., Bilodeau, M., & Enoka, R. M. (2000). Steadiness is reduced and motor unit discharge is more variable in old adults. *Muscle & Nerve*, *23*(4), 600-612.

Laporte, A., Nauenberg, E., & Shen, L. (2008). Aging, social capital, and health care utilization in Canada. *Health Economics, Policy and Law*, *3*(04), 393-411.

Larson, E. B., & Bruce, R. A. (1986). Exercise and aging. *Annals of Internal Medicine*, *105*(5), 783-785.

Larsen, A. H., Puggaard, L., Hämäläinen, U., & Aagaard, P. (2008). Comparison of ground reaction forces and antagonist muscle coactivation during stair walking with ageing. *Journal of Electromyography and Kinesiology*, *18*(4), 568-580.

Lattanzio, P. J., & Petrella, R. J. (1998). Knee proprioception: a review of mechanisms, measurements, and implications of muscular fatigue. *Orthopedics*, *21*(4), 463-471.

Lazaro, M., Gonzalez, A., Latorre, G., Fernandez, C., & Ribera, J. M. (2011). Postural stability in the elderly: Fallers versus non-fallers. *European Geriatric Medicine*, *2*(1), 1-5.

Liao, H. F., Liu, Y. C., Liu, W. Y., & Lin, Y. T. (2007). Effectiveness of loaded sit-to-stand resistance exercise for children with mild spastic diplegia: A randomized clinical trial. *Archives of Physical Medicine and Rehabilitation, 88*(1), 25-31.

Lieber, R. L., Fridén, J. O., Hargens, A. R., & Feringa, E. R. (1986). Long-term effects of spinal cord transection on fast and slow rat skeletal muscle: II. Morphometric properties. *Experimental Neurology*, *91*(3), 435-448.

Leiber, R.L. (1992). *Skeletal muscle structure and function: Implications for rehabilitation and sports medicine*. Baltimore, Maryland: Williams and Wilkins.

Lieber, R. L. (2002). *Skeletal muscle structure, function, and plasticity*. Lippincott Williams & Wilkins.

LeRoche, D.P., Cromin, K.A., Greenleaf, B, & Croce, R.V. (2010). Rapid torque development in older female fallers and non-fallers: A comparison across lower-extremity muscles. *Journal of Electromyography and Kinesiology, 20*, 482-488.

List, R., Gülay, T., Stoop, M., & Lorenzetti, S. (2013). Kinematics of the trunk and the lower extremities during restricted and unrestricted squats. *The Journal of Strength & Conditioning Research*, *27*(6), 1529-1538.

Lundin, T. M., Feuerbach, J. W., & Grabiner, M. D. (1993). Effect of Plantar Flexor and Dorsiflexor Fatigue on Unilateral Postural Control. *Journal of Applied Biomechanics*, *9*(3).

Lynch, N.A., Metler, E.J., & Lindle, R.S. (1999). Muscle quality. I. Age-associated differences between arm and leg muscle group. *Journal of Applied Physiology*, *86(*1), 188-194.

Mademli, L., Arampatzis, A., & Karamanidis, K. (2008). Dynamic stability control in forward falls: Postural corrections after muscle fatigue in young and older adults. *European Journal of Applied Physiology, 103*, 295-306.

Madhavan, S., & Shields, R. K. (2005). Influence of age on dynamic position sense: evidence using a sequential movement task. *Experimental brain research*, *164*(1), 18-28.

Mahler, H., Epp, J., Franklin, W., & Kickbusch, I. (1986). Ottawa charter for health promotion. *Health Promotion International, 1*(4), 405.

Manini, T., Visser, M., Won-Park, S., Patel, K.V., Stratmeyer, E.S., Chen, H., Goodpaster, B., DeRekeneire, N., Newman, A.B., Simonsick, E.M., Kritchevsky, S.B., Ryder, K., Schwarts, A.V., & Harris, T.B. (2007). Knee extension strength cutpoints for maintaining mobility. *JAGS, 55*, 451-457.

Mathiyakom, W., McNitt-Gray, J. L., Requejo, P., & Costa, K. (2005). Modifying center of mass trajectory during sit-to-stand tasks redistributes the mechanical demand across the lower extremity joints. *Clinical Biomechanics, 20*(1), 105-111.

McGibbon, C. A., & Krebs, D. E. (2001). Age-related changes in lower trunk coordination and energy transfer during gait. *Journal of Neurophysiology*, *85*(5), 1923-1931.

McGibbon, C. A., & Krebs, D. E. (2004). Discriminating age and disability effects in locomotion: neuromuscular adaptations in musculoskeletal pathology. *Journal of Applied Physiology*, *96*(1), 149-160.

McGibbon, C. A., Krebs, D. E., & Puniello, M. S. (2001). Mechanical energy analysis identifies compensatory strategies in disabled elders' gait. *Journal of Biomechanics*, *34*(4), 481-490.

McGibbon, C. A., Puniello, M. S., & Krebs, D. E. (2001). Mechanical energy transfer during gait in relation to strength impairment and pathology in elderly women. *Clinical Biomechanics*, *16*(4), 324-333.

Milner-Brown, H. S., Stein, R. B., & Yemm, R. (1973). The orderly recruitment of human motor units during voluntary isometric contractions. *The Journal of Physiology*, *230*(2), 359.

Missenard, O., Mottet, D., & Perrey, S. (2008). The role of co-contraction in the impairment of movement accuracy with fatigue. *Experimental Brain Research, 185*, 151-156.

Missenard, O., Mottet, D., & Perrey, S. (2009). Factors responsible for force steadiness impairment with fatigue. *Muscle & Nerve*, *40*(6), 1019-1032.

Moolyk, A. N., Carey, J. P., & Chiu, L. Z. (2013). Characteristics of lower extremity work during the impact phase of jumping and weightlifting. *The Journal of Strength & Conditioning Research*, *27*(12), 3225-3232.

Morita, M., Takamura, N., Kusano, Y., Abe, Y., Moji, K., Takemoto, T. I., & Aoyagi, K. (2005). Relationship between falls and physical performance measures among community-dwelling elderly women in Japan. *Aging Clinical and Experimental Research*, *17*(3), 211-216.

Mourey, F. Grishin, A., d'Athis, P., Pozzo, T., & Stapley, P. (2000). Standing up from a chair as a dynamic equilibrium task: A comparison between young and elderly subjects. *Journal of Gerontology: Biological Sciences, 55A* (9), B425-B431.

Muhlberg, W., & Sieber, C. (2004). Sarcopenia and frailty in geriatric patients: Implications or training and prevention. *Z Gerontol Geriat,* 37, 2-8.

Nagai, K., Yamada, M., Mori, S., Tanaka, B., Yemura, K., Aoyama, T., Ichihashi, N., & Tsuboyama, T. (2013). Effect of the muscle coactivation during quiet standing on dynamic postural control in older adults. *Arch Gerontol Geriatr, 56*(1), 129-133.

Nigg, B. M., & Herzog, W. (2007). *Biomechanics of the musculo-skeletal system*. John Wiley & Sons.

Nocera, J.R., Buckley, T., Waddell, D., Okun, M.S., & Hass, C. (2010). Knee extensor strength, dynamic stability, and functional ambulation: Are they related in Parkinson's disease? *Arch Phys Med Rehabil, 91*, 589-595.

Norris, A. H., Shock, N. W., & Wagman, I. H. (1953). Age changes in the maximum conduction velocity of motor fibers of human ulnar nerves. *Journal of Applied Physiology*, *5*(10), 589-593.

Ochoa, J., & Mair, W. G. P. (1969). The normal sural nerve in man. *Acta neuropathologica*, *13*(3), 217-239.

Oie, K. S., Kiemel, T., & Jeka, J. J. (2002). Multisensory fusion: simultaneous re-weighting of vision and touch for the control of human posture. *Cognitive Brain Research*, *14*(1), 164-176.

Pai, Y. C., Chang, H. J., Chang, R. W., Sinacore, J. M., & Lewis, J. L. (1994). Alteration in multijoint dynamics in patients with bilateral knee osteoarthritis. *Arthritis & Rheumatism*, *37*(9), 1297-1304.

Paillard, T. (2012). Effects of general and local fatigue on postural control: a review. *Neuroscience & Biobehavioral Reviews*, *36*(1), 162-176.

Papa, E., & Cappozzo, A. (2000). Sit-to-stand motor strategies investigated in able-bodied young and elderly subjects. *Journal of Biomechanics*, *33*(9), 1113-1122.

Patsika, G., Kellis, E., & Amiridis, I. G. (2011). Neuromuscular efficiency during sit to stand movement in women with knee osteoarthritis. *Journal of Electromyography and Kinesiology*, *21*(5), 689-694.

Perry, M. C., Carville, S. F., Smith, I. C. H., Rutherford, O. M., & Newham, D. J. (2007). Strength, power output and symmetry of leg muscles: effect of age and history of falling. *European Journal of Applied Physiology*, *100*(5), 553-561.

Petrella, J. K., Kim, J. S., Tuggle, S. C., Hall, S. R., & Bamman, M. M. (2005). Age differences in knee extension power, contractile velocity, and fatigability. *Journal of Applied Physiology*, *98*(1), 211-220.

Pollack, A. S., Durward, B. R., Rowe, P. J., & Paul, J. P. (2000). What is balance? *Clinical Rehabilitation, 14*(4), 402-406.

Prado, J.M., Mauro, C.M., & Duarte, M. (2011). Age-related difference on weight transfer during unconstrained standing. *Gait and Posture, 33*(1), 93-97.

Psek, J. A., & Cafarelli, E. (1993). Behavior of coactive muscles during fatigue. *Journal of Applied Physiology, 74*(1), 170-175.

Public Health Agency of Canada (2014). Healthy Aging in Canada: *A New Vision, A Vital Investment—A Discussion Brie*f

Puniello, M. S., McGibbon, C. A., & Krebs, D. E. (2001). Lifting strategy and stability in strength-impaired elders. *Spine*, *26*(7), 731-737.

Purkiss, S. B., & Robertson, D. G. E. (2003). Methods for calculating internal mechanical work: comparison using elite runners. *Gait & Posture*, *18*(3), 143-149.

Rao, G., Amarantini, D., & Berton, E. (2009). Influence of additional load on the moments of the agonist and antagonist muscle groups at the knee joint during closed chain exercise. *Journal of Electromyography and Kinesiology*, *19*(3), 459-466.

Reid, K. F., & Fielding, R. A. (2012). Skeletal muscle power: a critical determinant of physical functioning in older adults. *Exercise and Sport Sciences Reviews*, *40*(1), 4.

Reisman, D.S., Scholz, J.P., & Schoner, G. (2002). Coordination underlying the control of wholebody momentum during sit-to-stand. *Gait and Posture, 15,* 45-55.

Renshaw, D., Bice, M. R., Cassidy, C., & Eldridge, J. A. (2010). A Comparison of Three Computer-based Methods Used to Determine EMG Signal Amplitude. *International Journal of Exercise Science*, *3*(1).

Ribeira, F., Mota, J. and Oliveira, J. (2007). Effects of exercise-induced fatigue on position sense of the knee in elderly. *European Journal of Applied Physiology, 99(*4), 379-385.

Riley, P. O., Krebs, D. E., & Popat, R. A. (1997). Biomechanical analysis of failed sit-to-stand. *Rehabilitation Engineering, IEEE Transactions on*, *5*(4), 353-359.

Robertson, G., Caldwell, G., Hamill, J., Kamen, G., & Whittlesey, S. (2004). *Research Methods in Biomechanics*. Human Kinetics.

Robertson, D. G., Wilson, J. M., & St Pierre, T. A. (2008). Lower extremity muscle functions during full squats. *Journal of Applied Biomechanics*, *24*(4), 333-9.

Robertson, G., & Winter, D. A. (1980). Mechanical energy generation, absorption and transfer amongst segments during walking. *Journal of Biomechanics*, *13*(10), 845-854.

Roebroeck, M. E., Doorenbosch, C. A. M., Harlaar, J., Jacobs, R., & Lankhorst, G. J. (1994). Biomechanics and muscular activity during sit-to-stand transfer. *Clinical Biomechanics*, *9*(4), 235-244.

Roos, M.R., Rice, C.L., & Vandervoort, A.A. (1997). Age-related changes in motor unit function. M*uscle and Nerve*, *20*, 679-690.

Rothwell, J. C. (1998). *Control of human voluntary movement*. Springer Science & Business Media.

Ruhe, A., Fejer, R., & Walker, B. (2010). The test–retest reliability of centre of pressure measures in bipedal static task conditions–a systematic review of the literature. *Gait & Posture*, *32*(4), 436-445.

Ryushi, T., Kumagai, K., Hayase, H., Abe, T., Shibuya, K., & Ono, A. (2000). Effect of resistive knee extension training on postural control measures in middle ages and elderly persons. *Journal of Physiol Anthropol*, *19*(3), 143-149.

Sahlin, K., Tonkonogi, M., & Söderlund, K. (1998). Energy supply and muscle fatigue in humans. *Acta Physiologica Scandinavica*, *162*(3), 261-266.

Sandrey, M. A., & Kent, T. E. (2008). The effects of eversion fatigue on frontal plane joint position sense in the ankle. *Journal of Sport Rehabilitation*, *17*(3), 257.

Sato, A., Sato, Y., & Suzuki, H. (1985). Aging effects on conduction velocities of myelinated and unmyelinated fibers of peripheral nerves. *Neuroscience Letters*, *53*(1), 15-20.

Savelberg, H. H. C. M., Fastenau, A., Willems, P. J. B., & Meijer, K. (2007). The load/capacity ratio affects the sit-to-stand movement strategy. *Clinical Biomechanics*, *22*(7), 805-812.

Scarborough, D. M., McGibbon, C. A., & Krebs, D. E. (2007). Chair rise strategies in older adults with functional limitations. *Journal of Rehabilitation Research and Development*, *44*(1), 33.

Schenkman, M., Hughes, M. A., Samsa, G., & Studenski, S. (1996). The relative importance of strength and balance in chair rise by functionally impaired older individuals. *Journal of the American Geriatrics Society*, *44*(12), 1441-1446.

Schenkman, M., Riley, P. O., & Pieper, C. (1996). Sit to stand from progressively lower seat heights—alterations in angular velocity. *Clinical Biomechanics*, *11*(3), 153-158.

Schultz, A.B., Alexander, N.B., & Ashton-Miller, J.A. (1992). Biomechanical analysis of rising from a chair. *Journal of Biomechanics, 25*(12), 1383-1391.

Scott, W., Stevens, J., & Binder–Macleod, S. A. (2001). Human skeletal muscle fiber type classifications. *Physical therapy*, *81*(11), 1810-1816.

Shaffer, S. W., & Harrison, A. L. (2007). Aging of the somatosensory system: a translational perspective. *Physical Therapy*, *87*(2), 193-207.

Shepherd, R. B., & Gentile, A. M. (1994). Sit-to-stand: functional relationship between upper body and lower limb segments. *Human Movement Science*, *13*(6), 817-840.

Sheppard, R.J. (2002). *Gender, physical activity, and aging*. New York, NY: CRC Press.

Shumway-Cook, A., & Woollacott, M. H. (2001). Aging and postural control. *Motor Control: Theory and Practical Applications, 2nd Ed. Baltimore: Williams & Wilkins*, 222-247.

Sibella, F., Galli, M., Romei, M., Montesano, A., & Crivellini, M. (2003). Biomechanical analysis of sit-to-stand movement in normal and obese subjects. *Clinical Biomechanics*, *18*(8), 745-750.

Silverthorn, D. U. (2007). *Human physiology: an integrated approach. Benjamin Cummings, San Francisco*.

Skinner, H. B., Barrack, R. L., & COOK, S. D. (1984). Age-related decline in proprioception. *Clinical orthopaedics and related research*, *184*, 208-211.

Skinner, H. B., Wyatt, M. P., Hodgdon, J. A., Conard, D. W., & Barrack, R. L. (1986). Effect of fatigue on joint position sense of the knee. *Journal of Orthopaedic Research*, *4*(1), 112-118.

Søgaard, K., Gandevia, S. C., Todd, G., Petersen, N. T., & Taylor, J. L. (2006). The effect of sustained low-intensity contractions on supraspinal fatigue in human elbow flexor muscles. *The Journal of Physiology*, *573*(2), 511-523.

Sparto, P.J., Parnianpour, M., Reinsel, T.E., & Simon, S. (1997a). The effect of fatigue on multijoint kinematics and load sharing during a repetitive lifting test. *Spine, 22*, 2647-2654.

Sparto, P.J., Parnianpour, M., Reinsel, T.E., & Simon, S. (1997b). The effect of fatigue on multi-joint kinematics, coordination, and postural stability during a repetitive lifting test. *Journal of Orthopaedic and Sports Physical Therapy Association, 25(*1), 3-12.

Special Senate Committee on Aging (SSCA). (2009). *Canada's aging population: Seizing the opportunity* [online] – [Cited December 3rd, 2011] - - Retrieved from http://www.parl.gc.ca/Content/SEN/Committee/402/agei/rep/AgingFinalReport-e.pdf

Stapley, P., Pozzo, T., & Grishin, A. (1998). The role of anticipatory postural adjustments during whole body forward reaching movements. *Neuroreport*, *9*(3), 395-401.

