Influence of Gender and Obesity on Motor Performance, Neuromuscular Control and Endurance in Older Adults

By

Xu Duan

Thesis submitted to the faculty of the
Virginia Polytechnic Institute and State University
In partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE
In
Industrial and Systems Engineering

Divya Srinivasan, Chair
Sunwook Kim
Ranjana K. Mehta
Maury A. Nussbaum

December 12, 2017
Blacksburg, VA

Keywords: Motor Variability, Elderly, Fatigue, Sex differences, Intermittent tasks, Knee extension, Handgrip

Influence of Gender and Obesity on Motor Performance, Neuromuscular Control and Endurance in Older Adults

Xu Duan

ABSTRACT

The rapid growth of an older demographic is an increasing concern around the world. Older people have been reported to suffer from physiological and neuromuscular declines in several systems including skeletal muscles, central nervous system, cardiovascular processes and respiratory function. These age-related changes are often reflected through impairments in functional performance of occupational tasks as well as activities of daily living. This may make an older population more prone to musculoskeletal disorders and injuries. In addition, health problems and injury risks are likely amplified by factors such as obesity. Obesity has emerged as a serious health concern in the United States in recent decades. However, obesity-related changes in performance and motor control as well as how they will be modified by gender, specifically among older adults, are still largely unexplored. As motor variability has recently been reported to be associated with fatigue development and may have the potential to reveal underlying mechanisms of neuromuscular control, the main goals of this study were to investigate the influence of gender and obesity on motor performance, neuromuscular control and endurance in the elderly, by examining differences in motor variability during intermittent submaximal isometric exertions of the knee and hand.

Fifty-two older participants with age over 65 were recruited into four groups: obese male (9), obese female (13), non-obese male (15) and non-obese female (15). The obese groups consisted of those whose BMI was greater than 30 kg/m^2. Participants were asked to perform intermittent (15s on and 15s off) isometric handgrip and knee extensions at 30% MVC until exhaustion. Force and muscle activations of the Vastus Lateralis, Rectus Femoris, Extensor Carpi Radialis and Flexor Carpi Radialis muscles were collected through the endurance task. Motor variability was quantified using the coefficient of variation (CV) and sample entropy (SaEn) of the surface electromyography (EMG) and force signals.

Motor variability during exercise differed both between males and females, and between obese and non-obese people, reflecting different motor strategies employed in order to prolong endurance. Overall, across all individuals, we observed a significant positive correlation between cycle-to-cycle variability of knee extensor muscle activation during the baseline period of the task and endurance time. As for gender differences, males exhibited longer endurance times than females, and seemed to achieve that through utilizing a motor strategy involving a more variable (higher CV) and less complex (lower SaEn) agonistic muscle activity. Since this was accompanied by a lower fluctuation in the force signal (lower CV) and a higher complexity of force (SaEn), we interpreted this to be a motor strategy involving more variable recruitment of synergistic and antagonistic motor units during the knee extension task to prolong endurance time, among males compared to females. As for obesity differences, there were no obesity-related changes in endurance time. However, obese individuals exhibited a greater cycle-to-cycle variability that was positively correlated with endurance time during the knee extension task, indicating a larger alteration in the recruitment of motor units across successive contractions, which contributed to comparable endurance time and performance with their non-obese counterparts. During the hand-grip tasks, variabilities in force and muscle activity followed similar trends as the knee extension task. However, there were no significant gender or obesity differences in endurance time, and there also weren't any significant correlations between any of the dependent variables with endurance time.

Thus, this study was a basic investigation into changes in motor variability and how it was associated with the development of fatigue among older adults; and the potential influences of gender and obesity on the relationships. Two tasks of high relevance to both occupational life and activities of daily living, i.e. knee extension and hand-grip were considered. Our findings enhance the theoretical understanding of the underlying neuromuscular control patterns and their relationship with fatigue for different individuals. Given that both aging and obesity rates are rising continuously and becoming a substantial health and safety problem especially in the occupational environment, the results from this study are both timely and critical for practical design applications, especially by recognizing the importance of having a variable motor pattern in task performance, even among older adults.

Influence of Gender and Obesity on Motor Performance, Neuromuscular Control and Endurance in Older Adults

Xu Duan

GENERAL AUDIENCE ABSTRACT

Obesity rates in the geriatric population has emerged as serious health concern in recent decades. Yet, obesity-related differences in neuromuscular performance and neuromotor control during fatiguing tasks, as well as how they are modified by gender, specifically among older adults, are still largely unexplored. In recent decades, motor variability, referring to the natural variations in postures, movements and muscle activity, has been observed in all physical tasks and linked with fatigue development. It may have the potential to reveal underlying mechanisms of neuromuscular control. Thus, the main goals of this study were to investigate the influence of gender and obesity on motor variability and performance in the elderly, by studying intermittent isometric muscle contractions.

Fifty-two older adults (Mean age: 73 (SD 6) years) were recruited into four groups: 9 obese males, 13 obese females, 15 non-obese males, and 15 non-obese females 15. Participants performed intermittent (15s contraction and 15s rest) isometric knee extensions and handgrips at 30% maximum voluntary contraction (MVC) until exhaustion. Force and muscle activations of the Vastus Lateralis (VL), Rectus Femoris (RF), Extensor Carpi Radialis (ECR) and Flexor Carpi Radialis (FCR) muscles were collected during knee extension and handgrip tasks. Performance was quantified using endurance time and force fluctuations. Motor variability was quantified using the coefficient of variation (CV) and sample entropy (SaEn) of the muscle activation signals (surface electromyography (EMG)). The CV is a linear estimator that quantified the size of motor variability. The SaEn is the non-linear estimator that can show the complexity of the signal.

Across all individuals, larger cycle-to-cycle variability of baseline muscle activation was associated with longer endurance time during the knee extension task. Males exhibited longer endurance times than females, and probably achieved that by utilizing a motor strategy involving more variable recruitment of synergistic and antagonistic motor units during the knee extension task. No obesity-related changes in endurance time were found. However, obese individuals

exhibited a greater cycle-to-cycle variability during the knee extension task, indicating a larger alteration in the recruitment of motor units across successive contractions, which contributed to comparable endurance time and performance with their non-obese counterparts.

This study was a basic investigation into changes in motor variability and how it was associated with the development of fatigue among older adults; and the potential influences of gender and obesity on the relationships. Given that obesity rates in the older population is rising continuously and becoming a substantial health and safety problem especially in the occupational environment, the results from this study are both timely and critical for practical design applications, especially by recognizing the importance of having a variable motor pattern in task performance, particularly among older adults.

ACKNOWLEGEMENT

There are too many people to whom I would like to express my sincere thanks for their help along the process of my 2-year academic life. Among these, I want to firstly thank my advisor Dr. Srinivasan, who provided me opportunities, guided and encouraged me throughout my research study, which I believe would be one of the most memorable experience in my entire life. I would also like to thank particularly for her understanding and support when my research schedule was interrupted by the internships. There was no way I could complete my thesis without her professional expertise and instructions. My thanks would also go to other research committee members – Dr. Mehta, Dr. Kim and Dr. Nussbaum. Great thanks would be sent to Dr. Mehta and Dr. Rhee at Texas A&M for the resources and suggestions they provided for my research, including their massive work on the data collection, their patience on answering my questions, and Dr. Mehta's support in all meetings regarding this study even over the phone. I also want to thank Dr. Kim who gave me a lot of great help and instructions on the data analysis process. Last but not the least, many sincere thanks to Dr. Nussbaum for his valuable advice and timely reply to my questions on everything about the research, ranging from the drafting of this thesis to the scheduling of meetings.

Thanks to the entire ISE staff, especially the Human Factors and Ergonomics group for bringing me into the door of ergonomics, helping me grow from a complete novice all the way to my master graduation. I will also give my thanks to all the administrative staff particularly Hannah Parks and Rhonda Hawley for their help.

I would like to express my special thanks to Brian Sherman, who is the manager of the Ergonomics team at Tesla and my mentor during my internships there, and is also an outstanding alumnus of the Human Factors track at Virginia Tech. I have been given a great amount of guidance and opportunities from him, obtaining hands-on experience by applying ergonomic principles in real manufacturing environment. This incredibly increased my desire for learning, forced me to get out of my comfort zone and face my shortcomings, so that I was able to learn and improve very fast.

Finally, I want to give the deepest thanks to my parents for their unconditional love and support. I know I can never thank them enough, but I will continuously better myself as return.

I am truly grateful that I have got a warm family holding my back and met with so many excellent mentors and friends, who offered me guidance and support along the way.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

The number of older adults in the American work force is increasing dramatically: From 1990 to 2010, the percentage of workers in the U.S. civilian labor force aged 65 and older rose at an average annual rate of 3.4 percent, in contrast with a 0.9-percent average annual increase for those under 65 (BLS 2017). This was due largely to the increase in the labor force participation rate of the 65-and-older group: from 11.8 percent in 1990 to 17.4 percent in 2010 (BLS 2017). However, workers in the age group 55-64 have also been reported to suffer from the highest incidence rate of occupational injuries and illnesses (115.8 cases per 10,000 full-time workers in 2015) (BLS 2016). Age-related declines in muscular performance were not only affecting the work quality of old employees, but also their safety and morale. Thus, as increasing numbers of older adults are staying employed, understanding age-related changes in functional capacity and performance are critical to the design of safe jobs as well as for keeping older adults productively employed as part of the work force.

Aging is associated with several morphological and functional impairments in skeletal muscles that lead to a decrease in muscle force production capacity, which has consequently been associated with reduced physical function and independence in aging adults. Age-related changes in muscle fiber composition and reduction of active tissues have been linked to declining physiological capabilities such as reduced muscular strength and speed (Frontera, Hughes et al. 1991, Hughes, Johnson et al. 1999, Kent-Braun and Ng 1999). Skeletal muscle size decreases by about 1.4% per year after 50 years of age (Frontera, Hughes et al. 2000) and muscle strength decreases 2-5% per year (Delmonico, Harris et al. 2009). Nineteen percent age-related strength decline in older adults has been found for shoulder abductors (Yassierli, Nussbaum et al. 2007). Similarly, Hughes et al. demonstrated that isometric shoulder strength declined with aging for internal and external rotation, flexion, extension, abduction, and adduction functions (Hughes, Johnson et al. 1999). However, contrary results from other studies indicating no difference in shoulder strength between younger and older adults also exist (Lannersten, Harms-Ringdahl et al. 1993, Cavuoto and Nussbaum 2013).

Declining motor performance in older adults has been observed in several studies, especially in force-control tasks where older adults have been shown to be weaker and less steady (i.e., they exhibit greater fluctuations in force around a target force) than young adults (Enoka, Christou et al. 2003, Yoon, De-Lap et al. 2008). Decreased steadiness in older adults has been shown to be greatest during low-intensity constant-effort contractions involving upper and lower extremity muscle groups (Enoka, Christou et al. 2003, Tracy, Maluf et al. 2005, Marmon, Pascoe et al. 2011). However, evidence has also been found that older adults present more resistance to fatigue indicated by longer endurance times than young adults when tasks require exertions at fixed relative values (Narici, Bordini et al. 1991, Bazzucchi, Marchetti et al. 2005, Yassierli, Nussbaum et al. 2007). This has been attributed to different compositions of muscle fibers between old and young adults.

Older adults may have more type I muscle fibers (slow twitch), that help enable long endurance tasks, and fewer type II muscle fibers (fast-twitch) that are used for fast high force production but prone to fatigue. In a study conducted by Bazzucchi et al. (2005), endurance time was significantly longer in the older group compared to the younger group at 50% MVC and 80% MVC during isometric elbow flexions, while comparable results were found at 30% MVC (Bazzucchi, Marchetti et al. 2005). According to Bazzucchi et al. (2005), the interactive effect between age and force indicated that the motor units (MU) recruited (slow twitch, low threshold) are the same in both younger and older people at low levels of force demand. The fast twitch, rapidly fatiguing fibers, being the later recruited MUs, are those that are most affected by the ageing process (Bazzucchi, Marchetti et al. 2005). The MU recruitment strategy could also explain the finding reported by Bazzucchi et al. The younger group had a higher rate of decline of muscle fiber conduction velocity compared to the older group, when shifting to a higher force level or sustaining at the same relatively high force level, possibly indicating a greater recruitment of fast-twitch muscle fibers among younger individuals at higher force levels (Bazzucchi, Marchetti et al. 2005). In addition, changes in EMG measures during a sustained submaximal exertion also suggested a higher fatigue resistance for old adults. Older individuals have demonstrated lower rates of EMG amplitude changes during exercises involving the elbow flexors (Bilodeau, Erb et al. 2001). However, even though the reason for greater fatigue resistance of older adults was well explained, controversies regarding effects of aging on endurance time still exist. Some earlier studies didn't find any significant difference in muscle endurance between old and young age groups (Larsson and Karlsson 1978, Frontera, Hughes et al. 1991).

When maximal isokinetic contractions of elbow flexion at six fixed angular velocities were examined, peak torques for the older group were lower than the younger group at all angular velocities, suggesting an impairment of the neuromuscular system of older men, which is less powerful and less fatigable than that of young men (Bazzucchi, Marchetti et al. 2005). In summary, although many studies have shown that aging contributes to physiological declines and is associated with endurance changes, contradictory results regarding aging effects on strength loss and fatigue-resistance have been reported. This can probably be attributed to individual physiological differences among participants involved in different studies. Other factors such as experience and training that can have large influences on physical conditions and performance also introduce more variability and complexity into conducting studies and interpreting results on aging-fatigue relationships.

This thesis specifically examines the performance of force-control tasks by older adults, with the aim of contributing to better understanding and characterization of the changes in functional performance and associated neuromuscular control mechanisms that may expose older adults to higher and more severe risk of musculoskeletal disorders. The effects of two relevant and likely significant factors, gender and obesity, are considered in these studies, as elaborated below.

1.1 Obesity

Obesity is one of the key factors that contributes to high risk of injuries and diseases. Obese workers were 1.7 times more likely to be absent from work duties due to injuries or illnesses than non-obese workers, leading to substantial loss of productivity and cost (Schulte, Wagner et al. 2007). Obese people are more prone to diseases such as hypertension, dyslipidemia, type 2 diabetes, and arthritis (Hertz and McDonald 2004). Moreover, it was reported that over 600 million adults were obese in 2014 in the United States, with the number more than doubled since 1980 (WHO 2016). The increase of the prevalence of obesity gave rise to great concerns of obesity-induced health problems and occupation-related consequences. Further, studies have shown that fat mass increases with age and is higher among later birth cohorts peaking at about age 60-75 years

(Rissanen, Heliövaara et al. 1988, Drøyvold, Nilsen et al. 2006, Ding, Kritchevsky et al. 2007), whereas muscle mass and strength starts to decline progressively around the age of 30 years with a more accelerated loss after the age of 60 (Bassey 1998, Rantanen, Masaki et al. 1998, Frontera, Hughes et al. 2000, Stenholm, Harris et al. 2008). Due to such physiological changes with aging, obesity and low muscle mass, defined as sarcopenic obesity, maybe more likely to coexist in older adults, resulting in too low body strength relative to their body size (Stenholm, Harris et al. 2008). This in turn may expose obese older adults to more risks of being injured and developing disability in the future. Thus, the combined effect of obesity and aging is potentially a great ergonomic risk factor that deserves to be studied in more detail.

Several functional impairments have been found to be associated with obesity. A decrease in capillary density and blood flow was observed in obese people, resulting in limited supply of oxygen and energy sources to the muscles (Kern, Simsolo et al. 1999, Newcomer, Larson-Meyer et al. 2001). This in turn expedited the development of muscle fatigue and reduced the efficiency of recovery (Newcomer, Larson-Meyer et al. 2001). Thus, it is expected that obese people will experience more and faster fatigue than normal weight people when doing the same amount of task. Endurance time, strength loss, work performance, and ratings of perceived discomfort (RPD) are dependent measures that are commonly used to examine the effects of obesity-induced muscle fatigue. Those effects have been investigated during sustained and intermittent isometric contractions of specific muscle groups, as well as tasks in real occupational settings such as manual material handling and assembly, as elaborated below.

Numerous studies used sustained isometric tasks to investigate muscle fatigue and endurance. A significant negative correlation between BMI and endurance time was found in a study involving only males, where participants were asked to do sustained isometric hand grip at 30% maximal voluntary capacity (MVC) until exhaustion (Eksioglu 2011). Also, subjects who had longer endurance times turned out to need less recovery times (Eksioglu 2011). Similarly, Cavuoto and colleagues reported that the endurance time of a non-obese group was up to 18% longer than that of an obese group during sustained isometric shoulder flexions in two different shoulder postures (Cavuoto and Nussbaum 2013). They also found that even though obese participants presented up to 25% higher absolute strength (MVC) than non-obese participants, their relative strength (MVC/body mass) was 14% lower (Cavuoto and Nussbaum 2013). Although this study included both age and obesity as factors, they did not find an interactive effect of obesity and age on endurance time, and the results were inconclusive regarding acute fatigue effects for individuals who were older and obese. In another study, Kankaanpää and colleagues found that women with high BMI fatigued faster than women with normal or low BMI, indicated by shorter endurance time for the obese group when performing isometric back endurance tests (Kankaanpää, Laaksonen et al. 1998). However, contrary results were observed in another study conducted by Cavuoto and colleagues, involving only young people aged below 30 years. No significant differences in endurance time were observed between obese and non-obese groups in sustained isometric torso extension (Cavuoto and Nussbaum 2013). Conflicting results obtained in the previous studies could probably be due to the differences in experimental protocols, such as different muscle groups being examined, demands of the task, age and gender.

In studies examining intermittent tasks, one study has been conducted to investigate the effect of obesity on functional performance during intermittent hand-grip and shoulder flexion tasks. There was a significant difference between groups with the non-obese group having up to 60% longer endurance time compared to the obese group (Cavuoto and Nussbaum 2014). The obese group also showed a 32% higher RPD and higher rates of performance decrement than the non-obese group (Cavuoto and Nussbaum 2014). Another study found that force fluctuation was significantly higher in the obese group compared to the healthy group when performing intermittent hand-grip exertions at 30% MVC level (Shortz and Mehta 2013). Moreover, simulated real world manual material handling tasks were used for an earlier study to investigate the relationship between BMI, fatigue and performance, which suggested longer task completion times for the obese group compared to the non-obese group (Tetteh, Latif et al. 2009).

Overall, the majority of previous studies suggest a changed muscle physiology, faster onset of fatigue and impaired functional performance associated with obesity. The size of such effects would likely be modified by the specific tasks performed, muscles used, age, and gender, and the nature of these interactions is the subject of current ongoing research by several groups. However, with the exception of the Cavuoto and Nussbaum study (Cavuoto and Nussbaum 2013), where they studied the interactions of age and obesity, the effects of obesity on performance and motor control has rarely been studied specifically for older adults, and also not across multiple muscle groups. So age-specific decrements in physiology and motor control, accompanied with obesity-related changes may pose new challenges that are yet to be understood. This is essential to gain deeper understandings of the underlying mechanisms of neuromuscular control, which will then serve as useful principles for job design in order to reduce injuries and illnesses in their occupational and daily life.

1.2 Gender

Gender difference has been widely explored in the biomechanics, WMSD and motor control research communities in terms of fatigability and performance changes with fatigue, and yet, it has been particularly difficult to reach a broad consensus on the effects of gender on performance, fatigue and MSD risks. Men and women differ in anatomy and physiology, which results in marked sex differences in neuromuscular performance and fatigability. In general, the skeletal muscles of men are larger and some muscles possess a greater proportional area of metabolically and functionally faster Type II muscle fibers than that of women (Simoneau and Bouchard 1989, Staron, Hagerman et al. 2000, Jaworowski, Porter et al. 2002, Roepstorff, Thiele et al. 2006). Consequently, on average, the whole muscles of men are usually stronger and more powerful than that of women. When contractions are sustained or repeated, however, the relative reduction in force and power can differ between men and women when performed at the same relative intensity of contraction.

Several studies have demonstrated that women had longer endurance times when performing low-intensity contractions, but that such differences disappeared or diminished at high intensity levels. Maughan (Maughan, Harmon et al. 1986) reported a longer endurance time for women during an isometric knee extension at a lower effort level (20% MVC) compared to men, but no difference at higher force levels (50% or 80% MVC). Similar results were found for the dynamic elbow-flexion task in the same study. The female subjects were able to perform a greater number of repetitions than males at loads of 50%, 60% and 70% of one repetition maximum (RM), but there was no difference between gender at loads of 80% or 90% of 1RM (Maughan, Harmon et al. 1986).

Note that relative force levels were applied by Maughan et al. (1986). This may have influenced the results mentioned above, since males, who are usually stronger, sustain greater absolute forces when the target force is based on an individual's strength. It has been suggested that greater absolute forces are associated with increased intramuscular pressures, occlusion of blood flow, accumulation of metabolites, heightened metabo-reflex responses, and impairment of oxygen delivery to the muscle (Hunter and Enoka 2001). Furthermore, activation of the metabo-reflex, as measured by the rate of increase in the mean arterial pressure (MAP) and heart rate (pressor response), is inversely related to endurance time (Hunter and Enoka 2001). Thus, males would present shorter endurance time at the lower level contractions due to greater absolute force exerted than female. And when doing higher demanding tasks, females and males will both experience circulatory occlusion that will reduce endurance time in both genders. This speculation is reasonable, as tested in a subsequent study (SATO and OHASHI 1989), in which males had longer endurance times than females during sustained isometric elbow flexion, particularly at stronger contractions, when comparing absolute force levels. But when it came to the comparison between genders in terms of relative forces, the result was consistent with previous studies with females having longer endurance times (SATO and OHASHI 1989).

Many other subsequent studies have shown that when men and women were matched for strength, there were no differences in endurance or perceived fatigue (Hunter and Enoka 2001, Hatzikotoulas, Siatras et al. 2004), suggesting that a difference between men and women is probably be a strength effect, and not primarily related to gender. Cavuoto et al. reported a longer endurance time for males compared with females when participants exerted a fixed amount of force while doing hand-grip and shoulder flexion (Cavuoto and Nussbaum 2013). One study examining gender effects on fatigue during intermittent muscle contractions at 50% MVC closely matched the absolute force of male and female participants (Fulco, Rock et al. 1999). The researchers recruited male and female subjects with similar maximal voluntary contractions of the adductor pollicis muscle. Therefore, use of absolute force or relative force would not have any influence on the relationship between gender and endurance time as discussed in the preceding paragraph. The result of this study showed better fatigue-resistance and recovery mechanisms in females with slower MVC decrease, nearly two times longer endurance time, and faster strength recovery from fatigue compared to males (Fulco, Rock et al. 1999). When participants performed incremental isometric dorsiflexion however, the results suggested no effect of gender on fatigue in terms of maintaining target force and the decreasing pattern of MVC. In contrast, gender differences were found in the muscle contractile function and metabolism: 1) the majority of force potentiation occurred very rapidly (i.e., after baseline MVCs) in males, whereas potentiation reached its maximum later, during the exercise protocol, in females. 2) intracellular concentrations of Pi and H2PO4- increased more and pH levels decreased more in males than females during the incremental isometric exercise, indicating a greater reliance on non-oxidative sources of ATP in males compared with females. These results suggested that the underlying mechanisms of muscle response to fatigue was different between gender, even though no difference in the magnitude of fatigue was observed (Kent-Braun, Ng et al. 2002).

Most previous gender differences in fatigability have been attributed to differences in anthropometrical and functional body characteristics (e.g. size and strength). However, it has been found in recent studies that males and females differ in muscle coordination and movement strategies, which may indeed play an important role in the development of muscle fatigue and MSDs. In a study involving elbow flexion endurance tasks, forces exerted by females turned out to be less variable than those of males (Svendsen and Madeleine 2010). Another study examining gender difference in fatigability and motor control in a repetitive pointing task revealed that even though females and males did not differ in endurance time, males exhibited a higher increase in trapezius muscle variability, and a decrease in biceps muscle variability with fatigue. Women, however, showed an increase in the biceps muscle variability, indicating gender differences in the relative contributions of the shoulder and elbow towards maintaining the same multi-joint movements with fatigue (Srinivasan, Sinden et al. 2016). Another study using the same experimental protocol suggested associations between high initial variability in the upper trapezius and Supraspinatus with higher endurance for females, whereas initial low values in connectivity among muscle pairs were found to be associated with longer endurance time for males (Fedorowich, Emery et al. 2013). Differences between males and females in muscle coordination was found in another study, indicating less activation of agonist muscles and greater activation of synergist muscles for females than males during an isometric shoulder task (Anders, Bretschneider et al. 2004).