Sturnieks, D.L., St. George, R., & Lord, S.R. (2008). Balance disorder in the elderly [Troubles de l'equilibre chez les personnes agees]. *Clinical Neurophysiology, 38*, 467-478.

Tanaka, M., & Watanabe, Y. (2012). Supraspinal regulation of physical fatigue. *Neuroscience & Biobehavioral Reviews*, *36*(1), 727-734.

Tiedmann, A., Shimada, H., Sherrington, C., Murray, S., & Lord, S. (2008). The comparative ability of eight functional mobility tests for predicting falls in community-dwelling older people. *Age and Ageing*, *37*, 430-435.

Toebers, M.J.P., Hoozemans, M.J.M., Furrer, R., Dekker, J., & van Dieen, J.H. (2012). Local and dynamic stability and variability of gait are associated with fall history in elderly subjects. *Gait and Posture, 36*, 527-531.

Toussaint, H. M., de Winter, A. F., de Haas, Y., de Looze, M. P., Van Dieën, J. H., & Kingma, I. (1995). Flexion relaxation during lifting: implications for torque production by muscle activity and tissue strain at the lumbo-sacral joint. *Journal of Biomechanics*, *28*(2), 199-210.

Toussaint, H. M., Van Baar, C. E., Van Langen, P. P., De Looze, M. P., & Van Dieen, J. H. (1992). Coordination of the leg muscles in backlift and leglift. *Journal of Biomechanics*, *25*(11), 1279-1289.

Tucker, M.G., Kavanagh, J.J., Barrett, R.S., & Morrison, S. (2008). Age-related differences in postural reaction time and coordination during voluntary sway movements. *Human Movement Science*, *27*(5), 728-737.

Van der Heijden, M. M., Meijer, K., Willems, P. J., & Savelberg, H. H. (2009). Muscles limiting the sit-to-stand movement: an experimental simulation of muscle weakness. *Gait & Posture*, *30*(1), 110-114.

Vandervoort, A. A. (2002). Aging of the human neuromuscular system. *Muscle & Nerve*, *25*(1), 17-25.

van Dieën, J. H., Hoozemans, M. J., & Toussaint, H. M. (1999). Stoop or squat: a review of biomechanical studies on lifting technique. *Clinical Biomechanics*, *14*(10), 685-696.

Van Roie, E., Verschueren, S. M., Boonen, S., Bogaerts, A., Kennis, E., Coudyzer, W., & Delecluse, C. (2011). Force-velocity characteristics of the knee extensors: an indication of the risk for physical frailty in elderly women. *Archives of Physical Medicine and Rehabilitation, 92*(11), 1827-1832.

Van Zandwijk, J. P., Bobbert, M. F., Munneke, M. A. R. T. E. N., & Pas, P. I. E. T. E. R. (2000). Control of maximal and submaximal vertical jumps. *Medicine and science in sports and exercise*, *32*(2), 477-485.

Vigotsky, A. D., Harper, E. N., Ryan, D. R., & Contreras, B. (2015). Effects of load on good morning kinematics and EMG activity. *PeerJ*, *3*, e708.

Voronov, A.V. (2004). The roles of monoarticular and biarticular muscles of the lower limbs in terrestrial locomotion. *Human Physiology, 30,*476-484.

Vuillerme, N., Anziani, B., & Rougier, P. (2007). Trunk extensor muscles fatigue affects undisturbed postural control in young healthy adults. *Clinical Biomechanics*, *22*(5), 489-494.

Vuillerme, N., Danion, F., Forestier, N., & Nougier, V. (2002). Postural sway under muscle vibration and muscle fatigue in humans. *Neuroscience Letters*, *333*(2), 131-135.

Vuillerme, N., & Pinsault, N. (2007). Re-weighting of somatosensory inputs from the foot and the ankle for controlling posture during quiet standing following trunk extensor muscles fatigue. *Experimental Brain Research, 183*(3), 323-327.

Wagman, I. H., & Lesse, H. (1952). Maximum conduction velocities of motor fibers of ulnar nerve in human subjects of various ages and sizes. *Journal of Neurophysiology*, *15*(3), 235-244.

Walshe, A. D., Wilson, G. J., & Ettema, G. J. (1998). Stretch-shorten cycle compared with isometric preload: contributions to enhanced muscular performance. *Journal of Applied Physiology*, *84*(1), 97-106.

Watanabe, K., Kouzaki, M., Merletti, R., Fujibayashi, M., & Maritan, T. (2011). Spatial EMG potential distribution pattern of vastus lateralis muscle during isometric knee extension in young and elderly men. *Journal of Electromyography and Kinesiology*.

Williams, C., & Ratel, S. (Eds.). (2009). *Human muscle fatigue*. Routledge.

Willott, J.F. (1999). *Neurogerontology: Aging of the nervous system.*New York, NY: Springer Publishing Company Inc.

Winter, D. A. (1980). Overall principle of lower limb support during stance phase of gait. *Journal of Biomechanics*, *13*(11), 923-927.

Winter, D. A. (2009). *Biomechanics and motor control of human movement*. John Wiley & Sons.

Winter, D. A., & Eng, P. (1995). Kinetics: our window into the goals and strategies of the central nervous system. *Behavioural Brain Research*, *67*(2), 111-120.

Winter, D. A., Patla, A. E., Rietdyk, S., & Ishac, M. G. (2001). Ankle muscle stiffness in the control of balance during quiet standing. *Journal of Neurophysiology*, *85*(6), 2630-2633.

Wretenberg, P., & Arborelius, U. P. (1994). Power and work produced in different leg muscle groups when rising from a chair. *European Journal of Applied Physiology and Occupational Physiology*, *68*(5), 413-417.

Yang, J. F., & Winter, D. A. (1984). Electromyographic amplitude normalization methods: improving their sensitivity as diagnostic tools in gait analysis. *Arch Phys Med Rehabil*, *65*(9), 517-521.

Yim-Chiplis, P. K., & Talbot, L. A. (2000). Defining and measuring balance in adults. *Biological Research for Nursing*, *1*(4), 321-331.

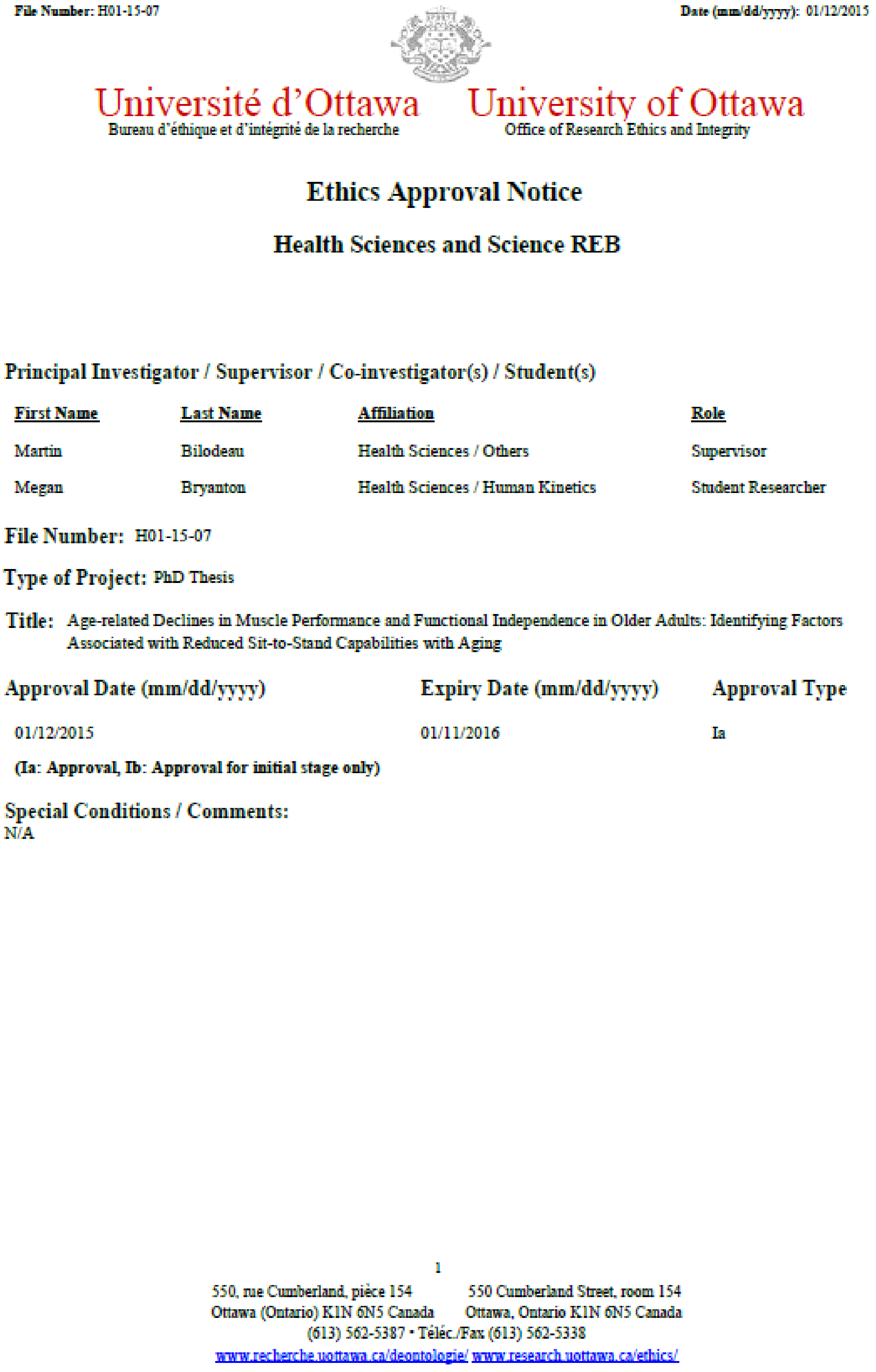
Yoon, T., De-Lap, B. S., Griffith, E. E., & Hunter, S. K. (2008). Age-related muscle fatigue after a low-force fatiguing contraction is explained by central fatigue. *Muscle & Nerve*, *37*(4), 457-466.

Yoshioka, S., Nagano, A., Himeno, R., & Fukashiro, S. (2007). Computation of the kinematics and the minimum peak joint moments of sit-to-stand movements. *Biomed Eng Online*, *6*(1), 26.

Zatsiorsky, V. M. (2002). *Kinetics of human motion*. Human Kinetics.

APPENDIX A

INSTITUTIONAL REVIEW BOARD DOCUMENTATION



File Number: H01-15-07

Date (mm/dd/yyyy): 01/12/2015

Université d'Ottawa University of Ottawa
Bureau d'éthique et d'intégrité de la recherche Office of Research Ethics and Integrity

Ethics Approval Notice

Health Sciences and Science REB

Principal Investigator / Supervisor / Co-investigator(s) / Student(s)

First Name	Last Name	Affiliation	Role
Martin	Bilodeau	Health Sciences / Others	Supervisor
Megan	Bryanton	Health Sciences / Human Kinetics	Student Researcher

File Number: H01-15-07

Type of Project: PhD Thesis

Title: Age-related Declines in Muscle Performance and Functional Independence in Older Adults: Identifying Factors Associated with Reduced Sit-to-Stand Capabilities with Aging

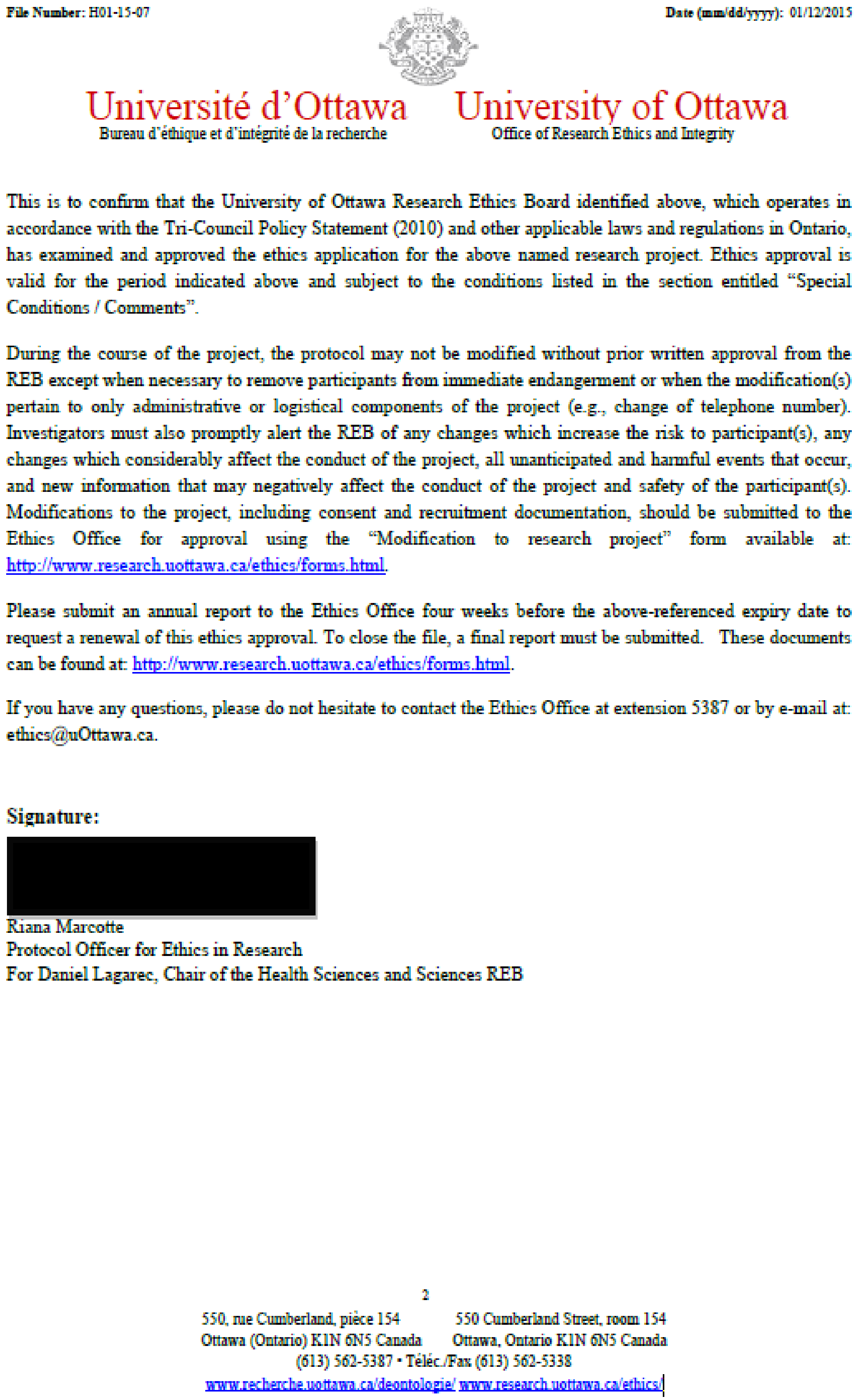
Approval Date (mm/dd/yyyy)	Expiry Date (mm/dd/yyyy)	Approval Type
01/12/2015	01/11/2016	Ia

(Ia: Approval, Ib: Approval for initial stage only)

Special Conditions / Comments:
N/A

1

550, rue Cumberland, pièce 154 550 Cumberland Street, room 154
Ottawa (Ontario) K1N 6N5 Canada Ottawa, Ontario K1N 6N5 Canada
(613) 562-5387 • Téléc./Fax (613) 562-5338
www.recherche.uottawa.ca/deontologie/ www.research.uottawa.ca/ethics/



File Number: H01-15-07 **Date (mm/dd/yyyy):** 01/12/2015

Université d'Ottawa University of Ottawa
Bureau d'éthique et d'intégrité de la recherche Office of Research Ethics and Integrity

This is to confirm that the University of Ottawa Research Ethics Board identified above, which operates in accordance with the Tri-Council Policy Statement (2010) and other applicable laws and regulations in Ontario, has examined and approved the ethics application for the above named research project. Ethics approval is valid for the period indicated above and subject to the conditions listed in the section entitled "Special Conditions / Comments".

During the course of the project, the protocol may not be modified without prior written approval from the REB except when necessary to remove participants from immediate endangerment or when the modification(s) pertain to only administrative or logistical components of the project (e.g., change of telephone number). Investigators must also promptly alert the REB of any changes which increase the risk to participant(s), any changes which considerably affect the conduct of the project, all unanticipated and harmful events that occur, and new information that may negatively affect the conduct of the project and safety of the participant(s). Modifications to the project, including consent and recruitment documentation, should be submitted to the Ethics Office for approval using the "Modification to research project" form available at: http://www.research.uottawa.ca/ethics/forms.html.