1.3 Muscle Fatigue and Motor variability

Muscle fatigue, the decline in muscular capacity to generate force, has been the focus of numerous investigations. It has been suggested to be related to impairment of performance, initiation of musculoskeletal disorders (MSDs), and occupational injuries (Takala 2002, Gallagher and Schall Jr 2017). Muscle fatigue can be caused by many different factors, ranging from the accumulation of metabolites within muscle fibers to the generation of an inadequate motor command in the motor cortex (Enoka and Duchateau 2008). Multiple individual and task-specific factors such as gender, age, body mass index (BMI), pain status, health condition (e.g. previous injury history), task, muscle groups used, and experience have been recognized as influencing fatigue-related performance declines and MSDs in adults (Bemben, Massey et al. 1996, Madeleine and Madsen 2009, Cavuoto and Nussbaum 2013). Recently, an increasing number of studies emphasize the link between variations in movements, muscle activities and coordination with the development of fatigue.

The natural variation in postures, movements and muscle activity observed to different extents in all tasks, even when an individual tries to achieve identical performance across repeats, is referred to as "motor variability" (Srinivasan and Mathiassen 2012). Variability of motor control is considered as an intrinsic trait of human activity, as it has been shown to occur even in highly controlled repetitive tasks (Fethke, Anton et al. 2007, Jackson, Mathiassen et al. 2009). Contrary to the traditional view that motor variability is just noise that is detrimental to performance, it is now widely accepted that increased motor variability may not lead to deterioration in performance (Newell and Slifkin 1998, van Emmerik and van Wegen 2000), and that motor variability may actually have an important functional role in skill acquisition and prevention of overuse injuries (Arutyunyan GH 1969, Hamill, van Emmerik et al. 1999, van Emmerik and van Wegen 2000, Riley and Turvey 2002, Mathiassen 2006, Madeleine 2010). An interest in motor variability has emerged in occupational research due to its associations with pain/discomfort, fatigue and performance (Srinivasan and Mathiassen 2012); in a clinical context focusing on pain, aging and diseases (van Emmerik and van Wegen 2000, Heiderscheit, Hamill et al. 2002), and rehabilitation (Field-Fote and Tepavac 2002, Daly, Sng et al. 2007), and in sports biomechanics because MV is associated with performance and injury risk (Davids, Glazier et al. 2003, Bartlett, Wheat et al. 2007, Preatoni, Ferrario et al. 2010).

In the context of fatigue, motor variability has been of particular interest as previous research indicates that it may have a close relationship with development of muscle fatigue. Fluctuations or variabilities, used to be perceived as noise and disturbance to the signal, have been demonstrated to exhibit a degree of order that can be attributed to the operation of an adaptive control system (Falla and Farina 2007). More variability in motor strategies has been suggested to be representative of new motor solutions to look for ways to reduce fatigue-induced discomfort and deterioration in performance. Studies have shown that inter-individual differences in motor variability may be an important factor in determining individual differences in susceptibility to developing fatigue, pain and musculoskeletal disorders caused by repetitive tasks: specifically in the context that higher motor variability may be related to stronger resistance to muscle fatigue and better adaptation to task demands (van Dieën, Oude Vrielink et al. 1993, Mathiassen, Möller et al. 2003, Madeleine 2010, Srinivasan and Mathiassen 2012).

However, there are still open questions about the motor control mechanisms explaining age-related declines in performance and rises in fatigability, specifically when involving interactions between gender, obesity and muscle group in older adults. Additionally, motor variability traits of muscle activity and performance in the early period of an endurance task may contain the information on individual differences in fatigability. However, whether systematic gender differences exist in motor variability, how they would vary by obesity, and the associations between motor variability and fatigability in older adults has been largely unexplored. As recent demographics presents an older and more obese workforce, more data are needed to facilitate the design of jobs to reduce ergonomic risks. Thus, it is imperative to explore ergonomic impacts of different body types on task performance, as well as the underlying reasons by in-depth examinations on the muscle activation patterns with a specific focus on motor variability.

1.4 Summary and Aims

Given the trends of increased aging and obesity among the workforce, the limited understanding of neuromuscular control strategies employed by older adults during the performance of endurance tasks, and how they vary with gender and obesity, is a critical gap in research to be answered. The main goals of this thesis were to understand whether the performance of intermittent endurance tasks by older adults was associated with gender and obesity, and whether muscle activation and force control patterns observed at baseline could predict inter-individual differences in endurance time.

1.4.1 Specific aims

1) Determine obesity and gender differences in endurance time, among older adults performing intermittent knee extension and hand-grip tasks until exhaustion;
2) Quantify the correlations between variability in muscle activity and force control at baseline with endurance time, during the performance of intermittent knee-extension and hand grip tasks by older adults;
3) Estimate the effects of obesity, gender and time on fatigue-related changes in force control and variation in muscle activation patterns during the performance of intermittent handgrip and knee extension tasks performed until exhaustion by older adults.

1.4.2 Hypotheses

Based on the evidence from prior literature, we expected that the obese group will exhibit less variability in muscle activity than the non-obese group, which will be associated with a shorter endurance time. Males and females were expected to differ in variability of muscle activities, reflecting different neuromuscular control mechanisms, which would be associated with gender differences in performance (force fluctuation) and endurance time. We also expected that baseline variation in muscle activation patterns will be related to endurance, and that variation in muscle activation and force control would increase with fatigue, and that fatigue-related changes in these variables would significantly differ with gender and obesity.

1.4.3 Choice of tasks and metrics

Knee extension and hand grip tasks were specifically investigated in this thesis since the majority of occupational and daily living tasks involve hand activities, and the knee is important for controlling balance and movement. Also, in many cases, particularly for old people, hand grip and knee extensions are performed collectively to accomplish several basic tasks, such as transition from sitting to standing, climbing stairs or ladders with the assistance of hand, and squat lifting.

Variability in muscle activation patterns and force were investigated using both linear and non-linear estimators. Linear measures commonly used are standard deviation and coefficient of variation. These approaches provide information about the quantity of variability of a signal, which can reflect the result of motor control. However, they generate an average picture of the variability in the movement patterns, which removes the temporal variations and masks the true structure of variability present in the movement (Harbourne and Stergiou 2009). Thus linear measures alone are often not adequate to depict the full picture of neuromuscular control. Non-linear estimators such as approximate entropy (ApEn) or sample entropy (SaEn) are usually used to quantify the structure of variability. These are regularity statistics that quantify the amount of randomness in a time series (Boker, Schreiber et al. 1998, Madeleine and Madsen 2009). In terms of muscle activity, entropy is used to quantify the complexity in the muscle activation pattern, thus reflecting how much a muscle is actively controlled by the central nervous system using online corrections (over and above an underlying motor program). Therefore, both linear and non-linear measurements were used in this study.

1.4.4 Anticipated findings

The results of this study will enhance our knowledge regarding how obesity affects physical functioning in older women and men. This will provide insights on the underlying neuromuscular control strategies used by older adults, which would have critical implications for the design of work and training for specific populations to reduce injuries and risks.

2.0 METHODS

2.1 Participants

Fifty-two right-hand dominant older adults (Age > 65, Mean Age = 73) were recruited from the local community who formed four experimental groups: obese male, obese female, non-obese male, and non-obese female. The obese group comprised of 9 males and 13 females. The non-obese group consisted of 15 males and 15 females. Participants whose BMI were greater than 30 kg/m^2 were considered to be obese. Otherwise, they belonged to the non-obese group. Demographic data of the participants are shown in Table 2.1. All participants were right-hand dominant based on self-report and reported to be sedentary to recreationally active individual without any musculoskeletal injuries or known disorders within the past year. Fitness was measured using the International Physical Activity Questionnaire (IPAQ) survey (Appendix A). The participants provided written informed consent before participation in the study and the Institutional Review Board at Texas A&M University approved the procedures.

Table 2.1 Demographic data: Note that all measures are presented as mean (SD)

Group	**Number**	**Age (years)**	**Stature (cm)**	**Body Mass (kg)**	**BMI (kg/m^2)**	**Knee extension strength (Nm)**	**Hand-grip strength (Nm)**	**Waist circumference (cm)**	**No. of hours of moderate PA during previous 1 week (from IPAQ)**
Non-obese male	15	74 (6)	178 (7.8)	77 (8.6)	24.45 (1.22)	107.94 (30.59)	11.56 (2.85)	99.06 (4.94)	6.06 (6.76)
Non-obese female	15	72 (5)	164 (5.8)	61 (6.9)	22.7 (1.89)	72.35 (13.54)	9 (1.9)	88.37 (9.32)	1.42 (2.0)
Obese male	9	73 (7)	180 (7.6)	119 (16.8)	36.33 (3.7)	104.77 (45.7)	12.19 (3)	131.09 (10.08)	1.45 (1.88)
Obese female	13	71 (5)	160 (5)	99 (18)	38.32 (5.88)	62.04 (19.67)	8.50 (1.71)	118.39 (12.42)	1.46 (2.42)

2.2 Procedures

Participants attended two study sessions 1) isometric handgrip and 2) isometric knee extension exercise on separate days. In each session, the participants were instrumented with several bio-instruments. In the handgrip exercise session, participants were asked to sit upright with their upper arm at their side, elbow flexed at 90^{o} and lower arm supported on an armrest and performed isometric handgrip contractions with their dominant (right) hands using a hand dynamometer (TSD121C Hand Dynamometer, BIOPAC, CA, USA). During the knee extension exercise session, the knee force exertions were measured using an isokinetic dynamometer (Humac NORM, Computer Sports Medicine, Stoughton, MA). Participants were seated upright with the dominant (right) hip and knee flexed to 90^{o}. The epicondyles of their femur were aligned with the dynamometer's center-of-rotation and then locked with a dynamometer pad secured above the ankle, anterior to the tibia (Figure 2.1). The participant's upper body was secured firmly in the chair to minimize upper body motion caused by lower extremity muscle contraction.

Figure 2.1 Knee extension experimental setup

Three isometric maximum voluntary contractions (MVCs) in the postures described above, were measured prior to hand grip and knee extension tasks for each participant. Each subject was verbally encouraged to achieve maximal force. Two minutes of rest were provided in between each MVC trial to enable good recovery. The greatest force achieved by the subject was taken as the MVC force. The target force level of 30% MVC was determined accordingly for the following experimental trials.

Following the MVC trials and prior to the actual experimental data collection, participants were provided with practice sessions to familiarize with the task. After the familiarization and a period of adequate rest, participants performed intermittent isometric hand grip or knee extension at 30% MVC until exhaustion. Each contraction lasted for 15 seconds with 15 seconds rest between each trial (Figure 2.2). Participants were asked to control their force generation against the target moment on the screen, which corresponded to a force of 30% MVC, as closely as possible based on real-time visual feedback provided. Participants continued performing the task until they were not able to maintain the 30% MVC force during the fifteen-second exertion or they felt they were too fatigued to continue. An MVC trial was performed immediately after the task was completed, to objectively quantify fatigue using changes in strength.

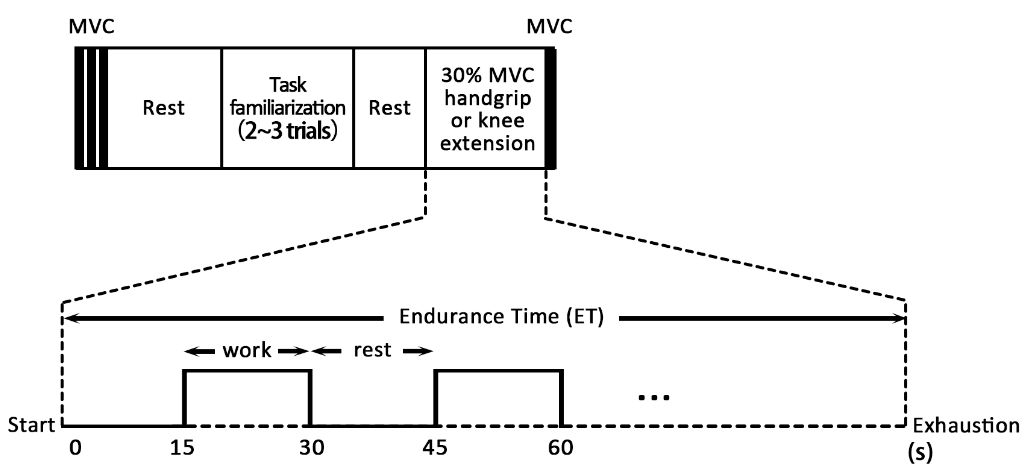

Figure 2.2 Experiment Protocol

2.3 Measurements

Handgrip force, handgrip and knee extension electromyogram (EMG) signals were recorded at 1000 Hz during the entire exercise session (Biopac Inc., Ca, USA, Biopac MP Systems).