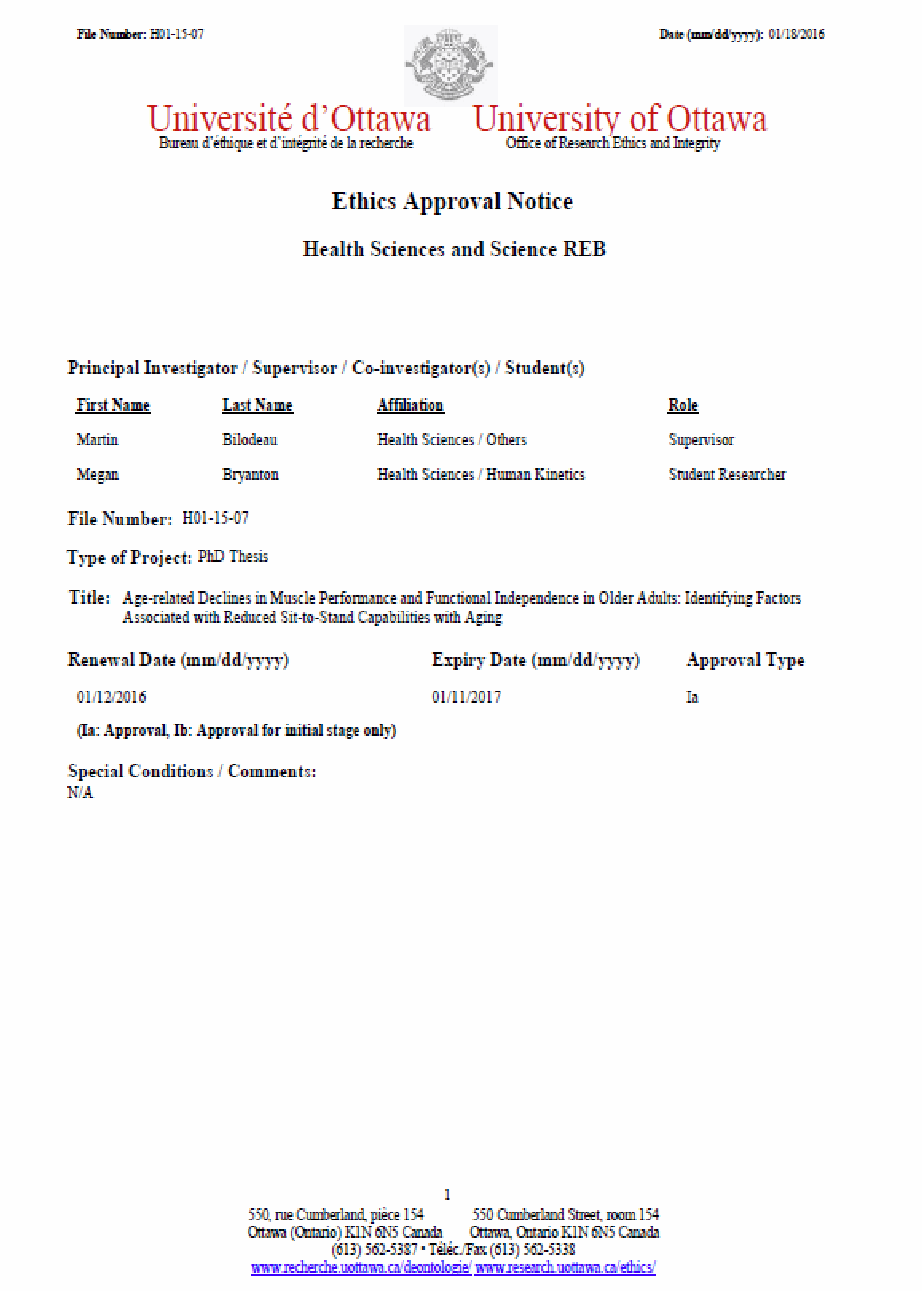
Please submit an annual report to the Ethics Office four weeks before the above-referenced expiry date to request a renewal of this ethics approval. To close the file, a final report must be submitted. These documents can be found at: http://www.research.uottawa.ca/ethics/forms.html.

If you have any questions, please do not hesitate to contact the Ethics Office at extension 5387 or by e-mail at: ethics@uOttawa.ca.

Signature:

[redacted]

Riana Marcotte
Protocol Officer for Ethics in Research
For Daniel Lagarec, Chair of the Health Sciences and Sciences REB



File Number: H01-15-07 **Date (mm/dd/yyyy):** 01/18/2016

Université d'Ottawa University of Ottawa
Bureau d'éthique et d'intégrité de la recherche Office of Research Ethics and Integrity

Ethics Approval Notice

Health Sciences and Science REB

Principal Investigator / Supervisor / Co-investigator(s) / Student(s)

First Name	Last Name	Affiliation	Role
Martin	Bilodeau	Health Sciences / Others	Supervisor
Megan	Bryanton	Health Sciences / Human Kinetics	Student Researcher

File Number: H01-15-07

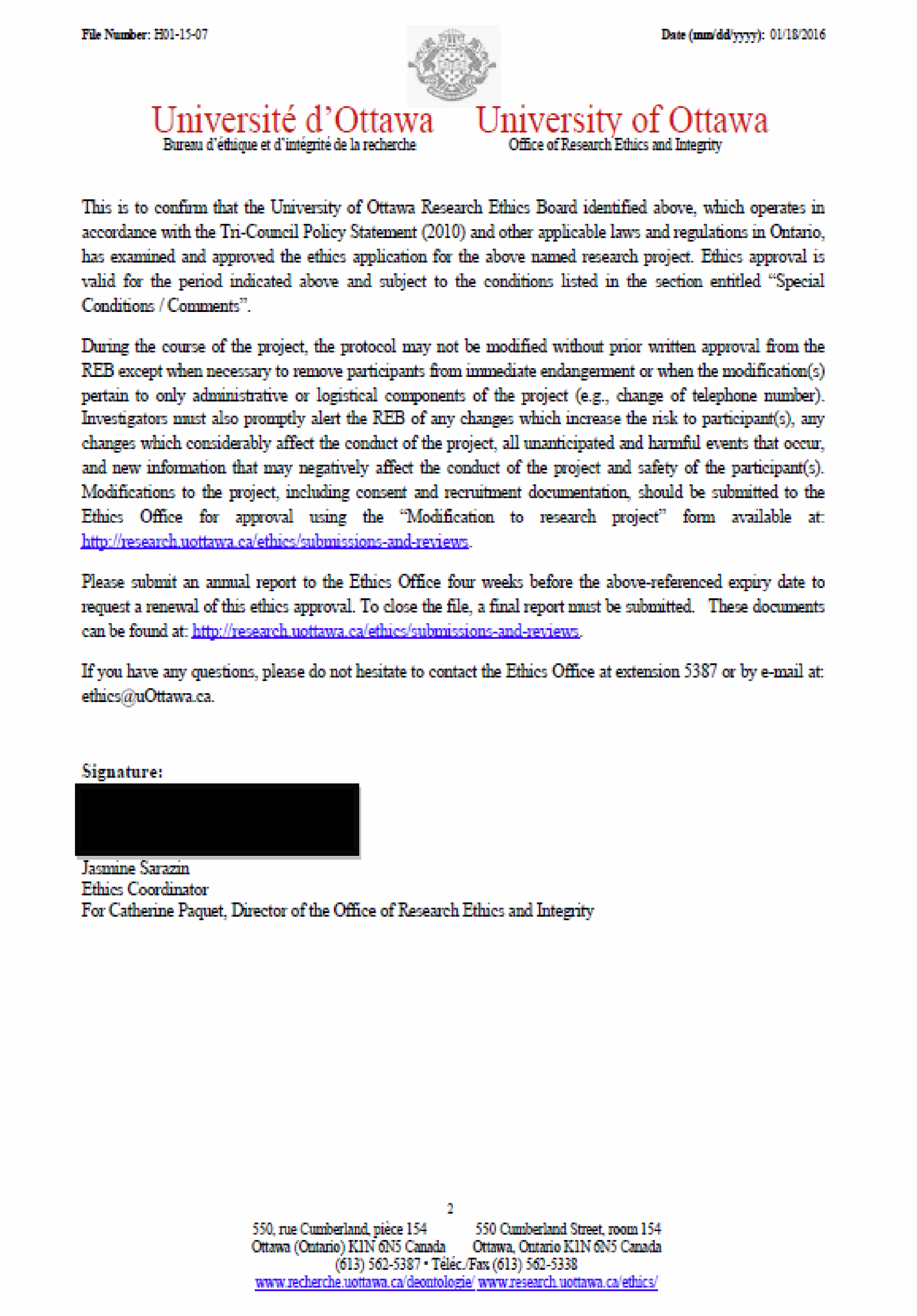
Type of Project: PhD Thesis

Title: Age-related Declines in Muscle Performance and Functional Independence in Older Adults: Identifying Factors Associated with Reduced Sit-to-Stand Capabilities with Aging

Renewal Date (mm/dd/yyyy)	Expiry Date (mm/dd/yyyy)	Approval Type
01/12/2016	01/11/2017	Ia

(Ia: Approval, Ib: Approval for initial stage only)

Special Conditions / Comments:
N/A



File Number: H01-15-07

Date (mm/dd/yyyy): 01/18/2016

Université d'Ottawa
Bureau d'éthique et d'intégrité de la recherche

University of Ottawa
Office of Research Ethics and Integrity

This is to confirm that the University of Ottawa Research Ethics Board identified above, which operates in accordance with the Tri-Council Policy Statement (2010) and other applicable laws and regulations in Ontario, has examined and approved the ethics application for the above named research project. Ethics approval is valid for the period indicated above and subject to the conditions listed in the section entitled "Special Conditions / Comments".

During the course of the project, the protocol may not be modified without prior written approval from the REB except when necessary to remove participants from immediate endangerment or when the modification(s) pertain to only administrative or logistical components of the project (e.g., change of telephone number). Investigators must also promptly alert the REB of any changes which increase the risk to participant(s), any changes which considerably affect the conduct of the project, all unanticipated and harmful events that occur, and new information that may negatively affect the conduct of the project and safety of the participant(s). Modifications to the project, including consent and recruitment documentation, should be submitted to the Ethics Office for approval using the "Modification to research project" form available at: http://research.uottawa.ca/ethics/submissions-and-reviews.

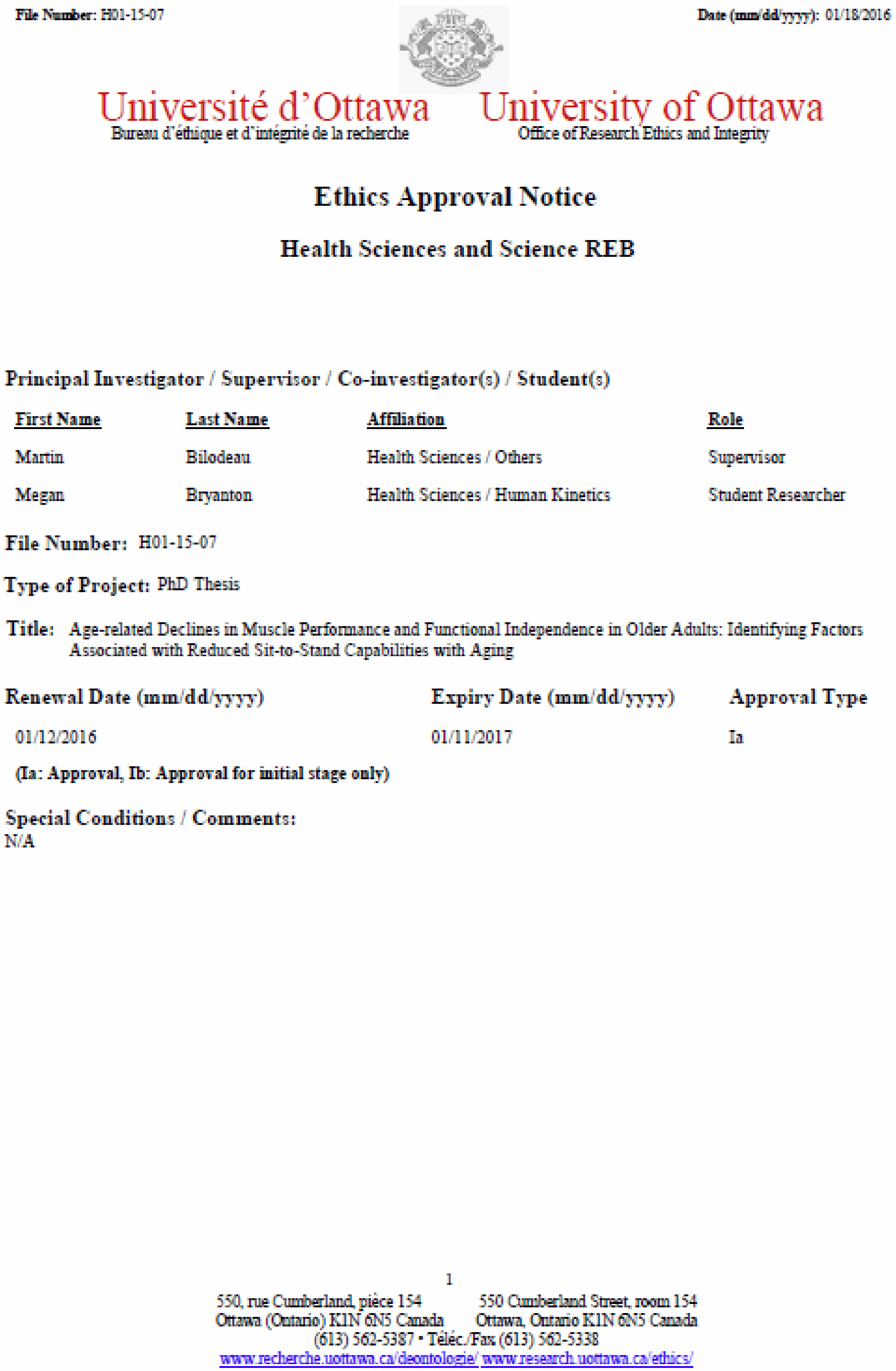
Please submit an annual report to the Ethics Office four weeks before the above-referenced expiry date to request a renewal of this ethics approval. To close the file, a final report must be submitted. These documents can be found at: http://research.uottawa.ca/ethics/submissions-and-reviews.

If you have any questions, please do not hesitate to contact the Ethics Office at extension 5387 or by e-mail at: ethics@uOttawa.ca.

Signature:

[redacted]

Jasmine Sarazin
Ethics Coordinator
For Catherine Paquet, Director of the Office of Research Ethics and Integrity



File Number: H01-15-07 **Date (mm/dd/yyyy):** 01/18/2016

Université d'Ottawa University of Ottawa
Bureau d'éthique et d'intégrité de la recherche Office of Research Ethics and Integrity

Ethics Approval Notice

Health Sciences and Science REB

Principal Investigator / Supervisor / Co-investigator(s) / Student(s)

First Name	Last Name	Affiliation	Role
Martin	Bilodeau	Health Sciences / Others	Supervisor
Megan	Bryanton	Health Sciences / Human Kinetics	Student Researcher

File Number: H01-15-07

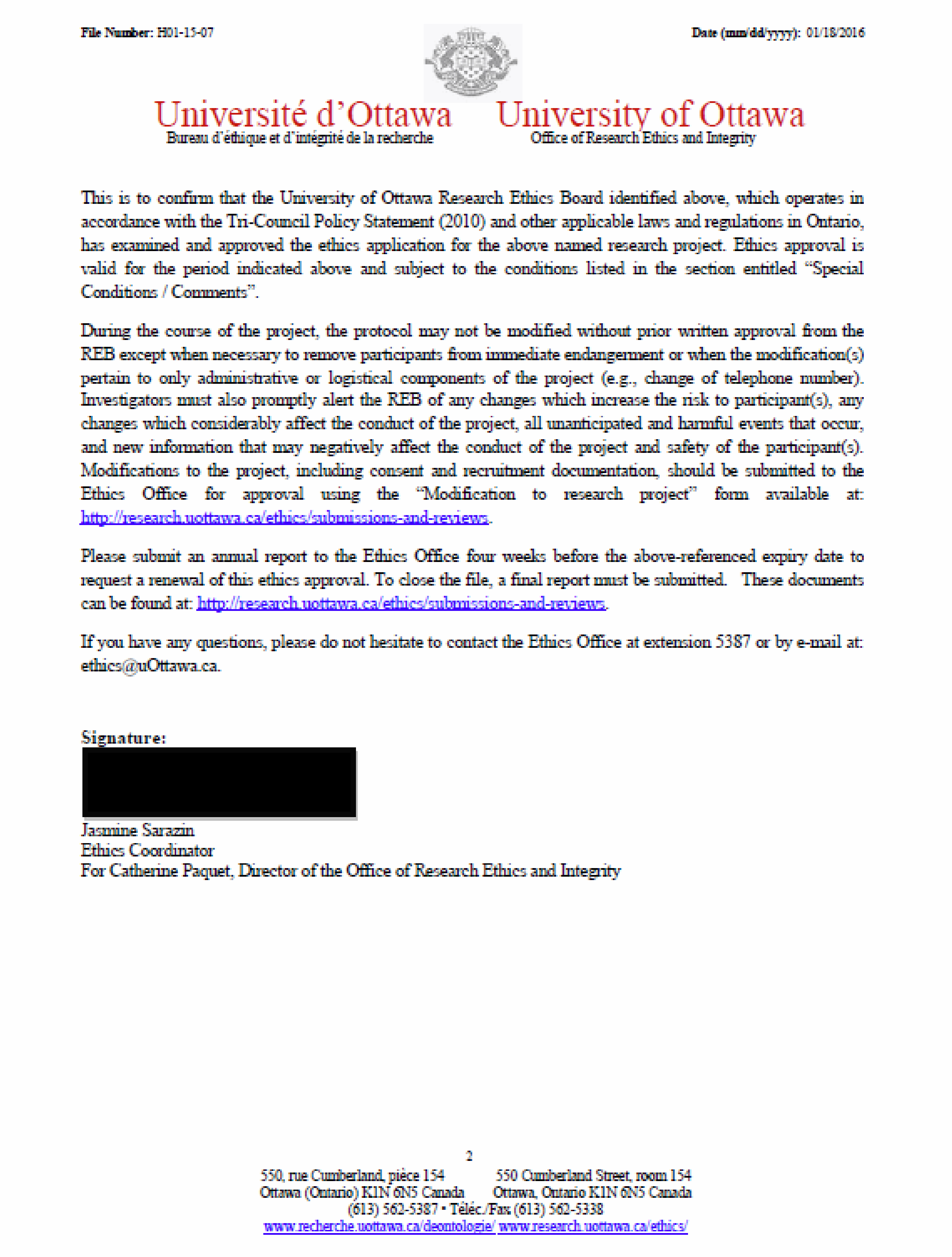
Type of Project: PhD Thesis

Title: Age-related Declines in Muscle Performance and Functional Independence in Older Adults: Identifying Factors Associated with Reduced Sit-to-Stand Capabilities with Aging

Renewal Date (mm/dd/yyyy)	Expiry Date (mm/dd/yyyy)	Approval Type
01/12/2016	01/11/2017	Ia

(Ia: Approval, Ib: Approval for initial stage only)

Special Conditions / Comments:
N/A



File Number: H01-15-07

Date (mm/dd/yyyy): 01/18/2016

Université d'Ottawa
Bureau d'éthique et d'intégrité de la recherche

University of Ottawa
Office of Research Ethics and Integrity

This is to confirm that the University of Ottawa Research Ethics Board identified above, which operates in accordance with the Tri-Council Policy Statement (2010) and other applicable laws and regulations in Ontario, has examined and approved the ethics application for the above named research project. Ethics approval is valid for the period indicated above and subject to the conditions listed in the section entitled "Special Conditions / Comments".

During the course of the project, the protocol may not be modified without prior written approval from the REB except when necessary to remove participants from immediate endangerment or when the modification(s) pertain to only administrative or logistical components of the project (e.g., change of telephone number). Investigators must also promptly alert the REB of any changes which increase the risk to participant(s), any changes which considerably affect the conduct of the project, all unanticipated and harmful events that occur, and new information that may negatively affect the conduct of the project and safety of the participant(s). Modifications to the project, including consent and recruitment documentation, should be submitted to the Ethics Office for approval using the "Modification to research project" form available at: http://research.uottawa.ca/ethics/submissions-and-reviews.

Please submit an annual report to the Ethics Office four weeks before the above-referenced expiry date to request a renewal of this ethics approval. To close the file, a final report must be submitted. These documents can be found at: http://research.uottawa.ca/ethics/submissions-and-reviews.

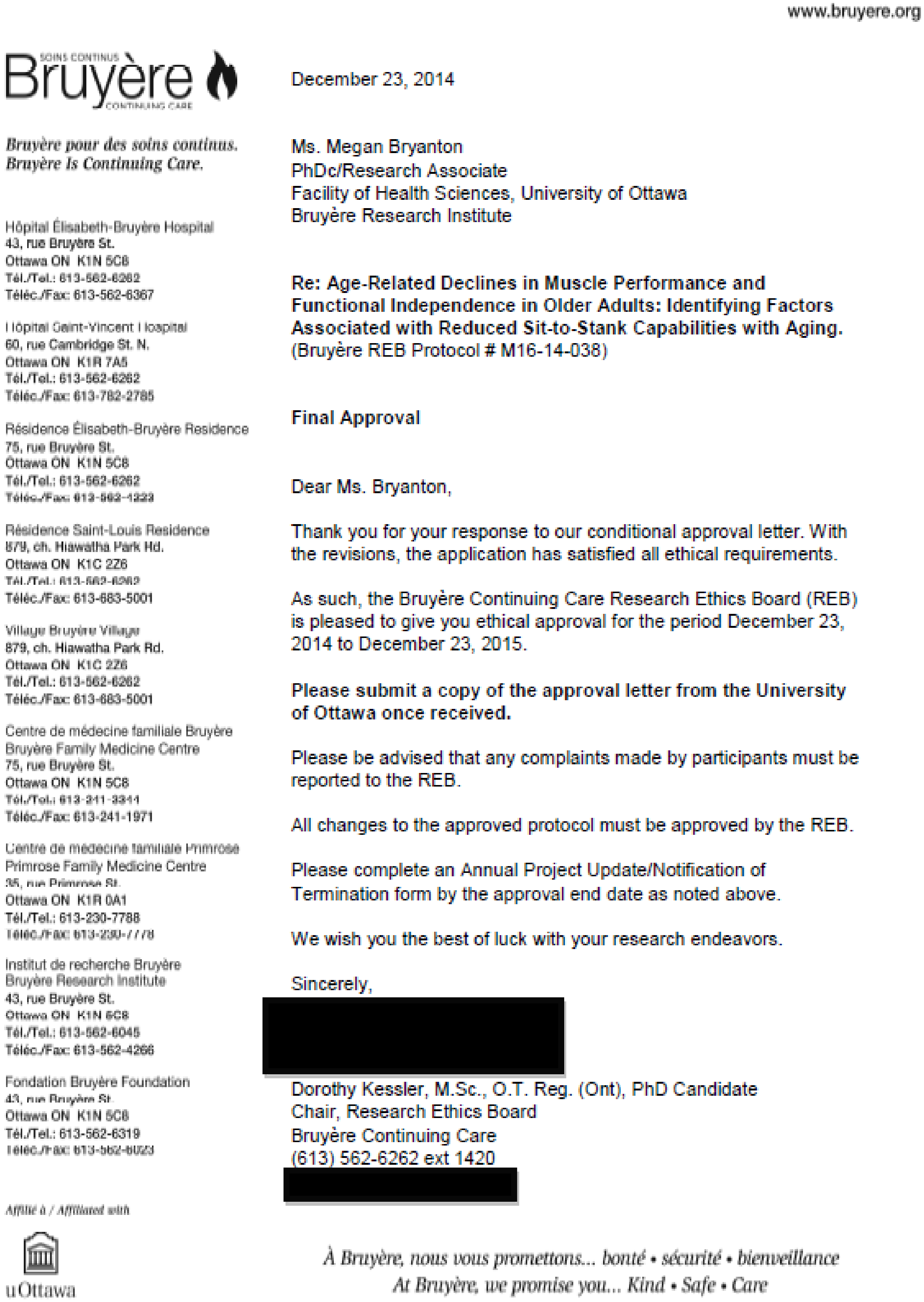
If you have any questions, please do not hesitate to contact the Ethics Office at extension 5387 or by e-mail at: ethics@uOttawa.ca.

Signature:

[redacted]

Jasmine Sarazin
Ethics Coordinator
For Catherine Paquet, Director of the Office of Research Ethics and Integrity

550, rue Cumberland, pièce 154 550 Cumberland Street, room 154
Ottawa (Ontario) K1N 6N5 Canada Ottawa, Ontario K1N 6N5 Canada
(613) 562-5387 • Téléc./Fax (613) 562-5338
www.recherche.uottawa.ca/deontologie/ www.research.uottawa.ca/ethics/



www.bruyere.org

Soins continus Bruyère Continuing Care

Bruyère pour des soins continus.
Bruyère Is Continuing Care.

Hôpital Élisabeth-Bruyère Hospital
43, rue Bruyère St.
Ottawa ON K1N 5C8
Tél./Tel.: 613-562-6262
Téléc./Fax: 613-562-6367

Hôpital Saint-Vincent Hospital
60, rue Cambridge St. N.
Ottawa ON K1R 7A5
Tél./Tel.: 613-562-6262
Téléc./Fax: 613-782-2785

Résidence Élisabeth-Bruyère Residence
75, rue Bruyère St.
Ottawa ON K1N 5C8
Tél./Tel.: 613-562-6262
Téléc./Fax: 613-562-4223

Résidence Saint-Louis Residence
879, ch. Hiawatha Park Rd.
Ottawa ON K1C 2Z6
Tél./Tel.: 613-562-6262
Téléc./Fax: 613-683-5001

Village Bruyère Village
879, ch. Hiawatha Park Rd.
Ottawa ON K1C 2Z6
Tél./Tel.: 613-562-6262
Téléc./Fax: 613-683-5001

Centre de médecine familiale Bruyère
Bruyère Family Medicine Centre
75, rue Bruyère St.
Ottawa ON K1N 5C8
Tél./Tel.: 613-241-3344
Téléc./Fax: 613-241-1971

Centre de médecine familiale Primrose
Primrose Family Medicine Centre
35, rue Primrose St.
Ottawa ON K1R 0A1
Tél./Tel.: 613-230-7788
Téléc./Fax: 613-230-7778

Institut de recherche Bruyère
Bruyère Research Institute
43, rue Bruyère St.
Ottawa ON K1N 5C8
Tél./Tel.: 613-562-6045
Téléc./Fax: 613-562-4266

Fondation Bruyère Foundation
43, rue Bruyère St.
Ottawa ON K1N 5C8
Tél./Tel.: 613-562-6319
Téléc./Fax: 613-562-6023

Affilié à / Affiliated with

uOttawa

December 23, 2014

Ms. Megan Bryanton
PhDc/Research Associate
Facility of Health Sciences, University of Ottawa
Bruyère Research Institute

Re: Age-Related Declines in Muscle Performance and Functional Independence in Older Adults: Identifying Factors Associated with Reduced Sit-to-Stank Capabilities with Aging.
(Bruyère REB Protocol # M16-14-038)

Final Approval

Dear Ms. Bryanton,

Thank you for your response to our conditional approval letter. With the revisions, the application has satisfied all ethical requirements.

As such, the Bruyère Continuing Care Research Ethics Board (REB) is pleased to give you ethical approval for the period December 23, 2014 to December 23, 2015.

Please submit a copy of the approval letter from the University of Ottawa once received.

Please be advised that any complaints made by participants must be reported to the REB.

All changes to the approved protocol must be approved by the REB.

Please complete an Annual Project Update/Notification of Termination form by the approval end date as noted above.

We wish you the best of luck with your research endeavors.

Sincerely,

[redacted]

Dorothy Kessler, M.Sc., O.T. Reg. (Ont), PhD Candidate
Chair, Research Ethics Board
Bruyère Continuing Care
(613) 562-6262 ext 1420

[redacted]

À Bruyère, nous vous promettons... bonté • sécurité • bienveillance
At Bruyère, we promise you... Kind • Safe • Care

www.bruyere.org

SOINS CONTINUS Bruyère CONTINUING CARE

Bruyère pour des soins continus.
Bruyère Is Continuing Care.

Hôpital Élisabeth-Bruyère Hospital
43, rue Bruyère St.
Ottawa ON K1N 5C8
Tél./Tel.: 613-562-6262
Téléc./Fax: 613-562-6367

Hôpital Saint-Vincent Hospital
60, rue Cambridge St. N.
Ottawa ON K1R 7A5
Tél./Tel.: 613-562-6262
Téléc./Fax: 613-782-2785

Résidence Élisabeth-Bruyère Residence
75, rue Bruyère St.
Ottawa ON K1N 5C8
Tél./Tel.: 613-562-6262
Téléc./Fax: 613-562-4229

Résidence Saint-Louis Residence
879, ch. Hiawatha Park Rd.
Ottawa ON K1C 2Z6
Tél./Tel.: 613-562-6262
Téléc./Fax: 613-683-5001

Village Bruyère Village
879, ch. Hiawatha Park Rd.
Ottawa ON K1C 2Z6
Tél./Tel.: 613-562-6262
Téléc./Fax: 613-683-5001

Centre de médecine familiale Bruyère
Bruyère Family Medicine Centre
75, rue Bruyère St.
Ottawa ON K1N 5C8
Tél./Tel.: 613-241-3344
Téléc./Fax: 613-241-1971

Centre de médecine familiale Primrose
Primrose Family Medicine Centre
35, rue Primrose St.
Ottawa ON K1R 0A1
Tél./Tel.: 613-230-7788
Téléc./Fax: 613-230-7778

Institut de recherche Bruyère
Bruyère Research Institute
43, rue Bruyère St.
Ottawa ON K1N 5C8
Tél./Tel.: 613-562-6045
Téléc./Fax: 613-562-4266

Fondation Bruyère Foundation
43, rue Bruyère St.
Ottawa ON K1N 5C8
Tél./Tel.: 613-562-6319
Téléc./Fax: 613-562-6023

Affilié à / Affiliated with

uOttawa

October 20, 2015

Ms. Megan Bryanton
PhDc/Research Associate
Facility of Health Sciences, University of Ottawa
Bruyère Research Institute

Re: Age-Related Declines in Muscle Performance and Functional Independence in Older Adults: Identifying Factors Associated with Reduced Sit-to-Stank Capabilities with Aging.
(Bruyère REB Protocol # M16-14-038)

Amendment Approval

Dear Ms. Bryanton,

Thank you for submitting a request for approval of the item listed below for the above-named study.

☑ Approval to broaden the older adult participation inclusion criteria age range to 60 to 85 years

The following documents have been approved:

- Information Letter and Consent Form – Received October 16, 2015
- Recruitment Poster – Received October 16, 2015

The information received has been reviewed and I hereby give approval on behalf of the REB.

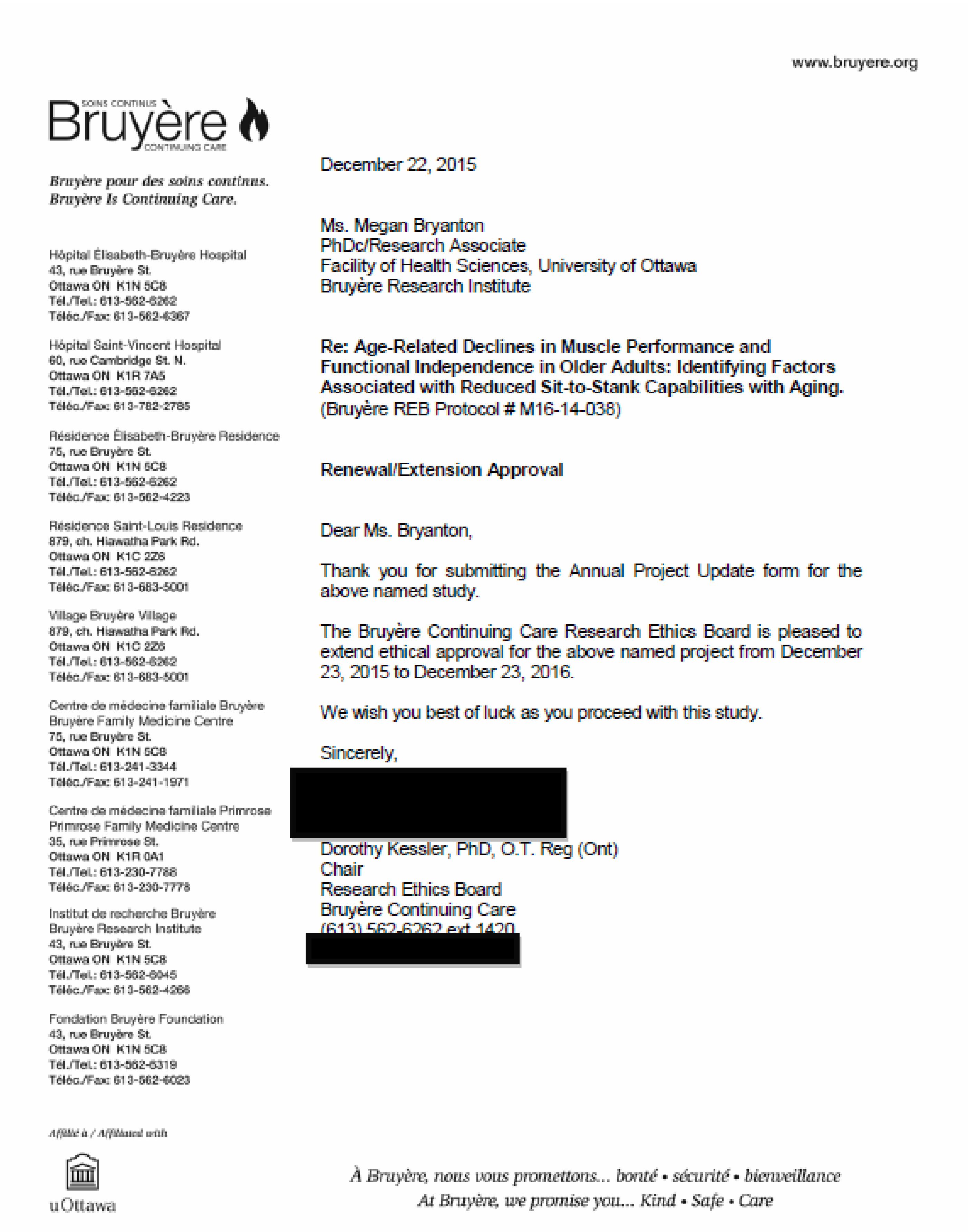
Please note that any future changes to the protocol must be submitted to the Research Ethics Board for approval.