The skin was cleaned using alcohol before placing the EMG electrodes. For the hand grip, EMG signals were obtained from the flexor carpi radialis (FCR) and extensor carpi radialis (ECR). Muscle activities of the rectus femoris (RF) and vastus lateralis (VL) were recorded using surface EMG for the knee extension exercise. Knee extension force was recorded at 100 Hz (Humac Norm Isokinetic Dynamometer, Computer Sports Medicine, Stoughton, MA). The recorded signals were transmitted to a dedicated PC using an A/D converter.

2.4 Data Analysis

Force and EMG data of the knee and hand were processed in Matlab R2017a (The MathWorks, Inc., Natick, MA, USA). Force data were filtered using a first-order, low-pass Butterworth filter at a cut-off frequency of 15 Hz. EMG signals from each muscle were band-pass filtered (20-450 Hz) using a sixth-order Butterworth filter. Then root mean squared (EMG RMS) value of the EMG signal was calculated and normalized with EMG RMS of MVC trials. The entire period of task performance of each individual was split equally into early, middle and late "task-periods" by splitting the data into each one-third portion. The first task-period was referred to as the "baseline" data.

The middle 10 seconds of each fifteen-second contraction were extracted from force and EMG data respectively for each subject and used in the data analysis. Exertions that were extremely irregular, including twitches, jerks or gaps during the contraction, were excluded from the analysis to avoid potential confounding influence on the result considering motor variability as the primary focus of this study. This procedure resulted in removal of 18 trials in total, representing less than 0.4% of data.

Variability was characterized using a combination of linear (coefficient of variation) and nonlinear techniques (sample entropy), to quantify the amount and structure of EMG and force variability (figure 2.3):

1) For computing the **within-cycle coefficient of variation (CV)**, mean and standard deviation of the middle 10 seconds of each contraction were calculated for both force and EMG data. Within-

cycle CV was estimated for a whole task-period by pooling the within-cycle CV from all cycles in that task-period: i.e. by dividing pooled within-cycle standard deviation of all cycles within a task-period by the average of the means from each cycle.

2) **Between-cycle CV** was quantified as standard deviation of the means from each cycle within a task-period relative to the mean across contractions in each period.

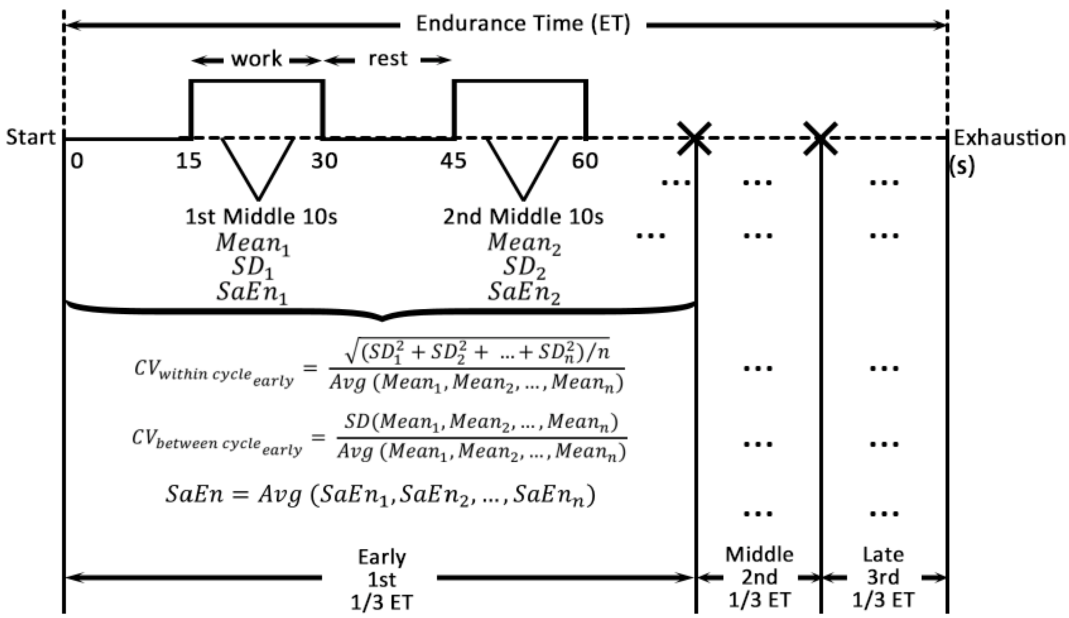

Figure 2.3 Data analysis (SD - standard deviation, CV - coefficient of variation, SaEn - sample entropy)

3) **Sample entropy (SaEn)** of each contraction was computed and averaged within each task-period using the middle ten-seconds of data (force and EMG. The algorithm of sample entropy employed in this study was listed step by step as below, referred from Richman an colleagues (Richman and Moorman 2000).

For a time series u of N points, described as $\{u(j): 1 \leq j \leq N\}$, embedding vectors x with time lag τ can be formed as follows:

$$x_m(i) = \{u(i + k * \tau): 0 \leq k \leq m - 1\} \quad (1)$$

In total, $N-(m-1)\tau$ embedding vectors can be formed for $\{i|1 \leq i \leq N-(m-1)\tau\}$, where $x_m(i)$ is the embedding vector of m data points from $u(i)$ to $u(i+(m-1)\tau)$.

<u>Embedding dimension</u>: m is the embedding dimension that was determined by applying the false nearest neighbor (FNN) approach. The FNN identifies the number of "false nearest neighbors", points that appear to be nearest neighbors because the embedding space is too small, of every point on the attractor as associated with the orbit u(j), j = 1,2, … , N (Kennel, Brown et al. 1992). The output is the percentage of FNN versus increasing embedding dimension, with the optimal embedding dimension found where the percentage is sufficiently small and not decreasing significantly for the higher dimension. An embedding dimension of m=4 was utilized here by taking the grand average of the computed values of the 8th contraction among all subjects.

<u>Time lag</u>: τ represents the time lag. Based on previous literature, the time lag for this study was chosen to be set at a delay at which the autocorrelation function of the time series falls by as much as 1/e (Rosenstein, Collins et al. 1993). The 8th contraction was randomly selected to be used to compute the time lag for every participant, and the grand average of the computed time lags was chosen. Time lags of τ=5 for the knee extension activity and τ=2 for the handgrip exercise were determined for this study.

For each embedding vector $x_m(i)$, $C_i^m(r)$ was calculated, which was defined as the probability that any vector $x_m(j)$ is within a tolerance distance (r) of $x_m(i)$.

$$C_i^m(r) = \frac{\{Number\ of\ x_m(j)\ such\ that\ d[x_m(i), x_m(j)] \leq r\}}{N-(m-1)\tau} \tag{2}$$

Where d, the distance between two vectors was defined to be:

$$d[x(i), x(j)] = \max\{|u(i+k*\tau) - u(j+k*\tau)| : 0 \leq k \leq m-1, i \neq j\} \tag{3}$$

i.e. the maximum difference of their corresponding scalar components.

The parameter r, a positive real number, referred to as the tolerance distance. It was recommended to be chosen between 0.1 and 0.25 times the standard deviation of the time series (Richman and Moorman 2000). 0.2 times the standard deviation was used in this study (Samani, Srinivasan et al. 2015). The next step was to compute $\Phi^{m}(r)$, representing the natural logarithms of the probability of matches $C_i^m(r)$, as given by:

$$\Phi^{m}(r) = \frac{\sum_{i=1}^{N-(m-1)\tau} \ln\,[C_i^m(r)]}{N-(m-1)\tau} \tag{4}$$

Sample entropy (SaEn), showing the negative logarithm of the relationship between the probability that two sequences coincide for m+1 and m points was computed as:

$$SaEn(m,r,N) = -\ln\left(\frac{\Phi^{m+1}(r)}{\Phi^{m}(r)}\right) \tag{5}$$

2.5 Statistical Analysis

A two-factor ANOVA (obesity × gender) with endurance time as the dependent variable, and obesity and gender as independent variables was conducted, to study the effects of gender and obesity on endurance time (Aim 1). Pearson's correlation coefficients were computed to determine the relationship between variability in force and EMG at baseline with endurance time (aim 2). Force variability was quantified as CV and SaEn & variation in muscle activation patterns were quantified by within-cycle CV, between-cycle CV and SaEn. For aim 3, a separate three-factor ANOVA (obesity × gender × time) was run to find differences between subject groups with time in dependent variables reflecting force control and variation in muscle activation patterns. The time variable in this analysis was set at three levels (early or baseline, middle and late periods). A significance level of $P < 0.05$ was used to identify statistical significance.

3.0 RESULTS

3.1 Task: Knee extension

The results for the knee extension task are presented below. Overall, the average knee extension endurance time across the 52 older adults tested in this study was 1445 (709) seconds. Results corresponding to each specific aim are presented below, in that order.

3.1.1 Aim1: Differences in endurance time as a function of obesity and gender

Figure 3.1 shows the average endurance times in each obesity and gender group. As can be seen in figure 3.1, male participants had 45% longer endurance time compared to females ($p = 0.005$). No statistically significant difference between obese and non-obese groups was observed. The corresponding statistical results are presented in table 3.1.

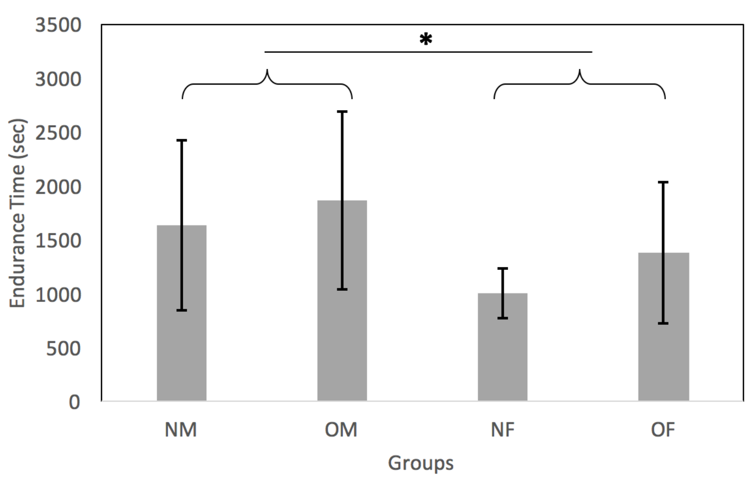

*Figure 3.1 Knee extension endurance times for each group with the between-subject standard deviation shown as error bars. NM: non-obese male, OM: obese male, NF: non-obese female, OF: obese female. The symbol * indicates a significant difference between genders.*

Table 3.1 Statistical results for the main and interactive effects of obesity and gender on endurance time, as obtained by a 2 factor ANOVA (significant results highlighted in bold)

Source	Nparm	DF	Sum of Squares	F Ratio	*p*
obesity	1	1	1260.81	2.63	0.11
gender	1	1	4213.67	8.79	**0.005***
obesity*gender	1	1	73.49	0.15	0.70

3.1.2 Aim 2: Correlations between force control & variation in muscle activation patterns at baseline with endurance time

As the Vastus Lateralis and the Rectus Femoris are both knee extensor muscle groups in the thigh having very similar functions during the knee extension task, results of these two muscles presented very similar trends. To simplify the presentation and ease the interpretation of the findings, only the results of the Vastus Lateralis (VL) are shown here, considering the fact that this muscle presented the strongest trends.

Correlations between coefficient of variation (CV) and sample entropy (SaEn) of force and endurance time (ET), as well as the correlations between within-cycle CV, cycle-to-cycle CV and SaEn of EMG with endurance time (ET) are plotted in figure 3.2 (a-e). Correlation coefficients and statistical results are summarized in table 2.

As seen in table 3.2 and figure 3.2 (a), force variability at baseline was significantly negatively correlated with endurance time. Cycle-to-cycle CV of VL EMG at baseline was also significantly correlated with endurance time, but in a positive manner for all participants (Table 3.2, Figure 3.2 (e)). SaEn of force and VL EMG, as well as within-cycle EMG CV were not found to be significantly correlated with endurance time (Table 3.2).