Sincerely,

[redacted]

Dorothy Kessler, PhD, O.T. Reg (Ont)
Chair
Research Ethics Board
Bruyère Continuing Care
(613) 562-6262 ext 1420
[redacted]

À Bruyère, nous vous promettons... bonté • sécurité • bienveillance
At Bruyère, we promise you... Kind • Safe • Care



www.bruyere.org

SOINS CONTINUS
Bruyère
CONTINUING CARE

Bruyère pour des soins continus.
Bruyère Is Continuing Care.

Hôpital Élisabeth-Bruyère Hospital
43, rue Bruyère St.
Ottawa ON K1N 5C8
Tél./Tel.: 613-562-6262
Téléc./Fax: 613-562-6367

Hôpital Saint-Vincent Hospital
60, rue Cambridge St. N.
Ottawa ON K1R 7A5
Tél./Tel.: 613-562-6262
Téléc./Fax: 613-782-2785

Résidence Élisabeth-Bruyère Residence
75, rue Bruyère St.
Ottawa ON K1N 5C8
Tél./Tel.: 613-562-6262
Téléc./Fax: 613-562-4223

Résidence Saint-Louis Residence
879, ch. Hiawatha Park Rd.
Ottawa ON K1C 2Z6
Tél./Tel.: 613-562-6262
Téléc./Fax: 613-683-5001

Village Bruyère Village
879, ch. Hiawatha Park Rd.
Ottawa ON K1C 2Z6
Tél./Tel.: 613-562-6262
Téléc./Fax: 613-683-5001

Centre de médecine familiale Bruyère
Bruyère Family Medicine Centre
75, rue Bruyère St.
Ottawa ON K1N 5C8
Tél./Tel.: 613-241-3344
Téléc./Fax: 613-241-1971

Centre de médecine familiale Primrose
Primrose Family Medicine Centre
35, rue Primrose St.
Ottawa ON K1R 0A1
Tél./Tel.: 613-230-7788
Téléc./Fax: 613-230-7778

Institut de recherche Bruyère
Bruyère Research Institute
43, rue Bruyère St.
Ottawa ON K1N 5C8
Tél./Tel.: 613-562-6045
Téléc./Fax: 613-562-4266

Fondation Bruyère Foundation
43, rue Bruyère St.
Ottawa ON K1N 5C8
Tél./Tel.: 613-562-6319
Téléc./Fax: 613-562-6023

Affilié à / Affiliated with

uOttawa

December 22, 2015

Ms. Megan Bryanton
PhDc/Research Associate
Facility of Health Sciences, University of Ottawa
Bruyère Research Institute

Re: Age-Related Declines in Muscle Performance and Functional Independence in Older Adults: Identifying Factors Associated with Reduced Sit-to-Stank Capabilities with Aging.
(Bruyère REB Protocol # M16-14-038)

Renewal/Extension Approval

Dear Ms. Bryanton,

Thank you for submitting the Annual Project Update form for the above named study.

The Bruyère Continuing Care Research Ethics Board is pleased to extend ethical approval for the above named project from December 23, 2015 to December 23, 2016.

We wish you best of luck as you proceed with this study.

Sincerely,

[redacted]

Dorothy Kessler, PhD, O.T. Reg (Ont)
Chair
Research Ethics Board
Bruyère Continuing Care
[redacted]

À Bruyère, nous vous promettons... bonté • sécurité • bienveillance
At Bruyère, we promise you... Kind • Safe • Care

www.bruyere.org/ireb
www.bruyere.org/ebri

Soins continus
Bruyère
Continuing Care

Institut de recherche
Élisabeth-Bruyère
Research Institute
Affilié à l'Université d'Ottawa
Affiliated with the University of Ottawa

INFORMATION LETTER AND CONSENT FORM

Adresse postale
Mailing Address
43, rue Bruyère St.
Ottawa ON K1N 5C8

Bureau central
Corporate Office
Tél./Tel.: 613-562-6045
Téléc./Fax: 613-562-4266

Éducation et recherche en soins palliatifs
Palliative Care Education and Research
Tél./Tel.: 613-562-6262 poste/ext. 4008
Téléc./Fax: 613-562-6371

Centre de recherche C.T. Lamont
en soins de santé primaires
C.T. Lamont Primary Health Care
Research Centre
Tél./Tel.: 613-562-6262 poste/ext. 1354
Téléc./Fax: 613-562-4266

Recherche sur la santé des personnes âgées
Health of the Elderly Research
Tél./Tel.: 613-562-6045
Téléc./Fax: 613-562-4266

Age-related Declines in Muscle Performance and Functional Independence in Older Adults: Identifying Factors Associated with Reduced Sit-to-Stand Capabilities with Aging

INVESTIGATORS

Megan Bryanton, Ph.Dc. **(Principal Investigator)**
Bruyère Research Institute & School of Human Kinetics,
Faculty of Health Sciences, University of Ottawa
(613) 562-6262, ext. 1419
[redacted]

Martin Bilodeau, Ph.D., PT. **(Co-Investigator)**
Bruyère Research Institute & School of Rehabilitation
Sciences, Faculty of Health Sciences, University of Ottawa
(613) 562-6262, ext. 1358

Invitation to participate: I am invited to take part in the study of the research team lead by Megan Bryanton. I am a healthy adult between 18 and 35 years or 60 and 85 years of age.

Purpose of the study: The purpose of this research study is to look at leg muscle fatigue when standing from a chair in young and older adults.

Participation: If I participate, I will come for two separate visits. Each visit will last about 60 and 90 minutes.

A. The first visit will be at the Elizabeth Bruyère Hospital. I will first fill out two forms, one about my health and the other about my physical activity level. Then the following will be done in this order:

1) First, sensors will be taped on the skin of my leg. Some of the sensors will be placed above and below my knee, and on the side of my buttock. I will be asked to push my leg as hard as I can against the hands of a researcher in six different directions.

2) I will stand up from a seated position when told by the researcher, and I will pause before sitting back down. I will be asked to do the same thing two more times.

3) I will be asked to sit in a device used to measure leg strength. My legs will be strapped to prevent unwanted movements. I will be asked to push as hard as I can up to five times with both my legs.

4) My leg muscles will be fatigued using the device in step 3. I will have to push with my legs at 50% or 80% of my maximum strength, until I can no longer continue.

5) I will repeat step 2.

B. The second visit will take part at the University of Ottawa's Lees Campus. The following will be done in this order:

1) First, sensors will be taped to the skin of my leg. I will have to push as hard as I can with my leg against the hands of a researcher in six different directions.

2) Small reflective markers will also be taped to my skin to measure my body movement using a camera system.

3) I will be asked to stand up and sit down from a chair to the beat of a metronome. I will do this until I can no longer keep the pace or am too tired to continue. I will then be asked to push as hard as I

can with my leg against the hands of a researcher as I did at the start of this visit.

Benefits: I understand that I may not benefit from taking part in this study. However, other people might benefit because of the knowledge gained from this study.

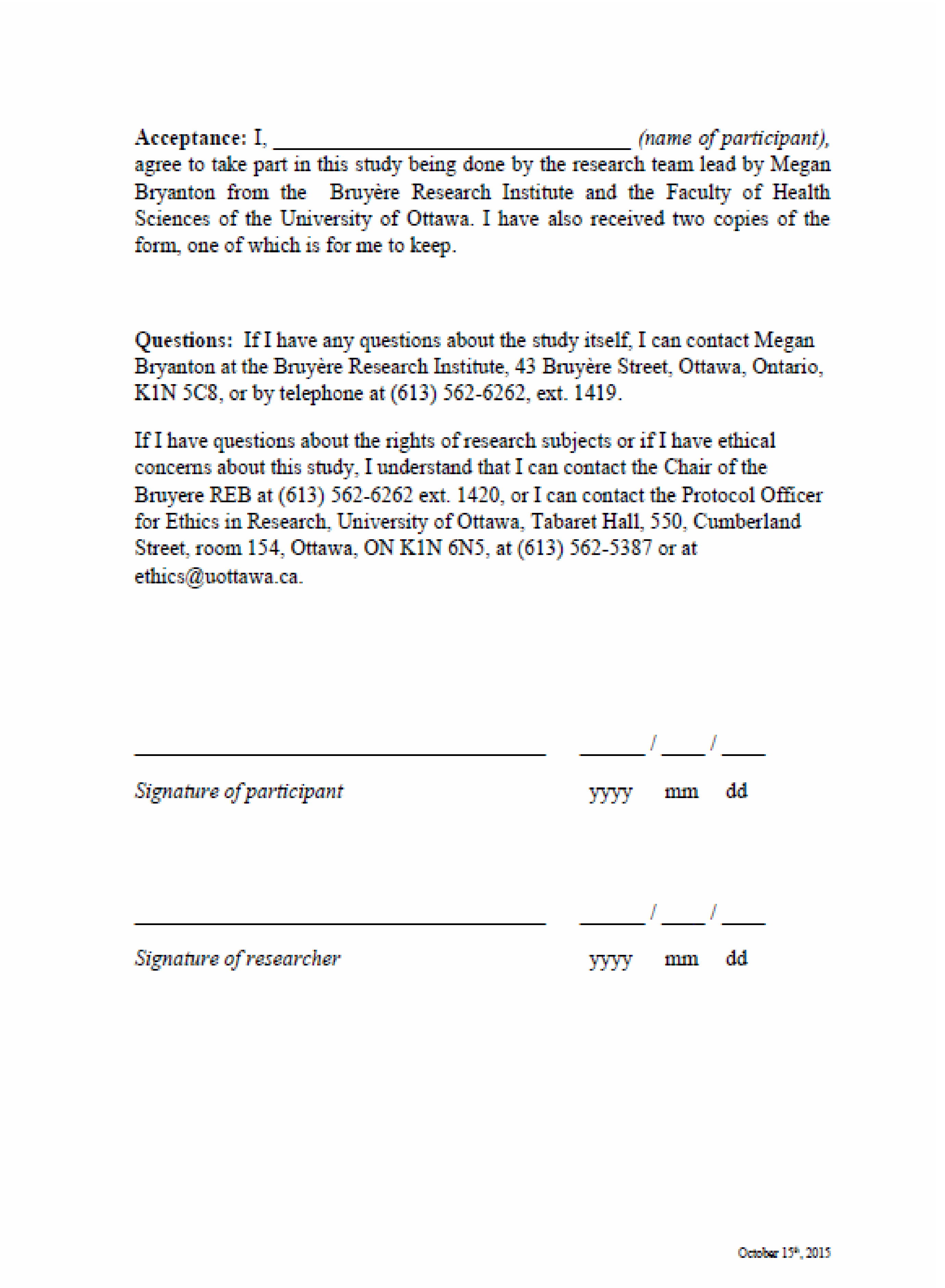
Risks: I understand that there are possible risks with taking part in this research study, such as:

1) **Skin irritation** from the sensors is possible, but not common. If this happens, it should go away in a few hours. Also, some discomfort is possible when taking off the sensor (like a Band-Aid).
2) **Muscle soreness** from doing physical activity with my legs might be felt after the visits. However, a warm-up will be done before testing. The warm-up should help decrease any soreness. For my safety, the researchers may decide to end a session at any time.
3) **The loss of balance** during testing is possible but I will be asked to wear a safety belt around my waist. A member of the research team will be close enough to give extra support if I need it.

Confidentiality: I understand that my taking part in this study is confidential to the extent permitted by law. My identity will be kept confidential by using a subject code instead of my name. Any document with my personal information will only be used by the researchers. This information will be kept in a locked cabinet in a locked office at the Elisabeth Bruyere Hospital laboratory.

Data storage: I understand that the results of this study will be used for conferences and publication in scientific journals. Results will be summarized so that I cannot be identified. I understand that all data will be destroyed after 7 years.

Freedom to withdraw: I understand that taking part in this research study is voluntary. If at any time I change my mind, I may withdraw from the study by telling the researcher and I will not be penalized in any way. I also understand that I may not qualify to take part in the second session of this study if the researcher thinks I should not perform very intense exercise. I have also been told that my cost of travel will not be covered for my two visits.



Acceptance: I, ______________________________ *(name of participant),* agree to take part in this study being done by the research team lead by Megan Bryanton from the Bruyère Research Institute and the Faculty of Health Sciences of the University of Ottawa. I have also received two copies of the form, one of which is for me to keep.

Questions: If I have any questions about the study itself, I can contact Megan Bryanton at the Bruyère Research Institute, 43 Bruyère Street, Ottawa, Ontario, K1N 5C8, or by telephone at (613) 562-6262, ext. 1419.

If I have questions about the rights of research subjects or if I have ethical concerns about this study, I understand that I can contact the Chair of the Bruyere REB at (613) 562-6262 ext. 1420, or I can contact the Protocol Officer for Ethics in Research, University of Ottawa, Tabaret Hall, 550, Cumberland Street, room 154, Ottawa, ON K1N 6N5, at (613) 562-5387 or at ethics@uottawa.ca.

________________________________ ______/____/____

Signature of participant yyyy mm dd

________________________________ ______/____/____

Signature of researcher yyyy mm dd

October 15th, 2015

APPENDIX B

SUPPLEMENTAL DATA

Table B1. Group Mean STS Phase Times (seconds) (±SD) of Young and Older Adult Participants with respect to % Total Time of Exhaustive Fatigue Protocol (n=12 Young; n=12 Old)

		% Total Time				
		0	**25**	**50**	**75**	**100**
Young	*Prep*	0.41 (0.07)	0.40 (0.07)	0.41 (0.06)	0.42 (0.04)	0.40 (0.08)
	Ascend	0.76 (0.13)	0.77 (0.07)	0.78 (0.08)	0.79 (0.10)	0.81 (0.09)
	Total	1.17 (0.16)	1.17 (0.05)	1.19 (0.07)	1.21 (0.10)	1.21 (0.10)
Old	*Prep*	0.46 (0.10)	0.42 (0.07)	0.46 (0.08)	0.47 (0.11)	0.47 (0.13)
	Ascend	0.93 (0.12)*	0.98 (0.18)*	0.98 (0.19)*	0.94 (0.19)*	0.97 (0.17)*
	Total	1.39 (0.12)*	1.40 (0.20)*	1.44 (0.23)*	1.41 (0.24)*	1.43 (0.25)*

** denotes significant age group difference from young.*

Table B2. Group Mean Ankle, Knee and Hip Angular Velocities (deg·s^{-1}; ± SD) with respect to STS Phase (Negative Values Denote Flexion Directionality) (n=10 Young; n=12 Old)

		% Total Time									
		0		**25**		**50**		**75**		**100**	
		Y	**O**	**Y**	**O**	**Y**	**O**	**Y**	**O**	**Y**	**O**
Ankle	*Prep*	-7.84 *(1.84)* b,c,d,e	-8.00 *(5.42)* b,c,d,e	-10.98 *(2.76)* a	-11.26 *(6.09)* A	-11.45 *(2.78)* a	-12.77 *(8.27)* a	-11.45 *(3.33)* a	-11.74 *(6.67)* a	-11.82 *(3.75)* a	-12.30 *(7.20)* a
	Ascend	20.63 *(6.85)* c,d,e	16.81 *(6.20)* c,d,e	19.31 *(6.49)* c,d,e	15.51 *(6.27)* c,d,e	17.73 *(7.35)* a,b,e	14.96 *(6.71)* a,b,e	16.63 *(7.81)* a,b	15.01 *(6.50)* a,b	15.71 *(7.55)* a,b,c	14.46 *(7.66)* a,b,c
Knee	*Prep*	11.78 *(4.53)* e	9.17 *(6.70)* e	10.39 *(8.06)* e	5.81 *(11.67)* E	8.81 *(8.82)* e	6.02 *(11.66)* e	8.49 *(11.13)* e	5.65 *(10.48)* e	6.23 *(11.06)* a,b,c,d	3.20 *(12.92)* a,b,c,d
	Ascend	115.78 *(16.72)* e	93.81 *(19.36)* *,e	113.03 *(14.88)* e	90.63 *(17.51)* *,e	112.24 *(13.29)*	88.96 *(18.80)* *	110.07 *(14.01)*	87.89 *(20.72)* *	106.13 *(15.54)* a,b	87.66 *(19.93)* *,a,b
Hip	*Prep*	-24.16 (8.22) b,c,d,e	-24.24 *(8.03)* b,c,d,e	-33.45 *(13.15)* a	-32.63 *(12.33)* A	-37.76 *(15.32)* a	-32.60 *(14.12)* a	-39.93 *(12.51)* a	-32.36 *(12.08)* a	-40.66 *(14.13)* a	-32.33 *(12.13)* a
	Ascend	102.72 *(26.70)*	73.52 *(17.42)* *	100.33 *(23.65)*	74.22 *(17.13)* *	105.10 *(24.07)*	73.27 *(16.54)* *	105.07 *(22.12)*	70.39 *(17.83)* *	99.76 *(23.21)*	72.22 *(23.02)* *

a denotes significant difference from 0%, b denotes significant difference from 25%, c denotes significant difference from 50%, ^{d} *denotes significant difference from 75%,* ^{e} *denotes significant difference from 100%.*

** denotes significant age group difference from young.*

Table B3. Knee Extensor Net Joint Moments in Young and Older Participants Who Did and Did Not (<30mins) Make it to the 30 Minute Cut-off Time.

		STS Task Time			
Group		Start (0%)		End (100%)	
		PEAK	ASCEND	PEAK	ASCEND
Young	30 mins (n=5)	1.10 (0.12)	0.45 (0.11)	1.06 (0.15)	0.41 (0.13)
	<30 mins (n=5)	1.33 (0.22)	0.52 (0.09)	1.14 (0.23)	0.42 (0.09)
Old	30 mins (n=2)	1.01 (0.10)	0.31 (0.02)	0.93 (0.22)	0.23 (0.11)
	<30 mins (n=10)	1.00 (0.08)	0.47 (0.06)	0.87 (0.12)	0.43 (0.13)

Table B4. Hip Extensor Net Joint Moments in Young and Older Participants Who Did and Did Not (<30mins) Make it to the 30 Minute Cut-off Time.

		STS Task Time			
Group		Start (0%)		End (100%)	
		PEAK	ASCEND	PEAK	ASCEND
Young	30 mins (n=5)	-0.92 (0.23)	-0.33 (0.11)	-0.96 (0.22)	-0.32 (0.08)
	<30 mins (n=5)	-0.73 (0.05)	-0.29 (0.05)	-0.77 (0.12)	-0.32 (0.08)
Old	30 mins (n=2)	-1.00 (0.01)	-0.45 (0.02)	-0.88 (0.11)	-0.39 (0.08)
	<30 mins (n=10)	-0.84 (0.20)	-0.40 (0.10)	-1.05 (0.30)	-0.52 (0.15)

Table B5. Ankle Plantar-Flexor Net Joint Moments in Young and Older Participants Who Did and Did Not (<30mins) Make it to the 30 Minute Cut-off Time.

		STS Task Time			
Group		Start (0%)		End (100%)	
		PEAK	ASCEND	PEAK	ASCEND
Young	30 mins (n=5)	-0.28 (0.02)	-0.14 (0.04)	-0.34 (0.05)	-0.19 (0.01)
	<30 mins (n=5)	-0.31 (0.04)	-0.11 (0.07)	-0.33 (0.13)	-013 (0.11)
Old	30 mins (n=2)	-0.28 (0.08)	-0.13 (0.03)	-0.29 (0.03)	-0.19 (0.03)
	<30 mins (n=10)	-0.34 (0.08)	-0.22 (0.07)	-0.47 (0.15)	-0.31 (0.17)

Table B6. Joint Flexion Angles (±SD) at Moment of Seat-off (degrees) with STS Exercise Progression in Young (Y) and Older (O) Participants.

	% Total Time									
	0		**25**		**50**		**75**		**100**	
	Y	**O**	**Y**	**O**	**Y**	**O**	**Y**	**O**	**Y**	**O**
Ankle	84.1 (5.3) b,c,d,e	84.5 (5.2) b,c,d,e	82.8 (5.7) a,d,e	83.2 (5.1) a,d,e	81.5 (6.4) a,e	82.9 (5.1) a,e	80.8 (6.5) a,b	82.4 (5.6) a,b	80.3 (6.5) a,b,c	82.0 (6.4) a,b,c
Knee	-95.1 (11.2)	-91.4 (7.7)	-94.8 (10.7)	-92.5 (7.7)	-92.5 (12.0)	-91.4 (6.8)	-92.7 (11.7)	-91.1 (6.9)	-93.0 (11.1)	-90.0 (7.6)
Hip	84.0 (21.2) b,c,d,e	70.0 (9.2) *,b,c,d,e	86.1 (21.2) a,d,e	71.0 (8.8) *a,d,e	87.2 (22.9) a,d	71.4 (7.9) *a,d	89.6 (22.3) a,b,c	72.1 (9.1) *,a,b,c	90.0 (24.6) a,b	71.8 (8.9) *,a,b
L5/S1	25.2 (12.4) c,d,e	35.1 (7.8) *,c,d,e	25.0 (13.6) c,d,e	38.9 (9.6) *,c,d,e	27.2 (15.0) a,b,e	40.6 (10.5) *,a,b,e	27.6 (14.7) a,b,e	42.0 (10.6) *,a,b,e	29.8 (15.8) a,b,c,d	43.1 (11.9) *,a,b,c,d

[a] denotes significant difference from 0%, [b] denotes significant difference from 25%, [c] denotes significant difference from 50%, [d] denotes significant difference from 75%, [e] denotes significant difference from 100%.
** denotes significant age group difference from young.*

Table B7. Group Mean COM and COP (% kinetic foot length; ± SD) with respect to Distal End of Kinetic Foot (Y; Lateral Mallelous to Distal 2nd Metacarpal) and % Foot Width (X) with respect to Medial Foot Border at Seat-off in Young (Y) and Older (O) Participants (n=10 young; n=12 old). Negative Values Indicate Positions Posterior to Distal End of Kinetic Foot (y) or Averaged Distribution Towards the Left (x).

		% Total Time									
		0		**25**		**50**		**75**		**100**	
		X	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**
COP	**Young**	-4.4 (4.3)	-48.0 (6.8) e	-3.7 (4.7)	-47.2 (7.0) c,e	-3.6 (5.0)	-45.6 (7.0) b	-3.0 (4.9)	-45.0 (7.4)	-3.2 (4.5)	-45.3 (-6.8) a,b
	Old	-2.9 (4.5)	-39.9 (7.6) *,e	-0.18 (8.2)	-38.7 (10.2) *,c,e	-0.1 (11.6)	-36.2 (10.5) *,b	-1.9 (5.2)	-36.2 (12.5) *	3.0 (2.1)	-33.3 (10.6) *,a,b
COM	**Young**	-0.9 (5.9)	-54.1 (5.0)	0.3 (5.1)	-53.9 (4.4)	-0.4 (6.4)	-53.9 (4.6)	-0.5 (6.5)	-53.8 (4.5)	-0.9 (6.6)	-53.9 (4.4)
	Old	-1.3 (4.6)	-54.7 (4.7)	-0.5 (5.5)	-54.6 (5.7)	-1.0 (9.3)	-54.6 (6.0)	0.2 (7.5)	-54.6 (5.9)	0.3 (9.1)	-54.3 (6.2)

[a] denotes significant difference from 0%, [b] denotes significant difference from 25%, [c] denotes significant difference from 50%, [d] denotes significant difference from 75%, [e] denotes significant difference from 100%.
** denotes significant age group difference from young.*

Table B8. Preparatory Phase Joint Contributions (%) to Total Lower Extremity Impulse (±SD) in Young and Older Adult Participants.

		% Total STS Time				
		0	**25**	**50**	**75**	**100**
Ankle	Young	7.4 (5.3)	7.5 (5.2)	9.0 (5.2)	8.0 (5.9)	7.1 (4.8)
	Old	8.8 (6.4)	7.1 (11.4)	11.1 (8.1)	11.3 (7.6)	11.5 (8.0)
Knee	Young	69.1 (13.6)	69.3 (11.4)	67.5 (17.7)	63.1 (13.1)	61.8 (18.4)
	Old	45.7 (31.1) *	43.1 (38.4) *	47,2 (25.1) *	43.1 (1.3) *	39.7 (21.3) *
Hip	Young	23.5 (16.5)	23.2 (12.9)	23.6 (17.1)	29.0 (13.0)	31.0 (19.4)
	Old	23.4 (55.9)	20.4 (66.2)	41.7 (26.1)	45.6 (25.1)	48.8 (25.0)

[a] denotes significant difference from young adult participants

Table B9. Young adult individual subject characteristics, and Borg (0-10), average ascending KE NJM (Nm/kg), and QF EMG(%MVIC) data at the start (0%) and end (100%) total STS task times.

Subject	**Age**	**Gender**	**Godin**	**Total Time**	**Borg**		**KE NJM**		**QF EMG**	
					0%	**100%**	**0%**	**100%**	**0%**	**100%**
Y01	31	M	45	21	2	10	0.49	0.33	62	94
Y02	29	F	46	21	3	10	0.40	0.38	49	75
Y03	23	F	39	26	1	10	0.61	0.39	64	70
Y04	29	M	22	26	1	10	0.52	0.44	48	57
Y06	24	F	49	30	1	8	0.31	0.27	36	49
Y10	35	F	27	30	2	5	0.40	0.39	56	48
Y11	25	M	30	30	2	7	0.27	0.32	31	65
Y12	19	F	30	20	2	10	0.23	0.19	38	74
Y13	21	F	96	30	2	8	0.46	0.33	31	69
Y14	20	M	78	30	2	8	0.45	0.49	71	59
Y15	20	M	73	22	1	10	0.60	0.58	90	104
Y16	23	M	33	30	1	7	0.61	0.59	42	65

Table B10. Older adult individual subject characteristics, and Borg (0-10), average ascending KE NJM (Nm/kg), and QF EMG (%MVIC) data at the start (0%) and end (100%) total STS task times.

Subject	**Age**	**Gender**	**Godin**	**Total Time**	**Borg**		**KE NJM**		**QF EMG**	
					0%	**100%**	**0%**	**100%**	**0%**	**100%**
A01	60	F	21	8	3	10	0.46	0.37	94	148
A02	68	M	35	12	3	10	0.39	0.42	53	151
A03	62	F	77	9	4	10	0.59	0.41	100	111
A04	73	F	29	13	3	10	0.51	0.43	42	59
A05	61	F	21	12	1	10	0.42	0.25	116	85
A06	69	M	71	30	2	6	0.30	0.27	46	79
A07	74	M	119	26	1	9	0.53	0.74	44	101
A08	74	F	21	5	2	10	0.44	0.40	87	131
A09	65	M	3	7	2.5	10	0.47	0.50	79	119
A10	66	M	77	30	1	7	0.33	0.37	42	59
A11	66	F	25	14	2	10	0.51	0.42	100	111
A12	64	M	58	24	2	10	0.39	0.39	56	61

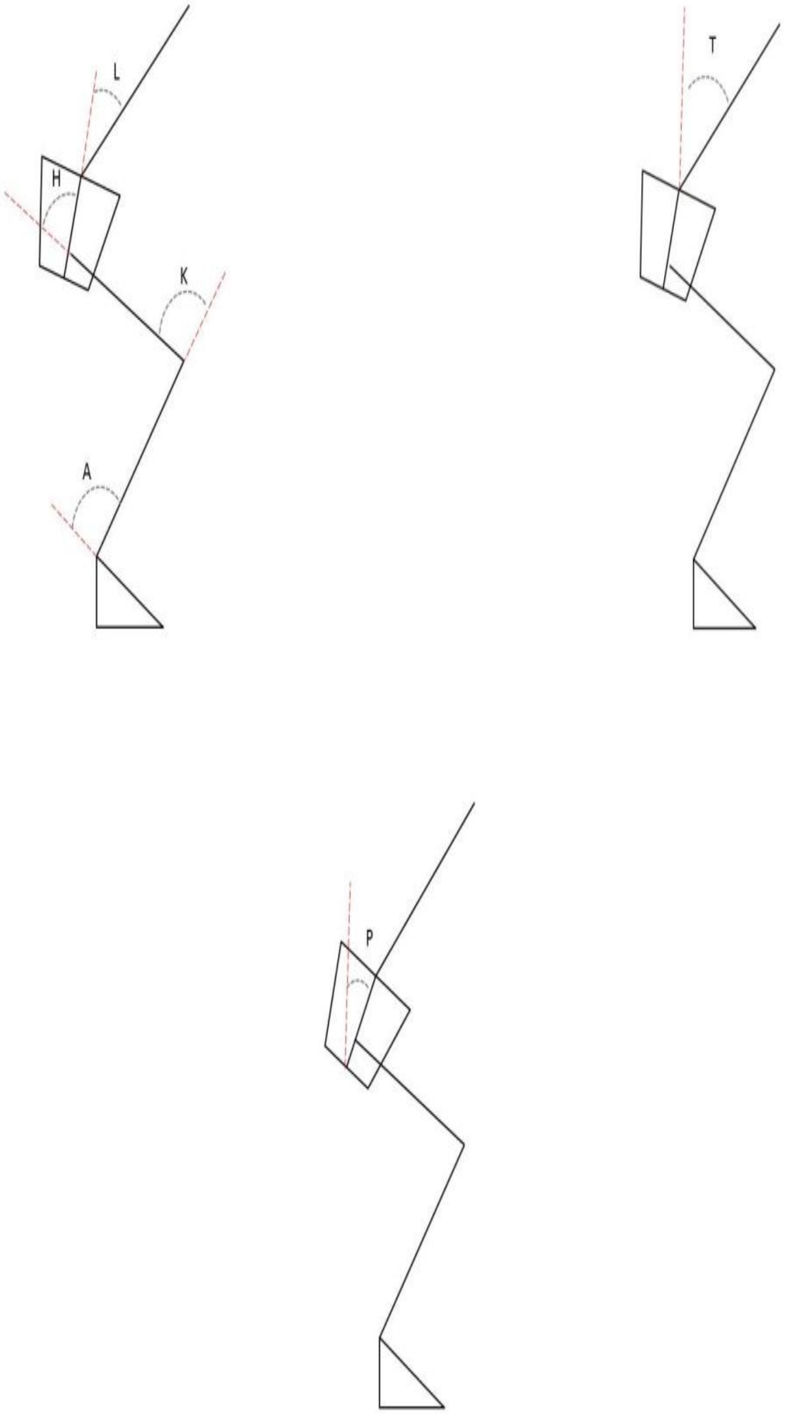


Figure B1. Schematic diagram representing ankle (A), knee (K), hip (H) and L5/S1 (L) joint angle references, as well as pelvis (P) and torso (T) segment angles.

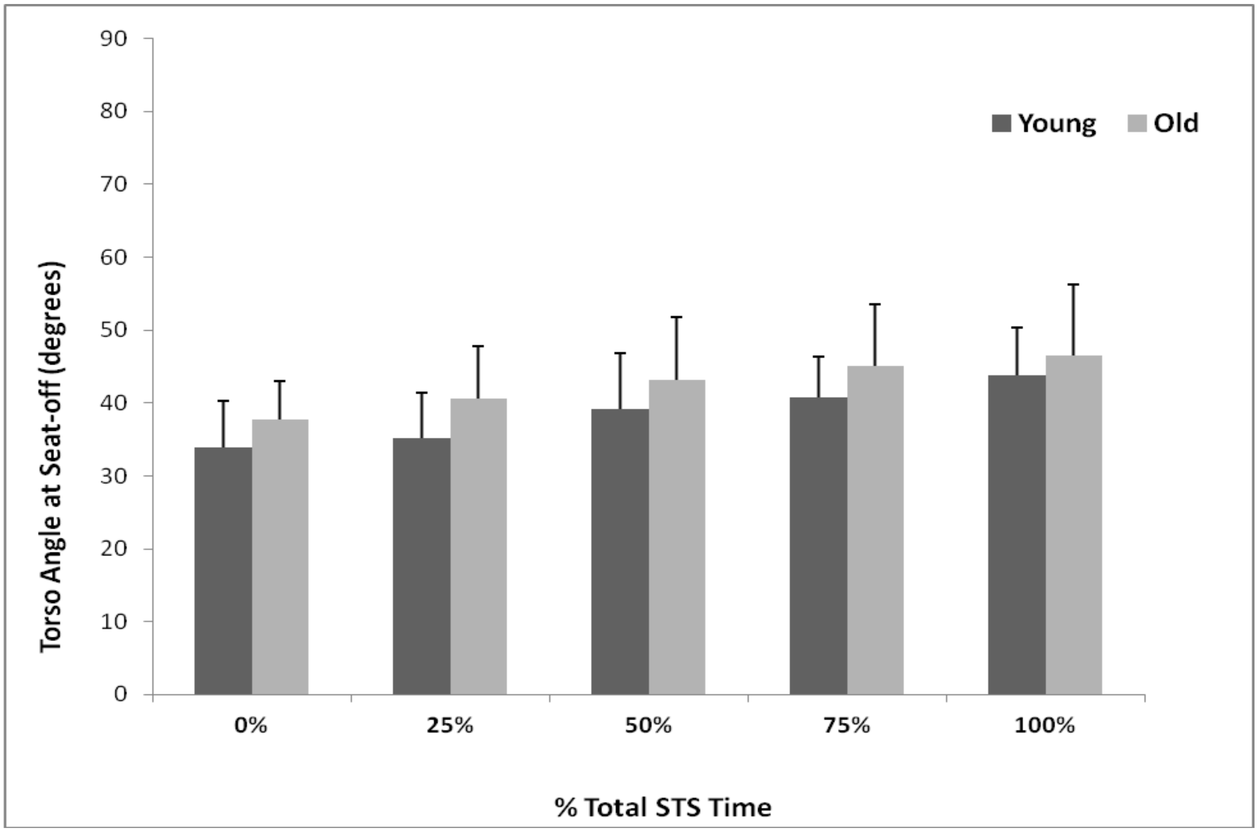


Figure B2. Torso angle at seat off relative to the vertical in young and older adult participants with respect to total STS exercise time.