Table 3.2 Pearson's correlation coefficients and statistical results for correlations between variabilities in force and muscle activation with endurance time (significant results highlighted in bold)

	r	*p*
Force CV – ET	**-0.34**	**0.02***
Force SaEn – ET	0.16	0.27
VL CV – ET	0.13	0.36
VL SaEn – ET	-0.26	0.07
VL cycle-to-cycle CV – ET	**0.47**	**<0.001***

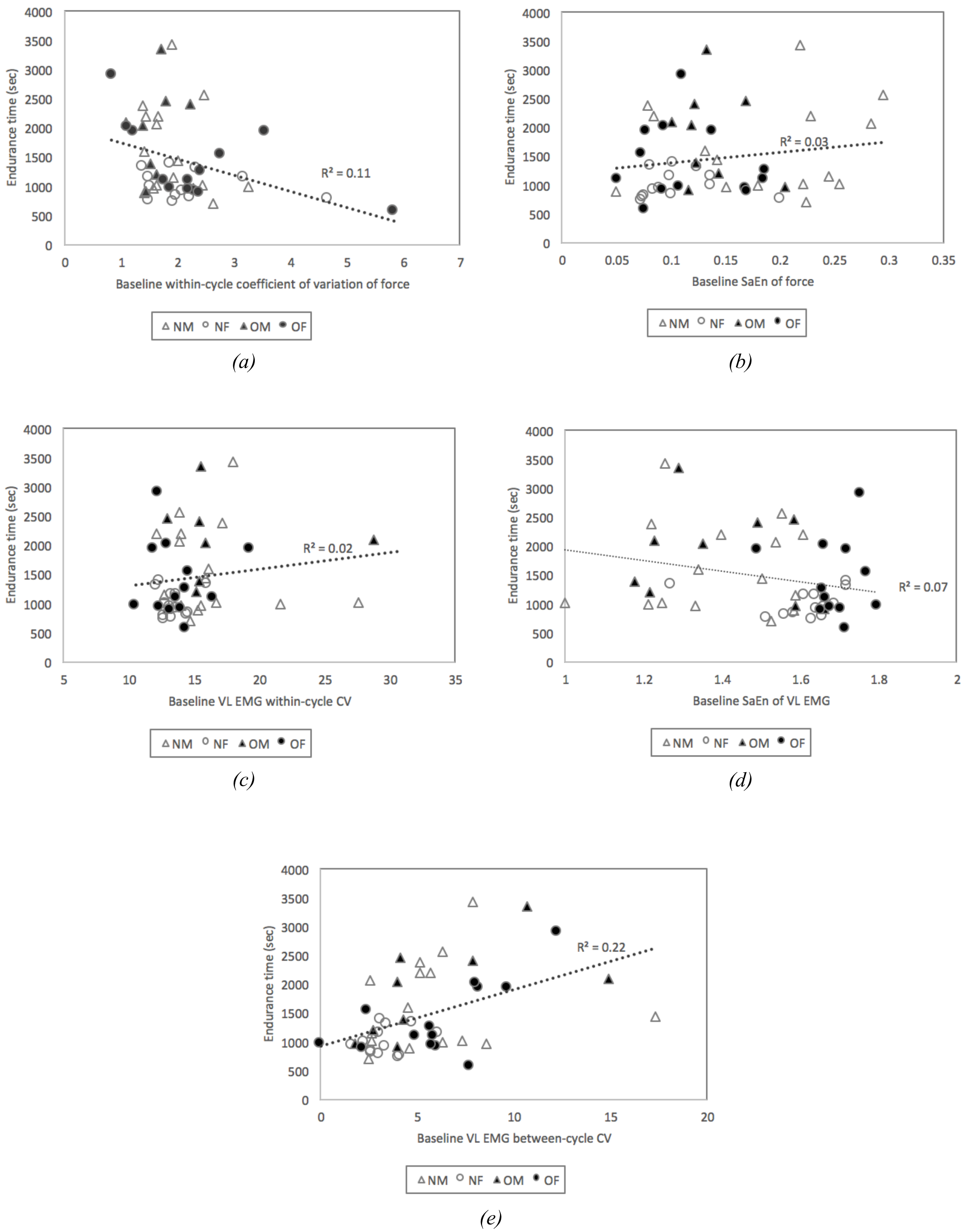

Figure 3.2 Correlations between endurance time and (a) force CV, (b) force SaEn, (c) within-cycle EMG CV, (d) EMG SaEn and (e) cycle-to-cycle EMG CV at baseline in the Vastus Lateralis; NM: non-obese male, OM: obese male, NF: non-obese female, OF: obese female

3.1.3 Aim 3: The effects of obesity, gender and time on force control and variation in muscle activation patterns

Force CV

Figure 3.3 shows means and standard deviations of force CV for each time period among different groups. As seen in the figure, males exhibited an increase in force CV with time, indicating a loss in force steadiness with fatigue. However, female participants showed a drop in force CV from the first to the second one-third period, but the force CV increased from the second to the third one-third period. Statistical results for the main and interaction effects of obesity, gender and time on force CV are shown in table 3.3. As shown in table 3.3 and figure 3.4, significant gender*time interaction occurred from the early period to the middle period with females being higher in force CV in the early period while lower in the middle and late periods.

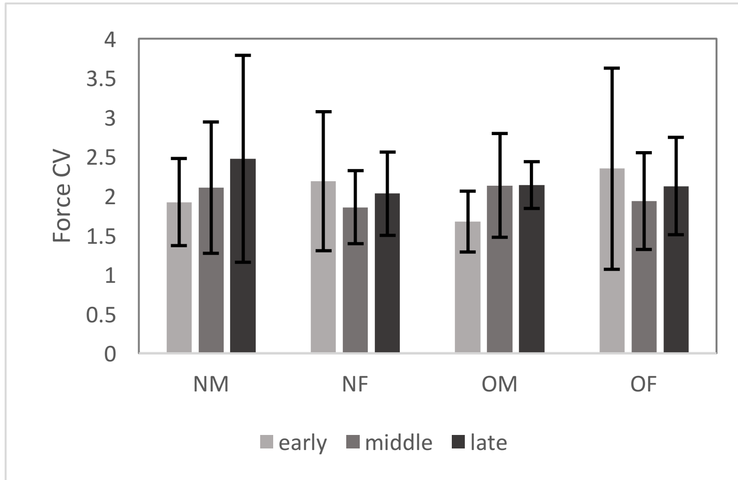

Figure 3.3 Mean values of force CV for each task-period of different groups with standard deviation bars, NM: non-obese male, OM: obese male, NF: non-obese female, OF: obese female

Table 3.3 Statistical results for the main and interactive effects of obesity, gender and time on force CV, as obtained by a 3 factor ANOVA (significant results highlighted in bold)

Source	Nparm	DF	Sum of Squares	F Ratio	*p*
obesity	1	1	0.00000481	0.08	0.78
gender	1	1	9.22448e-8	0.00	0.97
time	2	2	0.00009629	0.76	0.47
obesity*gender	1	1	0.00007948	1.25	0.26
obesity*time	2	2	0.00001840	0.15	0.87
gender*time	2	2	0.00039108	3.08	**0.05***
obesity*gender*time	2	2	0.00002690	0.21	0.81

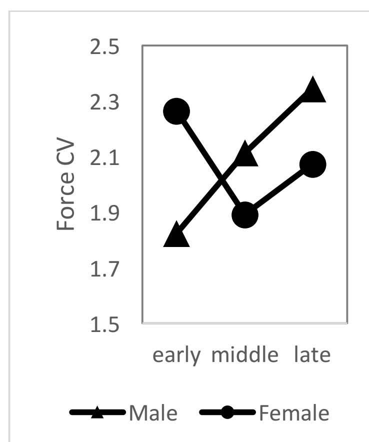

*Figure 3.4 Gender*time interaction effect on force CV*

Force SaEn

Means and standard deviations of force SaEn for different groups and time periods are presented in Figure 3.5. Gender difference in force SaEn among obese participants was marginal, whereas non-obese males were 82% higher than non-obese female. Moreover, non-obese male participants were also much higher in force SaEn compared to the other two obese groups, thus contributing to 45% greater force SaEn among males compared to females, and 20% higher SaEn in the non-obese group than the obese group. Statistical results (presented in Table 3.4) showed significant obesity, gender and obesity*gender interaction effects (Figure 3.6) on force SaEn. In terms of all of the subjects, obese participants had lower force SaEn compared to non-obese participants. In general, females were lower in force SaEn than males. However, such gender difference didn't exist among obese subjects, but was fairly great among non-obese people.

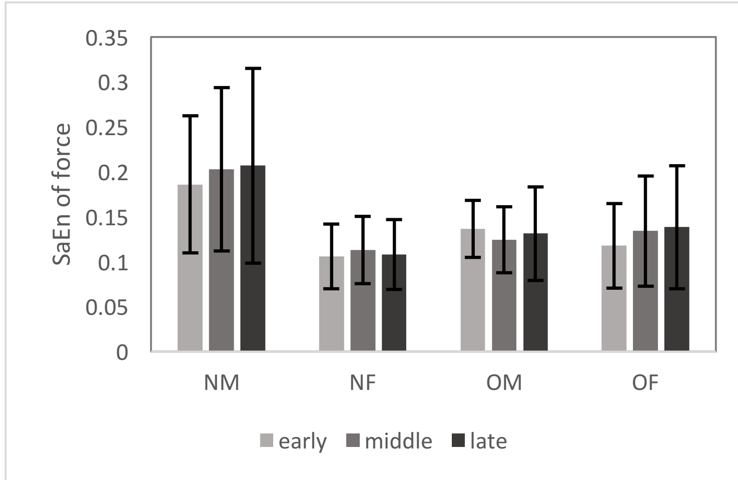

Figure 3.5 Mean values of SaEn of force for each time period of different groups with standard deviation bars, NM: non-obese male, OM: obese male, NF: non-obese female, OF: obese female

Table 3.4 Statistical results for the main and interactive effects of obesity, gender and time on SaEn of force, as obtained by a 3 factor ANOVA (significant results highlighted in bold)

Source	Nparm	DF	Sum of Squares	F Ratio	*p*
obesity	1	1	0.01974170	4.70	**0.03***
gender	1	1	0.07345635	17.47	**<.0001***
time	2	2	0.00235390	0.28	0.76
obesity*gender	1	1	0.07141216	16.99	**<.0001***
obesity*time	2	2	0.00059085	0.07	0.93
gender*time	2	2	0.00050384	0.06	0.94
obesity*gender*time	2	2	0.00354727	0.42	0.66

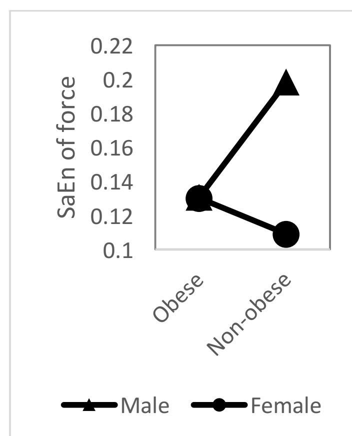

*Figure 3.6 Obesity*gender interaction effect on force SaEn*

Within-cycle EMG CV

Means and standard deviations of within-cycle CV of VL EMG for each period within each group can be seen from Figure 3.7. Male participants presented overall 19% greater within-cycle EMG CV in the Vastus Lateralis than female participants, and the gender difference was consistent across the obese and non-obese groups. In addition, within-cycle CV of VL EMG showed a slight decrease with time for all subjects. The statistical results were shown in table 3.5 and figure 3.8. Gender difference was found for within-cycle CV of VL EMG with male participants showing higher value, which indicated greater muscle activity during the contraction periods.

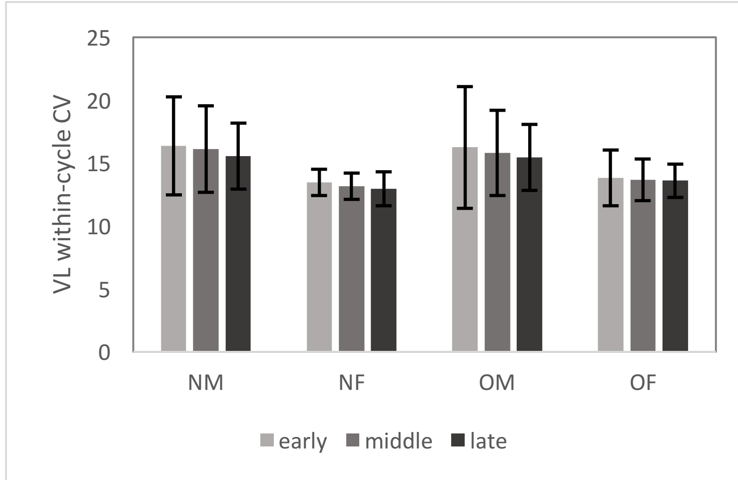

Figure 3.7 Mean values of within-cycle VL EMG CV for each time period of different groups with standard deviation bars, NM: non-obese male, OM: obese male, NF: non-obese female, OF: obese female

Table 3.5 Statistical results for the main and interactive effects of obesity, gender and time on within-cycle CV of VL EMG, as obtained by a 3 factor ANOVA (significant results highlighted in bold)

Source	Nparm	DF	Sum of Squares	F Ratio	*p*
obesity	1	1	0.00008427	0.12	0.73
gender	1	1	0.02214095	31.59	**<.0001***
time	2	2	0.00084733	0.60	0.55
obesity*gender	1	1	0.00041722	0.60	0.45
obesity*time	2	2	0.00002270	0.02	0.98
gender*time	2	2	0.00012295	0.09	0.92
obesity*gender*time	2	2	0.00001712	0.01	0.99

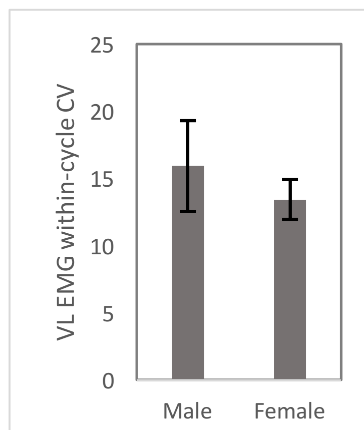

Figure 3.8 Means and standard deviations of within-cycle VL EMG CV for both gender

EMG SaEn

Figure 3.9 presents the means and standard deviations of SaEn for VL EMG among different groups. SaEn of VL EMG was 18% greater for females compared to males. Obese males had 4% lower EMG SaEn than the non-obese males, whereas obese females showed 4% higher values than the non-obese females. Additionally, for non-obese participants, SaEn of VL EMG slightly increased with time, while slight decreases were observed in the obese groups. Table 3.6 and figure 3.10 showed the statistical results. As seen in figure 3.10, EMG SaEn was significantly greater in female among all participants. The interaction between obesity and gender was also observed. Obese people were found to have lower EMG SaEn than non-obese people for males, whereas a reversed difference was shown for females.

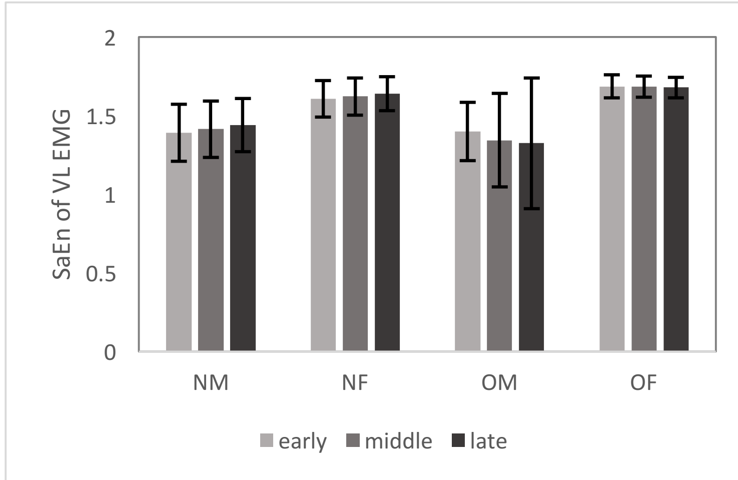

Figure 3.9 Mean values of SaEn of VL EMG for each time period of different groups with standard deviation bars, NM: non-obese male, OM: obese male, NF: non-obese female, OF: obese female

Table 3.6 Statistical results for the main and interactive effects of obesity, gender and time on SaEn of VL EMG, as obtained by a 3 factor ANOVA (significant results highlighted in bold)

Source	Nparm	DF	Sum of Squares	F Ratio	p
obesity	1	1	0.0000142	0.00	0.98
gender	1	1	2.5956319	83.12	**<.0001***
time	2	2	0.0006444	0.01	0.99
obesity*gender	1	1	0.1313556	4.21	**0.04***
obesity*time	2	2	0.0387683	0.62	0.54
gender*time	2	2	0.0051848	0.08	0.92
obesity*gender*time	2	2	0.0102656	0.16	0.85

*Figure 3.10 Obesity*gender interaction effect on VL EMG SaEn*

Cycle-to-cycle EMG CV

Cycle-to-cycle CVs of EMG in the VL muscle for each time period within different groups are shown in figure 3.11. Obese participants showed 18% higher cycle-to-cycle EMG CV than the non-obese participants. Males were 14% greater in cycle-to-cycle EMG CV than females. Significantly greater cycle-to-cycle CV in the Vastus Lateralis EMG was only observed for the obese group compared with the non-obese group as seen in table 3.7 and figure 3.12.

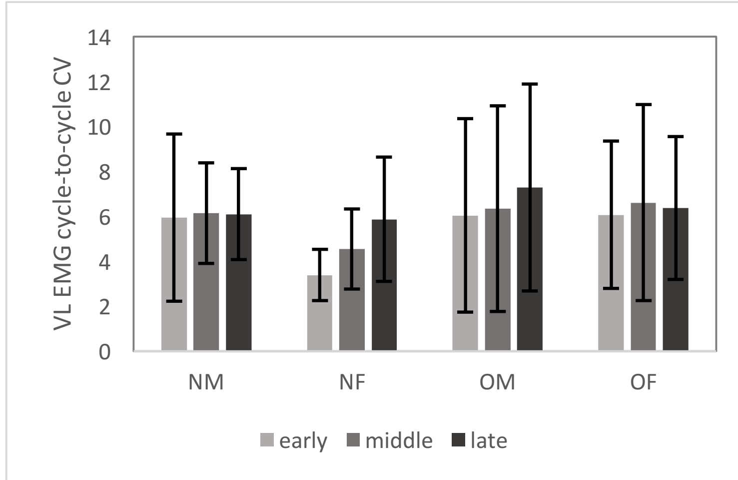

Figure 3.11 Mean values of cycle-to-cycle VL EMG CV for each time period of different groups with standard deviation bars, NM: non-obese male, OM: obese male, NF: non-obese female, OF: obese female

Table 3.7 Statistical results for the main and interactive effects of obesity, gender and time on cycle-to-cycle CV of VL EMG, as obtained by a 3 factor ANOVA (significant results highlighted in bold)

Source	Nparm	DF	Sum of Squares	F Ratio	*p*
obesity	1	1	0.00450531	4.35	**0.04***
gender	1	1	0.00250525	2.42	0.12
time	2	2	0.00263399	1.27	0.28
obesity*gender	1	1	0.00141802	1.37	0.24
obesity*time	2	2	0.00017831	0.09	0.92
gender*time	2	2	0.00035207	0.17	0.84
obesity*gender*time	2	2	0.00178593	0.86	0.42

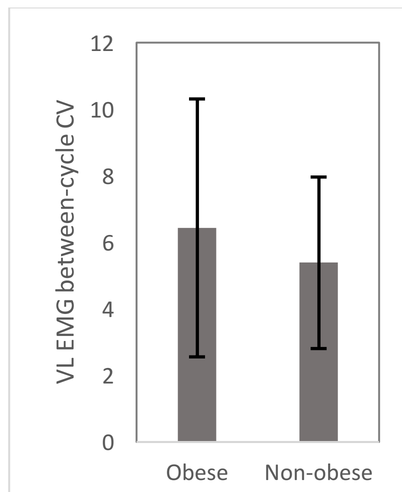

Figure 3.12 Means and standard deviations of cycle-to-cycle CV of VL EMG for the obese and non-obese groups

3.2 Task: Handgrip

As results of the two hand muscles, Extensor Carpi Radialis (ECR) and Flexor Carpi Radialis (FCR), showed similar trends, only ECR results are presented here.

Table 3.8 presents a summary of the means and standard deviations of endurance time, CV and SaEn of force, within-cycle and cycle-to-cycle CV, and SaEn of ECR EMG for each task-period (early, middle and late) within each group (NM: non-obese male, NF: non-obese female, OM: obese male, OF: obese female) during the handgrip exercise.

Table 3.8 Means and standard deviations of dependent variables (endurance time, CV and SaEn of force, within-cycle CV, SaEn, and cycle-to-cycle CV of ECR EMG) for each time period of different groups during the handgrip exercise

Gr-oup	Endurance time (s)	Force CV (%)			Force SaEn			ECR EMG within-cycle CV (%)			ECR EMG SaEn			ECR EMG cycle-to-cycle CV (%)		
		Early	Middle	Late	Early	Middle	Late	Early	Middle	Late	Early	Middle	Late	Early	Middle	Late
NM	1256 (524)	2.81 (1.03)	2.83 (1.22)	3.31 (1.51)	0.03 (0.01)	0.03 (0.01)	0.03 (0.01)	16.66 (2.11)	17.85 (2.77)	18.31 (3.16)	1.45 (0.22)	1.41 (0.23)	1.37 (0.26)	11.23 (5.68)	10.36 (4.38)	10.74 (4.66)
NF	1206 (621)	4.56 (2.71)	3.45 (1.56)	3.89 (1.92)	0.02 (0.01)	0.03 (0.01)	0.03 (0.01)	16.42 (2.96)	16.84 (3.39)	17.02 (2.81)	1.53 (0.13)	1.48 (0.16)	1.39 (0.31)	8.57 (3.66)	10.29 (5.80)	11.69 (4.68)
OM	1320 (388)	3.22 (1.64)	3.44 (1.27)	4.21 (1.82)	0.03 (0.01)	0.03 (0.01)	0.03 (0.01)	17.85 (3.81)	19.31 (4.51)	19.62 (3.92)	1.42 (0.23)	1.32 (0.28)	1.32 (0.31)	12.38 (8.45)	12.98 (6.59)	13.05 (7.00)
OF	1124 (539)	4.66 (2.81)	4.5 (2.40)	4.83 (1.93)	0.02 (0.01)	0.02 (0.01)	0.02 (0.01)	16.36 (3.93)	16.2 (3.74)	17.9 (4.30)	1.64 (0.17)	1.61 (0.19)	1.57 (0.22)	12.24 (7.58)	8.77 (4.33)	11.59 (3.81)

3.2.1 Aim1: Differences in endurance time between obesity conditions and gender

Table 3.9 shows the statistical results obtained from a 2 factor (obesity*gender) ANOVA assessing the differences in endurance time. Even though the endurance time for the hand grip exercise presented the same overall trend as in knee-extension of males having higher endurance time, no statistical differences, however, were detected in hand-grip endurance times due to gender or obesity.

Table 3.9 Obesity and gender effect on endurance time, as obtained by a 2 factor ANOVA

Source	**Nparm**	**DF**	**Sum of Squares**	**F Ratio**	***p***
obesity	1	1	1.14	0.003	0.95
gender	1	1	209.49	0.650	0.42
obesity*gender	1	1	73.85	0.229	0.63

3.2.2 Aim 2: Correlations between force control & variation in muscle activation patterns at baseline with endurance time

Pearson's correlation coefficients showing correlations between CV and SaEn of force, within-cycle and cycle-to-cycle CV, and SaEn of ECR EMG with ET are presented in table 3.10 including the statistical results. None of the correlations were found to be significant.

Table 3.10 Pearson's correlation coefficients and statistical results for correlations between force and muscle activation variations with endurance time

	r	*p*
Force CV – ET	-0.13	0.37
Force SaEn – ET	0.12	0.42
ECR CV – ET	-0.04	0.81
ECR SaEn – ET	-0.03	0.85
ECR cycle-to-cycle CV – ET	0.07	0.63

3.2.3 Aim 3: The effects of obesity, gender and time on force control and variation in muscle activation patterns

Statistical results for the main and interactive effects of obesity, gender and time on CV and SaEn of force, within-cycle and cycle-to-cycle CV, and SaEn of ECR EMG are presented in table 3.11.

Male participants presented significantly lower force CV, but higher force SaEn than female participants. In addition, males had greater CV but smaller SaEn in ECR EMG than females. As for obesity differences, force CV was significantly higher among obese subjects, but force SaEn was lower, compared to non-obese individuals. An interaction effect between obesity and gender was found with obese females showing higher ECR EMG SaEn than non-obese females, while obese males showed lower ECR EMG SaEn than non-obese males.