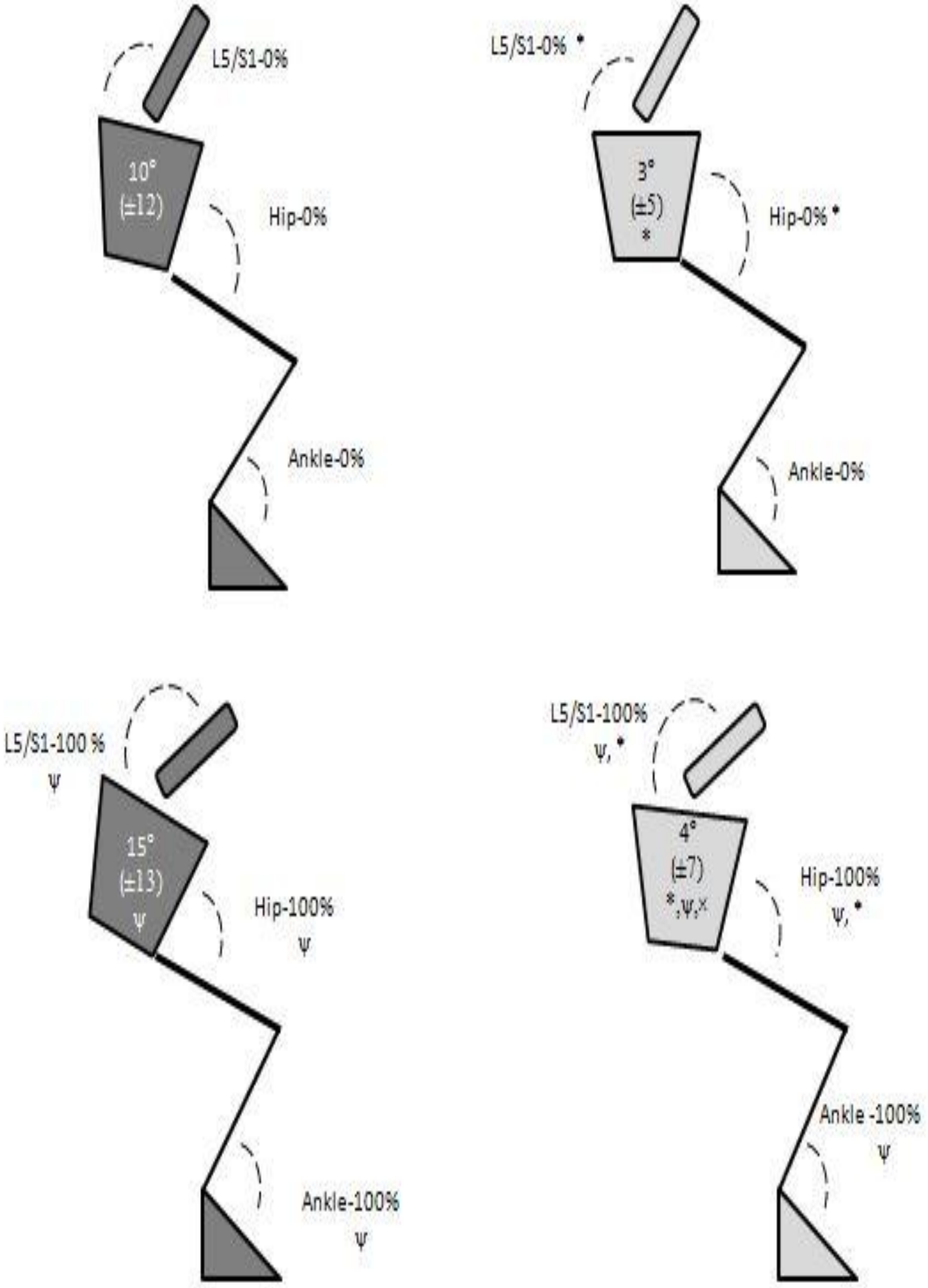


Figure B3. Young (left) and older (right) adult body positioning at moment of seat-off at the start (0%) and end (100%) of the repetitive STS exercise. * *denotes significant age group difference from young. Ψ indicates significant time difference from start. × denotes significant time x age interaction was found*

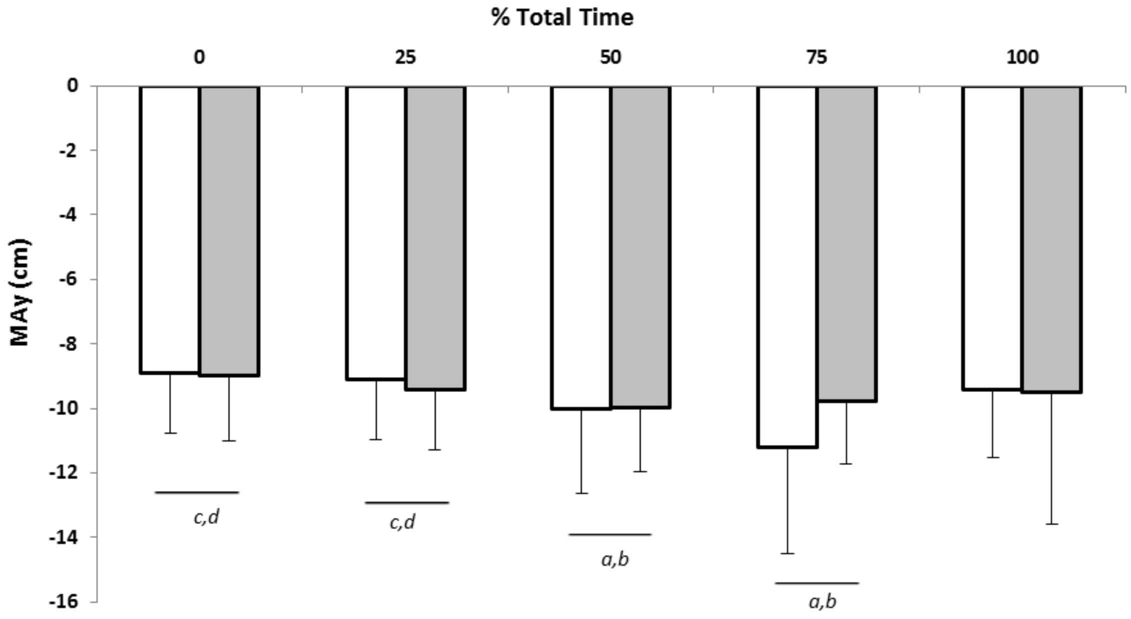


Figure B4. COMy-COPy moment arms (MAy; cm) at seat off with STS exercise progression in young (open) and older participants (grey). Error bars represent SDs. [a] *denotes significant difference from 0%,* [b] *denotes significant difference from 25%,* [c] *denotes significant difference from 50%,* [d] *denotes significant difference from 75%,* [e] *denotes significant difference from 100%.*

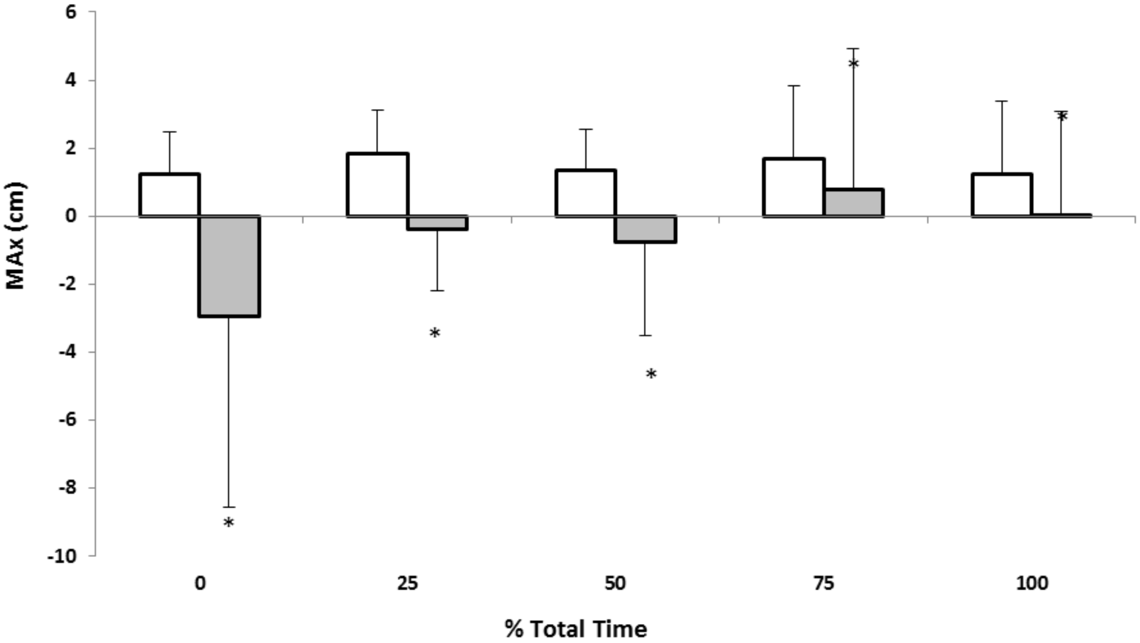


Figure B5. COMx-COPx moment arms (MAx; cm) at seat off with STS exercise progression in young (open) and older participants (grey). *Error bars represent SDs.*indicates a significant age group difference from young*

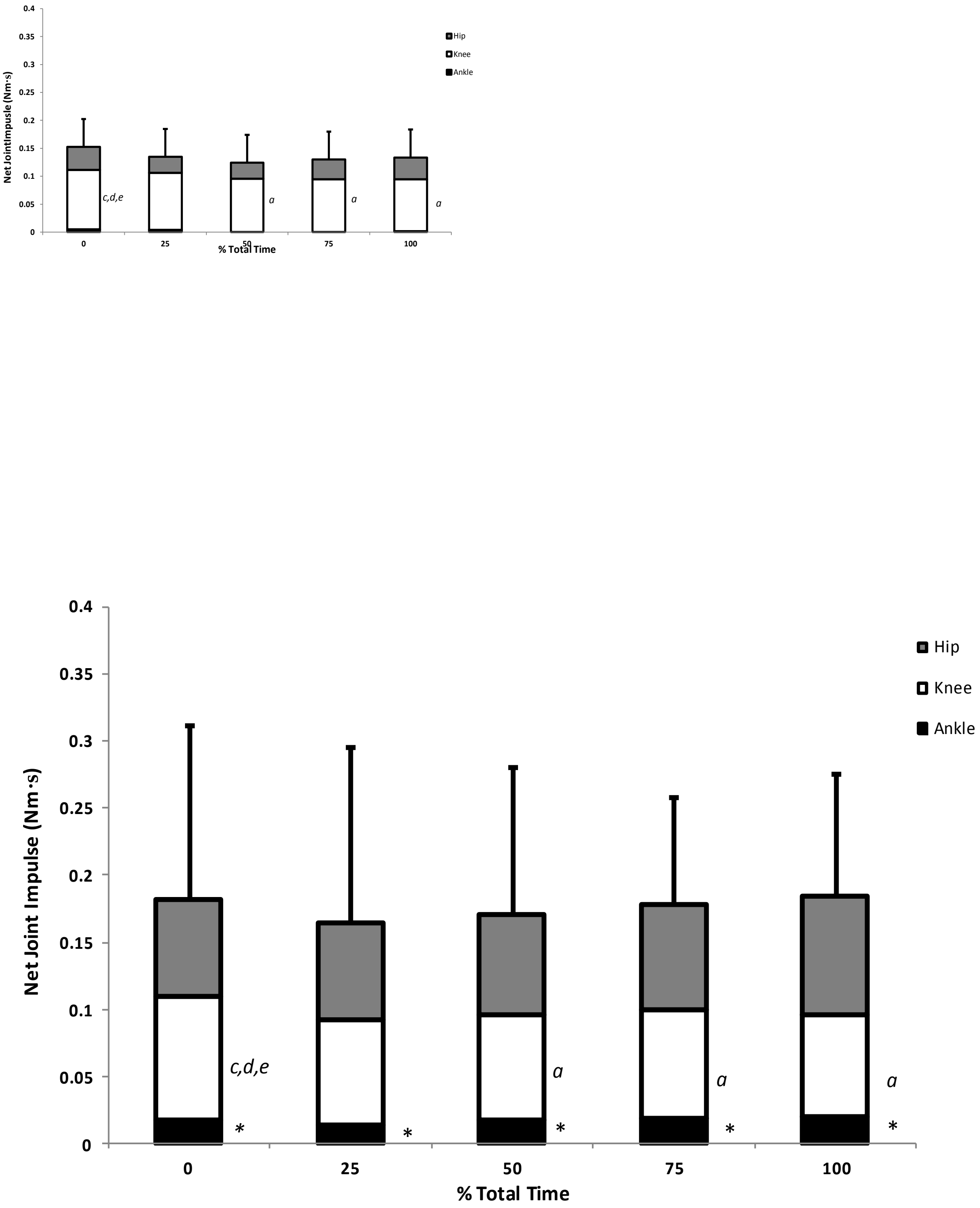


Figure B6. Young (top) and older (bottom) adult average net joint impulse (±SD) performed over the preparatory phase during repetitive STS exercise. Error bars represent stand deviations for total lower extremity work. [a] *denotes significant difference from 0%,* [b] *denotes significant difference from 25%,* [c] *denotes significant difference from 50%,* [d] *denotes significant difference from 75%,* [e] *denotes significant difference from 100%.* denotes significant age group difference from young.*

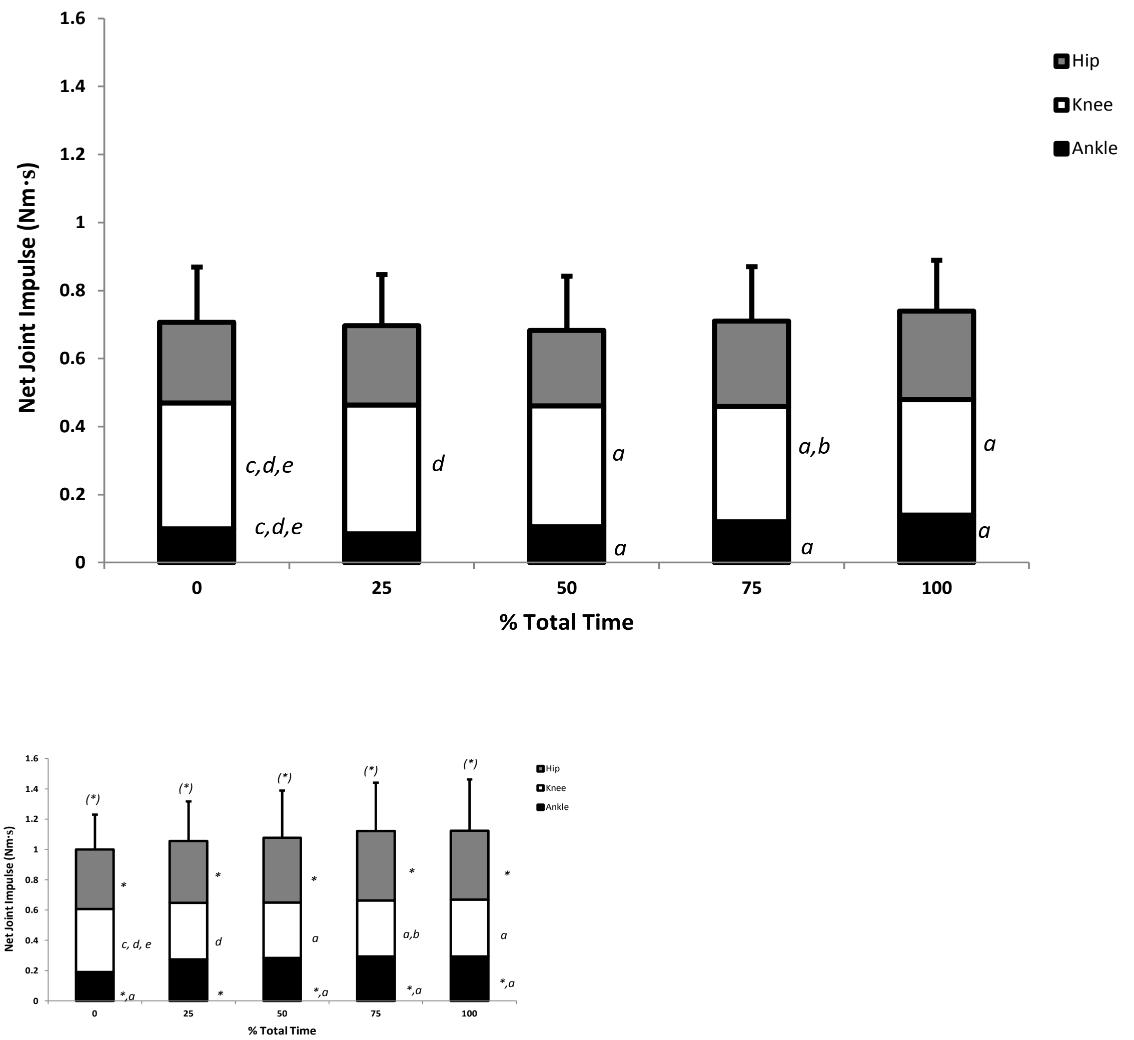


Figure B7. Young (top) and older (bottom) adult average net joint impulse (±SD) performed over the ascending phase during repetitive STS exercise. Error bars represent stand deviations for total lower extremity work. [a] *denotes significant difference from 0%,* [b] *denotes significant difference from 25%,* [c] *denotes significant difference from 50%,* [d] *denotes significant difference from 75%,* [e] *denotes significant difference from 100%.* * *denotes significant age group difference from young.*