Table 3.11 Statistical results for the main and interactive effects of obesity, gender and time on dependent variables (CV and SaEn of force, within-cycle CV, SaEn, and cycle-to-cycle CV of ECR EMG), as obtained by a 3 factor ANOVA (significant results highlighted

	Force CV		Force SaEn		ECR EMG CV		ECR EMG SaEn		ECR between-cycle CV	
	F Ratio	*p*	F Ratio	*p*	F Ratio	*p*	F Ratio	*p*	F Ratio	*p*
obesity	4.57	**0.03***	5.28	**0.02***	1.52	0.22	1.18	0.28	2.25	0.14
gender	10.48	**0.002***	31.58	**<.0001***	6.95	**0.009***	17.13	**<.0001***	1.95	0.16
time	0.87	0.42	1.05	0.35	2.06	0.13	2.39	0.10	0.56	0.57
obesity*gender	0.01	0.93	3.13	0.08	1.28	0.26	7.34	**0.008***	0.56	0.46
obesity*time	0.44	0.64	0.39	0.68	0.14	0.87	0.12	0.89	0.37	0.69
gender*time	0.92	0.40	0.37	0.69	0.39	0.68	0.15	0.86	0.37	0.69
obesity*gender*time	0.12	0.89	0.16	0.85	0.19	0.83	0.16	0.85	1.22	0.30

4.0 DISCUSSION

The present study investigated motor performance, neuromuscular control and endurance changes with obesity, gender and time among older adults performing intermittent submaximal knee extension and handgrip exercises. Motor performance and control were characterized by variability in force and muscle activity. Both the amount and structure of variability were quantified using the coefficient of variation (CV) and sample entropy (SaEn) metrics. In addition, variability in muscle activation within each contraction cycle as well as the cycle-to-cycle variability were quantified by computing within-cycle and between-cycle CV.

4.1 Knee extension task

4.1.1 Gender differences

Significant differences in endurance time were observed with gender, with males showing longer endurance time than females, in the knee-extension task. The majority of previous studies, including both in which men and women were matched for absolute strength or not, have reported either the same endurance time for both genders, or females exhibiting better fatigue resistance than males when performing knee extensions, in contrast with what was found in the current study. Numerous other studies involving various types of exercises performed by different muscles also mostly reported a longer endurance time for female participants (Fulco, Rock et al. 1999, Hunter, Critchlow et al. 2004, Hunter, Critchlow et al. 2004). However, it is noteworthy that nearly all studies examining gender difference in fatigability focused on only young healthy adults. Our study suggests that male older adults particularly showed longer endurance than female older adults in knee extension.

As mentioned in the preceding sections, aging has been suggested to be associated with enhanced fatigue resistance, but there was a lack of research targeting the older population specifically and exploring fatigue characteristics as a function of gender. One of a few studies investigating gender and age effects on fatigability, involved a thumb adduction task and found that older adults were significantly less fatigable than young adults, and older males benefited from such age-related rise of fatigue resistance more than older females (Ditor and Hicks 2000). The occurrence of changes in muscle fiber type distribution with aging has been demonstrated to account for the maintenance and enhancement of fatigue resistance. Older adults possess higher proportion of type I muscle fibers (slow- twitch), that help enable long endurance tasks, and fewer type II muscle fibers (fast-twitch) that are used for fast high force production but prone to fatigue. However, the amount of age-related increase in fatigue resistance can probably be modified by certain factors, such as gender. As a loss in estrogen has been seen in older females, their endurance advantage obtained from greater representation of type I muscle fibers may be mitigated, while muscular endurance of older males may predominantly benefit from histological changes alone (Ditor and Hicks 2000). In addition to the unclear gender differences, whether the slightly greater proportion of type I muscle fiber observed in young females persists during the aging process is yet known (Hicks, Kent-Braun et al. 2001). Thus, the longer endurance time presented among males in this study could possibly result from gender differences in the age-related changes in muscle fiber distribution.

There may also be other factors such as obesity, physical activity, lifestyle as well as cognitive factors, such as attitudes and beliefs about self-efficacy, that may play a role in explaining gender-related endurance differences.

From a motor control perspective, gender differences in both force and muscle activity variability were observed, indicating that males may use a more flexible motor strategy, thus being able to prolong endurance. The force CV at baseline (inverse of force “steadiness”) was negatively correlated with endurance time for all participants. The significant gender*time interaction that was found on force CV indicated a steadier force output for males compared to females during the baseline period, as opposed to a more variable pattern compared to females during later task-periods.

Force SaEn was significantly lower among females compared with males. It has been suggested that a reduction of complexity in physiological time series is associated with system dysfunction and loss of adaptability to physiological stress (Lipsitz and Goldberger 1992). In addition, Pincus pointed out that less complexity corresponded to greater component autonomy and isolation (Pincus 1994). As force was the product of complex interactions of neuromuscular system components, and was influenced by the pattern of activation within a muscle and across a group of synergistic and antagonistic muscles, smaller complexity in the force fluctuation may imply weaker neural compartments communication, less muscle coordination and less alterations in motor unit recruitment during static muscle contraction. Thus, a lower complexity of the force output observed among females may reflect poorer motor control and adaptation.

We interpreted the force CV and SaEn findings as jointly indicating that males controlled their force output more "tightly" than females, as reflected by the lower CV at baseline, and that they achieved this through greater corrections of the force signal, as reflected in the higher complexity of the signal as quantified by SaEn. We however, expected that such a tighter control on the force output by males would also imply that males would consequently fatigue at a faster rate thus leading to shorter endurance times. We were intrigued by the finding that despite more controlled force outputs, males actually showed longer endurance times than females.

As for variability in muscle activations, males presented higher EMG CV in the vastus lateralis muscle (knee extensor muscle) and lower sample entropy than females. When these findings are integrated with the findings on force control and endurance time, males thus presented with higher EMG CV, lower EMG SaEn, lower force CV, higher force SaEn and longer endurance time than females. This indicates that males somehow achieved a motor strategy in which they controlled the primary agonist muscle (vastus lateralis) to a "lower" extent, as reflected through higher CV and lower SaEn, while at the same time achieving better force control than females. The lower SaEn observed in the extensor muscle group activation indicates that the knee extensor muscle was controlled to a lower extent among males than females, and a consequent lower neuromuscular effort by the CNS in extensor muscle control.

Higher variability in muscle activation during an isometric contraction implies a more flexible motor control strategy. One possible strategy may be that alternate motor units within the same muscle, as well as other muscles with redundant function, may have been recruited and de-recruited to different extents to achieve the same overall force levels (note that the vastus lateralis is one of four knee extensor muscles in the quadriceps muscle group, indicating that this is a feasible motor control strategy). This explains both the longer endurance time that would then be achieved by not over-exerting the same motor units continually, and also the higher force SaEn as such muscle recruitment patterns would be reflected as higher complexity of the resultant force signal.

Finally, our results indicate that despite controlling a primary agonist muscle to a lower extent, males were still able to achieve better force control (lower force CV) than females. This may have been made possible by expending more effort in better antagonistic muscle control (flexor groups in this case) among males. Thus, the knee flexor muscle groups of males may obtain greater distribution of the neural effort, resulting in the lower sample entropy in the extensor muscle activity, so that the antagonists would do a better job in stabilizing the joint and assisting the control of the force output. This may have allowed the VL muscle activity to be more variable, which increased the fatigue resistance of the primary extensor, without affecting performance. Even though this hypothesis could not be verified in this study as the knee flexors were not included here, it is supported by findings from our previous studies: E.g. Women were shown to exhibit greater variation in antagonistic muscle activations and motor performance in spatial control tasks (as opposed to force control tasks here) than men (Casamento-Moran, Hunter et al. 2017). From a control perspective, other studies (Granata, Wilson et al. 2002) have also observed lower active stiffness of the quadriceps muscle in females during isometric knee extension when compared to males, which may in turn cause gender-based differential recruitment of agonists and antagonists in order to maintain sufficient joint stiffness.

Thus, male and female older adults appeared to differ in motor control patterns during intermittent submaximal knee extension exercises. Males may have employed better motor strategies to achieve a longer endurance probably by incorporating more antagonistic contractions to help maintain performance, so that the primary extensors would gain more freedom to seek for less fatigable motor solutions to slow down exhaustion.

4.1.2 Obesity differences

Obesity, as discussed in the introduction, has been found to be associated with impaired functional performance such as shorter endurance, faster development of discomfort, greater fatigue, inefficient motor control, reduced relative strength and task performance compared with normal weight people (Kankaanpää, Laaksonen et al. 1998, Maffiuletti, Jubeau et al. 2007, D'Hondt, Deforche et al. 2008, Eksioglu 2011, Shortz and Mehta 2013, Cavuoto and Nussbaum 2014). Thus, we expected the obese group to exhibit less variable and complex muscle activity as a reflection of poorer motor control and adaptation, which would finally result in poorer force control and shorter endurance time. However, we did not observe any obesity-related differences in endurance time or force fluctuation (CV) in this study. Force sample entropy was lower among the obese than non-obese participants during the knee extension exercise, indicating a dysfunction and reduced effectiveness of neuromuscular control (Lipsitz and Goldberger 1992, Pincus 1994) within each constant contraction interval. On the muscle activation side, no difference in the within-cycle muscle variability (VL EMG CV) was observed between obese and non-obese individuals. How obese older participants achieved the same performance as the non-obese participants when bearing the physiological and motor control disadvantages described above thus emerged as a critical question that needed to be addressed.

One study conducted by Shortz and colleagues involving intermittent handgrip and elbow flexion reported that obese subjects showed a higher force fluctuation during handgrip, but a lower force variability during elbow exertions (Shortz and Mehta 2013). Thus, the influence of obesity on neural and muscular responses has been shown to be muscle-dependent. The authors explained that the better performance observed among obese participants was a result of an increase in neural control, which only happened during elbow exertions in obese adults (Shortz and Mehta 2013).

However, whether this explanation of obese individuals using more active neuromuscular control to achieve similar or better performance than non-obese individuals is appropriate for the current study may be questioned, as the muscle discussed here is a knee extensor. In general, obesity has been shown to be linked with poorer motor performance in the knee extensor as obese individuals were able to achieve lesser motor unit activation (as elicited by electrical stimulation) than non-obese individuals. (Blimkie, Sale et al. 1990). Also, our finding of lower complexity (SaEn) in the force signal, and no differences between obese and non-obese groups in within cycle variability or complexity of muscle activations, seemed to contradict the speculation of an increased neural control in the obese.

While all these afore-mentioned factors merely accounted for variabilities within each individual contraction, considering that the test was an intermittent task involving regular rest periods between exertions, cycle-to-cycle muscle variability also deserved attention as it may reflect the pattern of neuromuscular control from a different perspective. It was observed that obese people displayed a significantly more variable muscle activation pattern between cycles. The increased variability across contractions among obese individuals can be interpreted either as a motor strategy that they used, to prolong endurance, or as a reflection of a loss of neuromuscular control from the very beginning of task performance.

As suggested in previous literatures, motor variability may be a representation of the motor unit recruitment pattern (Newell and Corcos 1993, Stergiou 2004, Davids, Bennett et al. 2006). In addition, a study examining the motor unit recruitment pattern in the Vastus Lateralis during submaximal intermittent knee extensions found a monotonic decrease in the recruitment threshold of all motor units, and that an increasing number of motor units were continuously active in subsequent contractions, all without a change of the recruitment order (Adam and De Luca 2003). Thus, the reason for a varying cycle-to-cycle muscle activity is probably that, during a cyclic endurance task, new motor units would be progressively recruited after the activation of old motor units in subsequent contractions following the same recruitment order, due to a decrease in the recruitment threshold of the motor units. Therefore, it was reasonable to speculate that the speed of such decrease was faster among obese people, leading to a faster increase in the number of motor unit recruitment along contractions, which was reflected by the greater cycle-to-cycle variability of EMG.

Through recruiting more (and different) motor units than non-obese people, individual motor unit of the obese participants would be able to be more “relaxed” while still maintaining the required effort output at the same time. In addition, as the cycle-to-cycle CV of the EMG was found to be positively correlated with endurance time for all subjects, a greater variability was very likely to reflect a beneficial motor strategy in terms of decelerating fatigability, and such a motor strategy appeared to be employed more extensively among obese subjects. Getting back to the Shortz’s study discussed earlier, the enhanced neural control proposed as a possible reason for the better performance observed in obese people during intermittent elbow exertions may also be the underlying neural mechanism for the obese group to achieve same endurance time as the non-obese in this study, just with stronger neural control reflected by altered cycle-to-cycle motor activation, rather than within cycle motor variability (Shortz and Mehta 2013). This neuromuscular control strategy, however, was muscle dependent as it was not seen during the handgrip in both Shortz's study and the current work, which will be discussed later.