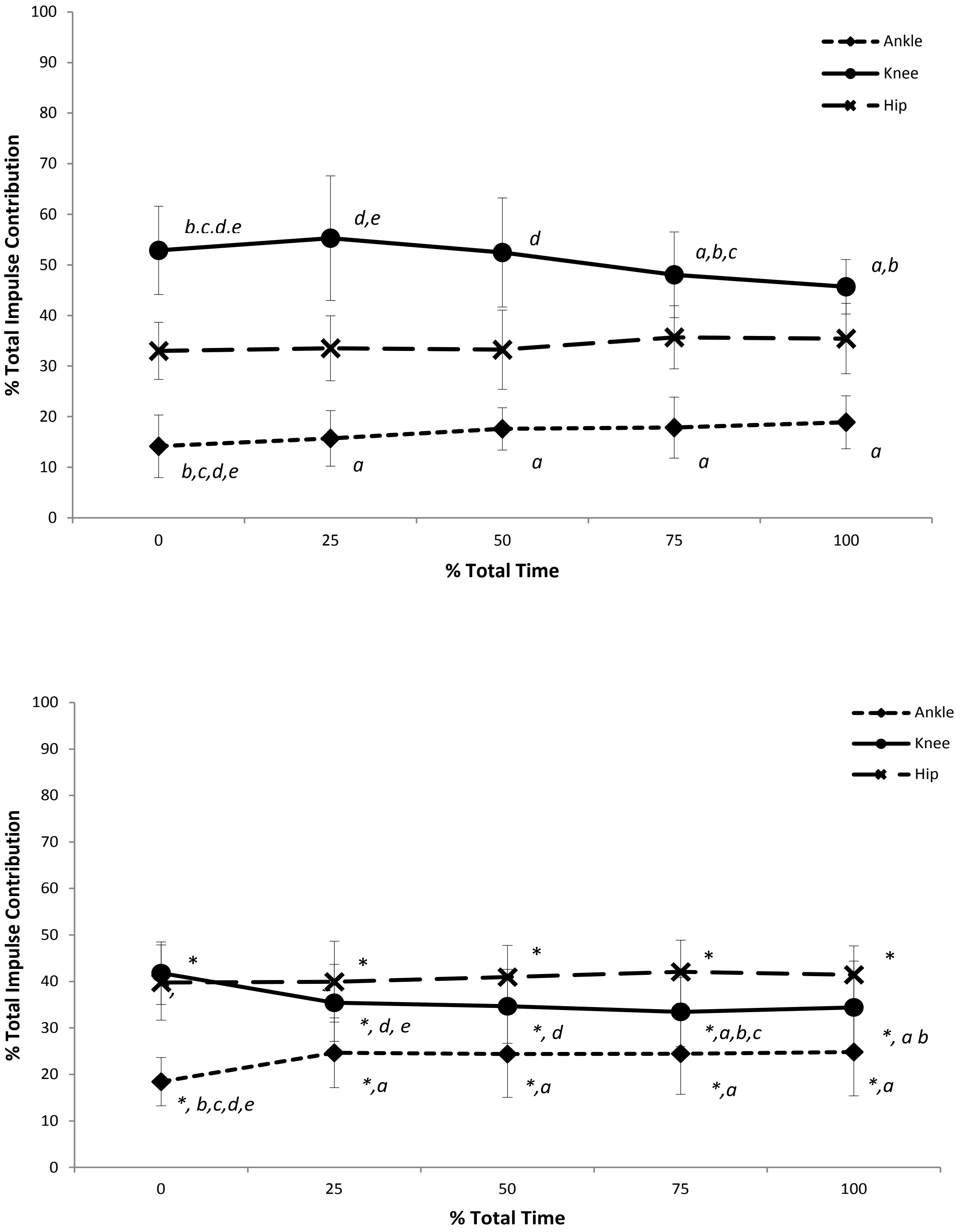


Figure B8. Young (top) and older (bottom) adult joint contributions to average ascending lower extremity support impulse with repetitive STS exercise. Error bars denote SDs. [a] *denotes significant difference from 0%,* [b] *denotes significant difference from 25%,* [c] *denotes significant difference from 50%,* [d] *denotes significant difference from 75%,* [e] *denotes significant difference from 100%.* denotes significant age group difference from young.*

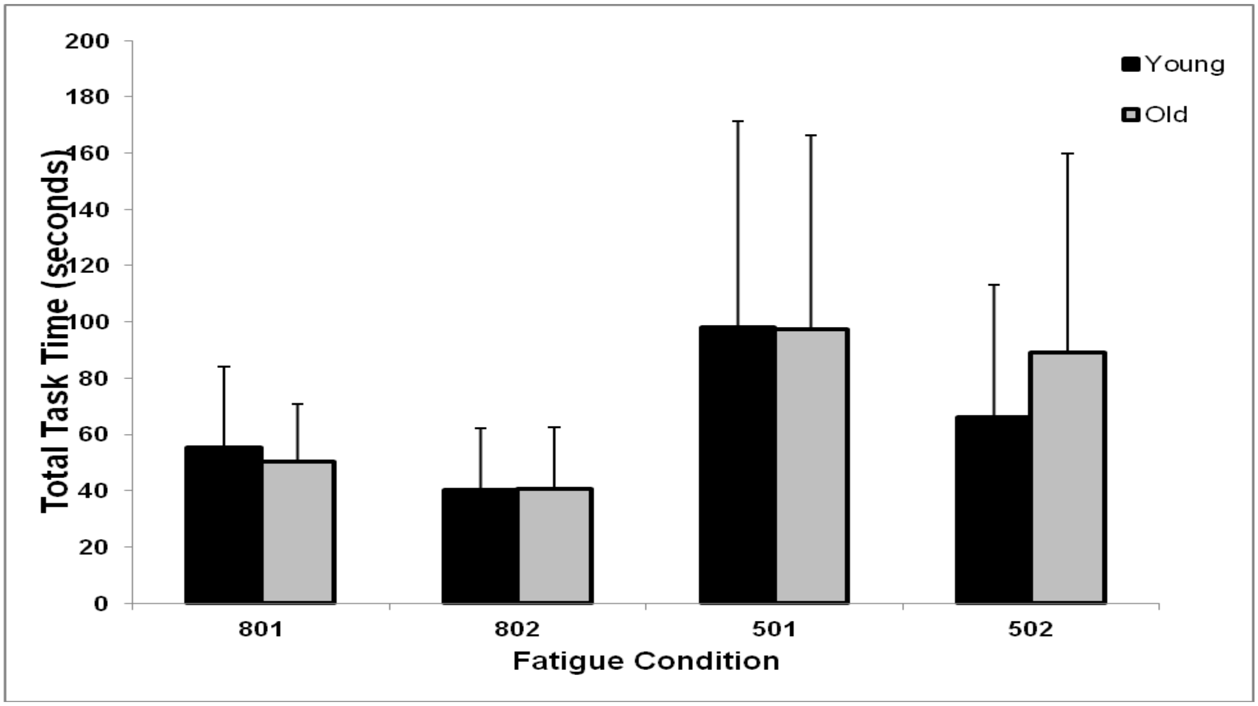


Figure B9. Total isolated KE fatigue task times with repect to condition intensity and age.

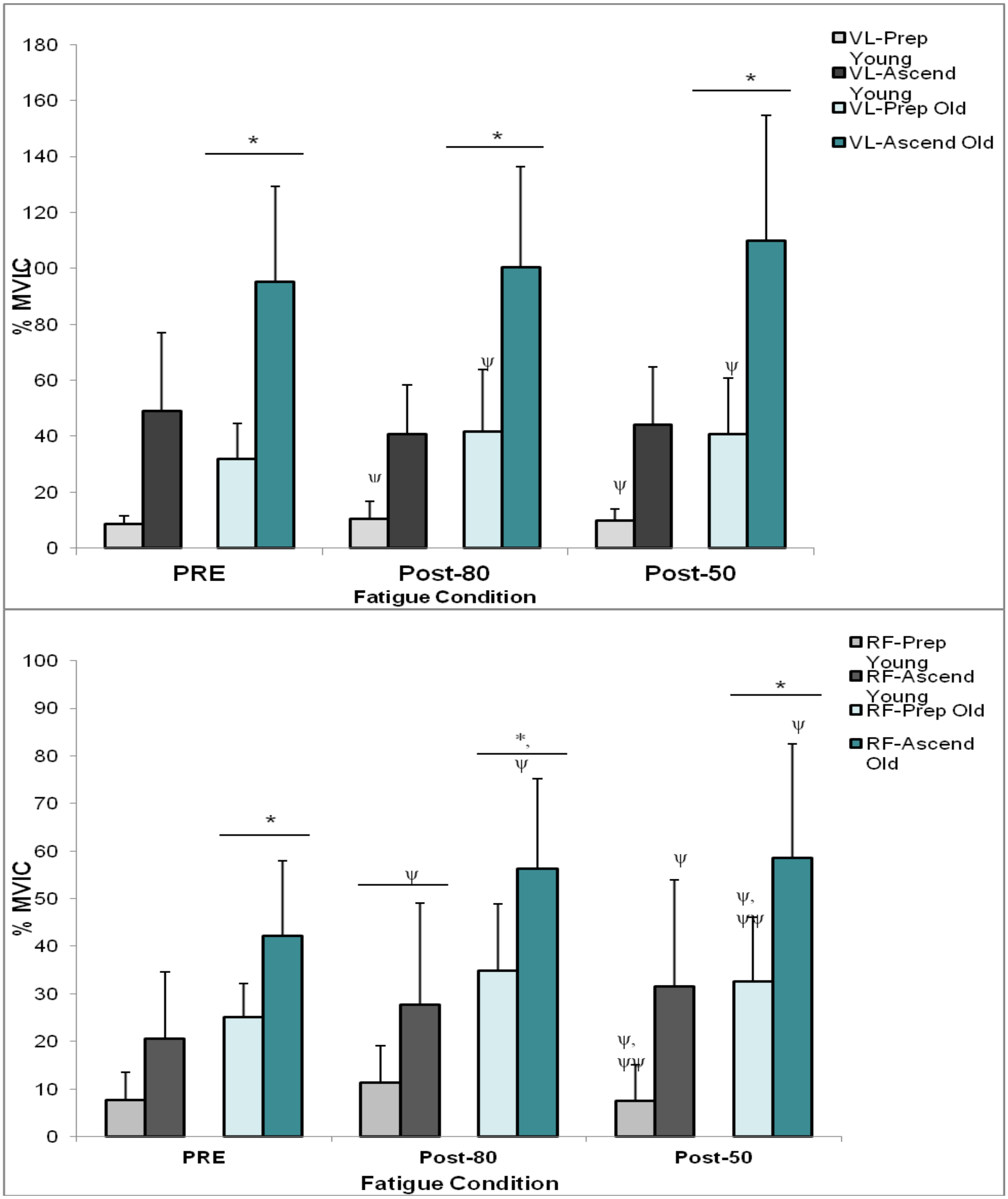
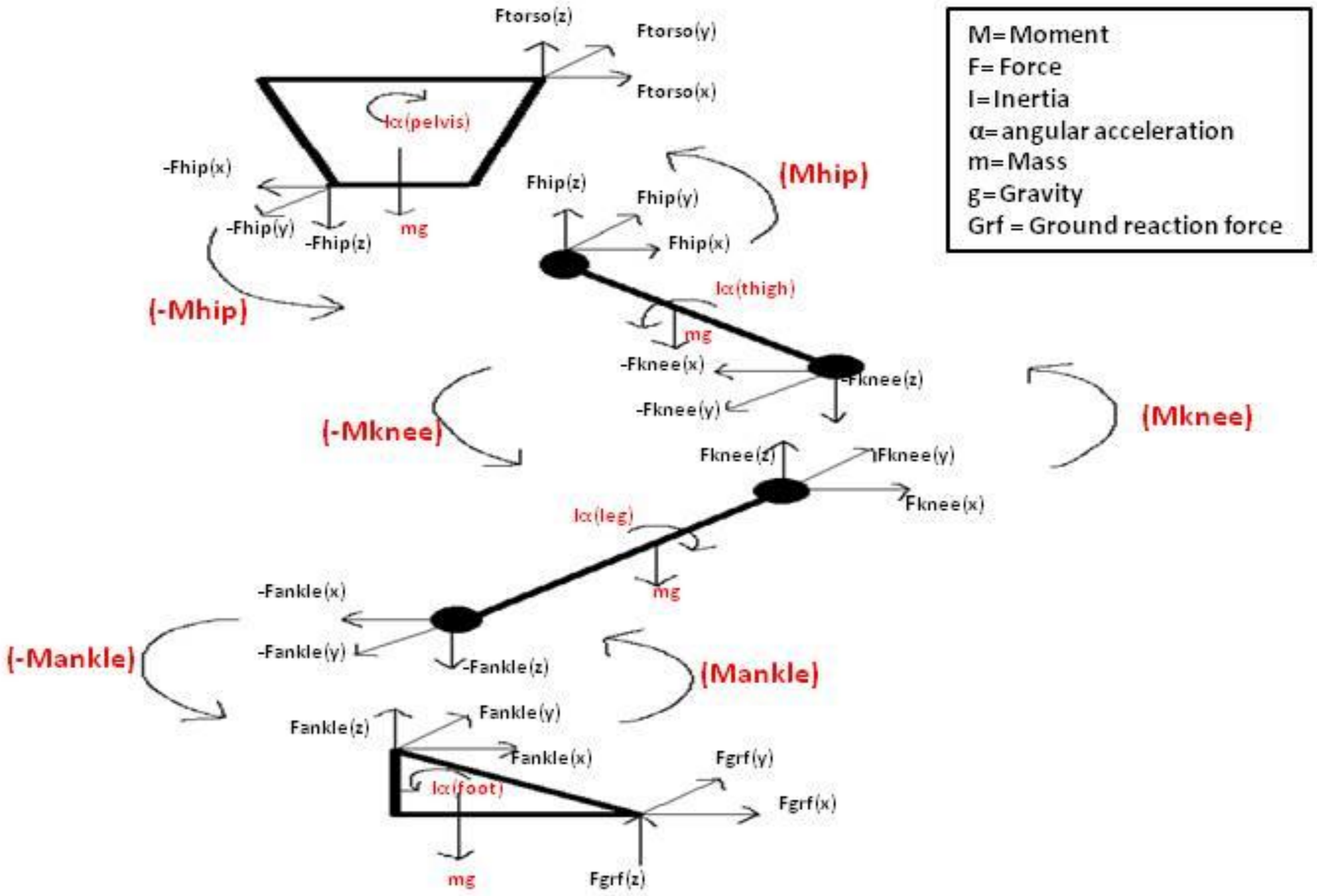


Figure B10. Vastus lateralis (VL) and rectus femoris (RF) MVIC average activity with respect to the preparatory (light) and ascending (dark) phases in young (Y; greyscale) and older (O; blue) adults. Error bars denote SDs. ψ denotes a significant difference from PRE, ψψ denotes a significant difference from previous condition. * dentoes signifcaitn difference from young adults.



$\{M=(Fgr \times rgr) + (Fankle \times rankle) = I\alpha foot$ (solve for Mankle)

$\{F= Fgr + Fankle + mg = mafoot$ (solve for Fankle)

$$Fgr= \begin{bmatrix} Fgr(x) \\ Fgr(y) \\ Fgr(z) \end{bmatrix} \quad rgr= \begin{bmatrix} rgr(x) \\ rgr(y) \\ rgr(z) \end{bmatrix} \quad Fankle= \begin{bmatrix} Fankle(x) \\ Fankle(y) \\ Fankle(z) \end{bmatrix} \quad rankle= \begin{bmatrix} rankle(x) \\ rankle(y) \\ rankle(z) \end{bmatrix}$$

$\{M=(Fankle \times rankle) + (Fknee \times rknee) + Mankle = I\alpha leg$ (solve for Mknee)

$\{F= Fankle + Fknee + mg = maleg$ (solve for Fknee)

$$Fknee= \begin{bmatrix} Fknee(x) \\ Fknee(y) \\ Fknee(z) \end{bmatrix} \quad rknee= \begin{bmatrix} rknee(x) \\ rknee(y) \\ rknee(z) \end{bmatrix}$$

$\{M=(Fknee \times rknee) + (Fhip \times rhip) + Mknee = I\alpha thigh$ (solve for Mhip)

$\{F= Fknee + Fhip + mg = mathigh$ (solve for Fhip)

$$Fhip= \begin{bmatrix} Fhip(x) \\ Fhip(y) \\ Fhip(z) \end{bmatrix} \quad rhip= \begin{bmatrix} rhip(x) \\ rhip(y) \\ rhip(z) \end{bmatrix}$$

Figure B11. Free body diagram and inverse dynamics calculation (moments are solved about the COM).