4.2 Handgrip tasks

Variabilities in force and muscle activity have been observed to be different between gender and obesity, with the majority of them following the same trend with results obtained from the knee extension task. Obese participants exhibited greater variability but less complexity in the handgrip force signal, showing an impaired performance compared with the non-obese group. This result was in accordance with findings from previous literatures involving handgrip tasks using a similar experimental protocol (Shortz and Mehta 2013, Mehta and Shortz 2014). Mehta and Shortz have reported that obesity was associated with higher force fluctuations and lower prefrontal cortex activation during handgrip exertions. In this study, the reduced neural activity could be also very likely to happen among obese individuals, probably reflected by their lower force complexity and finally resulting in the less stable force output. Supporting this, it has been suggested by a number of studies, demonstrating a link between obesity and neural dysfunction in the brain (Stanek, Grieve et al. 2011), and reduced neural efficiency and information processing (Gunning-Dixon and Raz 2000). This change in the neural system might be an essential factor that contributed to impaired motor control competency among the obese population, in addition to the negative effects of their extra body mass (D'Hondt, Deforche et al. 2008, Gentier, D'Hondt et al. 2013).

Additionally, unlike in the knee extension task, the motor strategy of a greater cycle-to-cycle muscle variability was not adopted by the obese participants during handgrip exertions. This may likely be related to the high opportunity for recruiting synergists in the knee extension task, but such an option to rotate activity among synergists with similar function being much more reduced for hand-grip exertions. The hand grip exertion was also different from knee extension in terms of fundamental biomechanical demands as it required simultaneous co-contractions by agonists and antagonists (i.e. both extensors and flexors), as opposed to the knee extension task where the extensors were clearly the agonist muscle group. The correlation between cycle-to-cycle muscle variability and endurance time was also thus not significant during hand-grip exertions. This loss of significance indicated that the mechanism employed to prolong endurance was muscle-dependent.

Given the afore-mentioned neuromuscular disadvantages of obese people, endurance time, however, didn't appear to be influenced by obesity, with both group insisting for the same-length period. This was not expected based on the preceding discussion, and was in conflict with some previous literatures that particularly investigated handgrip exercises, showing a shorter endurance time among obese subjects or a negative correlation between endurance time and BMI (Eksioglu 2011, Cavuoto and Mehta 2013). Nevertheless, a consensus has not been reached regarding the obesity-related difference in endurance time during endurance tasks including handgrip exercises, especially among older adults. In a study involving sustained activities of handgrip, shoulder flexion and torso extension, an overall 3 - 15% longer endurance times were observed in the obese group for the three tasks, though none was significant (Cavuoto and Nussbaum 2013). Various factors could probably play different roles in modifying the final result regarding obesity-related difference in fatigability, such as the degree of obesity of the involved participants, the experimental protocol (intermittent or sustained muscle contraction), muscle contraction level (maximal or submaximal). Finally, it should be noted that the studies mentioned were conducted on young people, as opposed to older adults that were the focus in this study. This difference matters since an increase in fatigue resistance was found to be associated with aging, probably due to changes in muscle fiber distributions (Ditor and Hicks 2000). However, in what way obesity would deviate the influence of the age-related difference in the physiological property was still not clear (Hicks, Kent-Braun et al. 2001).

Similar to the knee extension exercise, males exhibited greater force complexity and lower force fluctuation. As discussed earlier, higher force complexity might be a reflection of a more adaptable system that possessed greater fatigue and physiological stress resistance. Thus, the force signal obtained implied a better neuromuscular control mechanism among males compared with females. In addition, the fact that the more variable ECR muscle activity males presented, as indicated by higher EMG CV, didn't transform into a less stable force could probably be attributed to the coordination of muscles in the hand and arm that participated in the handgrip exercise. Even though the force and EMG variables of the handgrip session showed similar trend with those obtained from the knee extension task, gender difference in endurance time was not seen. This was possible since endurance can be affected by a variety of factors. As suggested in a previous paper, endurance was strongly influenced by the histological and biochemical properties of the fibers (cells) (Nicolay and Walker 2005), which could probably be muscle dependent. Endurance was also affected by individual motivation, nutritional state, tolerance to the accumulation of metabolic by-products, and a host of other factors (Nicolay and Walker 2005) that can possibly change across experimental sessions and was difficult to control. Thus, under the influence of several such factors, the extent of the significant effects may have been mitigated and not strong enough to cause difference in endurance time.

4.3 Study limitations

There are some limiting factors that reduced the generalizability of the current study. Firstly, the number of participants in each group was not equal, since fewer obese males and females were recruited than the non-obese groups at the time data analysis had to start due to the timing constrain for fulfilling a master thesis. The sample size of each group was small, with the lowest number of nine for the obese male group. This unbalanced participant pool may introduce different and bigger inter subject variability across groups, which had the potential to adversely influence results. There may also have been differences within each group in terms of participant characteristics, thus causing a large within-group distribution of studied effects, leading to weaker statistical significance for several explored measures. The possible confounding effects of strength, differences in physical activity and fitness between and within groups are also recognized: for example, from Table 2.1, it can be seen that male groups (both obese and non-obese) showed higher average strength in both knee extension and handgrip force than female groups.

A notable feature was that no time effect on force fluctuation was observed for the hand-grip or knee extension, which is in conflict with the vast majority of previous literatures reporting a more variable pattern of force output with fatigue (Furness, Jessop et al. 1977, Hunter and Enoka 2001, Pethick, Winter et al. 2015). This can probably be attributed to two reasons. The different participant groups may have fatigued to different extents at the end of the protocol, which may have caused the observed differences. In addition, the way data were split for analysis could possible contribute to the unseen time effect. Given the fact that some participants reached a relatively long endurance, with more than 27% of the studied subjects persisting for over 30 min and a few of them sustaining for almost one hour, the last one-third period during which apparent fatigue was expected to be seen continuously, turned out to be too long to capture fatigue related changes in motor performance and muscle activity across all individuals. In Hunter's study, data obtained from the first, middle and last 60s were used, and increased force alterations with time for both males and females were revealed (Hunter and Enoka 2001). Thus, to enhance the representativeness of the data for progressively changed motor performance and muscle activities with fatigue, picking shorter time intervals as expressed earlier or dividing the time-series data into more individual periods would probably be a better approach. In this way, it was expected that time effects would be more likely to get uncovered in the current study.

Various methods have been used as criteria to determine obesity, such as body fat percentage, hip-to-waist ratio, body density and BMI. Different methods may yield opposite results (e.g. some people who have high body fat percentage may also have an ideal hip-to-waist ratio). As BMI was chosen as the only approach in this study to determine obesity, the grouping and results obtained may be biased.

Another limitation was that the antagonistic muscle activities during the knee extension were not recorded and only two muscles were measured for the handgrip task, which left the coordination patterns between muscles unclear, also made the interpretation of the results and getting the full picture of neuromuscular controls more difficult. This limited our ability to completely explain our findings, thus needing further test and demonstration.

4.4 Directions for future research

Two intermittent submaximal isometric contractions were investigated in this study, all with a fixed work cycle and intensity of exertion. Future studies could continue this investigation by examining motor variability and neuromuscular control patterns under different cyclic patterns and force intensities. Moreover, as the vast majority of jobs and activities in the workplace and daily life involve dynamic motions and various levels of force exertions, future research should consider using more realistic and representative tasks to obtain more generalizable results. To gain a more complete picture of the neuromuscular control and coordination strategies used by different individuals, it is also recommended to incorporate agonistic, synergistic and antagonistic muscles, to the most feasible extent.

Finally, based on our own and others' previous research, one of the most notable observations we made is that findings on neuromotor control and performance, especially as they relate to fatigue, are often conflicting as they depend on so many factors. Age, gender, obesity and muscle dependency were the specific ones investigated in our work. A comprehensive and integrated model that brings together both basic and higher level factors to understand control and performance seems necessary to explain such different findings across studies. We recognize that this is a very complex problem as there are multiple such factors, including personal factors (e.g. age, gender, obesity), biological factors (e.g. muscle physiological, neurological, hormonal factors), behavioral factors (e.g. motor control and coordination, strength, physical fitness), environmental, psychological and social factors. This would require major efforts across multiple and currently-independent research disciplines but this now seems a necessary and critical requirement for major advances in this field.

4.5 Conclusions

Males and females, obese and non-obese individuals differed in their neuromuscular control mechanisms to resist fatigue and prolong endurance during intermittent submaximal muscle contractions, the difference of which was particularly evident for the knee extension exercise in this study. Males exhibited stronger fatigue-resistance than females during the knee extension task, which was probably attributed to a greater antagonistic control that slowed down the development of fatigue by allowing higher muscle variability in the primary knee extensor, while still maintaining the required force output. A motor control pattern with a greater cycle-to-cycle muscle variability at baseline was found to be associated with longer endurance time for the whole subject group in the intermittent knee extension activity. The obese group appeared to adopt this type of motor strategy in the Vastus Lateralis muscle more intensively during knee extension exercises, which was probably the reason why they were able to endure for the same amount of time with their non-obese counterparts.

No gender or obesity related differences in endurance time were found for the handgrip task, even though the motor variability parameters presented somewhat similar trends with those obtained from the knee extension task. The association of greater cycle-to-cycle variability of muscle activity with longer endurance time was not seen in the handgrip task, indicating that the motor strategy employed to prolong endurance in the knee extension activity was muscle-dependent. This may have been related to the handgrip force exertion requiring a different coordination pattern among muscles of the hand and arm compared to knee extension.

4.6 Contributions of this thesis

Thus, this study was a basic investigation on the changes in motor variability and how it was associated with the development of fatigue, among older adults, and the potential influences of gender and obesity on the relationships in two tasks of high relevance to both occupational life and activities of daily living. Our findings enhance the theoretical understanding of the underlying neuromuscular control patterns and their relationship with fatigue for different individuals.

Given that both aging and obesity rates are rising continuously and becoming a substantial health and safety problem especially in the occupational environment, and that the nature of industrial design is making occupational tasks more sedentary, monotonous (and in some cases repetitive), the results from this study are both timely and critical for practical applications also. Our findings can be applied for better design of jobs and products, especially by recognizing the importance of having a variable motor pattern in task performance, even among older adults.

REFERENCES

- Adam, A. and C. J. De Luca (2003). "Recruitment order of motor units in human vastus lateralis muscle is maintained during fatiguing contractions." Journal of Neurophysiology **90**(5): 2919-2927.
- Anders, C., S. Bretschneider, A. Bernsdorf, K. Erler and W. Schneider (2004). "Activation of shoulder muscles in healthy men and women under isometric conditions." Journal of Electromyography and Kinesiology **14**(6): 699-707.
- Arutyunyan GH, G. V., Mirskii ML (1969). "Organization of movements of a man carrying out an exactitude posture task." Biophysics **14**(1103–7).
- Bartlett, R., J. Wheat and M. Robins (2007). "Is movement variability important for sports biomechanists?" Sports Biomechanics **6**(2): 224-243.
- Bassey, E. J. (1998). "Longitudinal changes in selected physical capabilities: muscle strength, flexibility and body size." Age and Ageing **27**(suppl_3): 12-16.
- Bazzucchi, I., M. Marchetti, A. Rosponi, L. Fattorini, V. Castellano, P. Sbriccoli and F. Felici (2005). "Differences in the force/endurance relationship between young and older men." European Journal of Applied Physiology **93**(4): 390-397.
- Bemben, M. G., B. H. Massey, D. A. Bemben, J. E. Misner and R. A. Boileau (1996). "Isometric intermittent endurance of four muscle groups in men aged 20-74 yr." Medicine and Science in Sports and Exercise **28**(1): 145-154.
- Bilodeau, M., M. D. Erb, J. M. Nichols, K. L. Joiner and J. B. Weeks (2001). "Fatigue of elbow flexor muscles in younger and older adults." Muscle & Nerve **24**(1): 98-106.
- Blimkie, C. J., D. G. Sale and O. Bar-Or (1990). "Voluntary strength, evoked twitch contractile properties and motor unit activation of knee extensors in obese and non-obese adolescent males." European Journal of Applied Physiology and Occupational Physiology **61**(3): 313-318.
- BLS (2016). Nonfatal Occupational Injuries and Illnesses Requiring Days Away from Work, 2015, United States Department of Labor.
- BLS (2017). Occupational choices of the elderly. Monthly Labor Review, United States Department of Labor.

- Boker, S. M., T. Schreiber, B. Pompe and B. I. Bertenthal (1998). Nonlinear analysis of perceptual-motor coupling in the development of postural control. Nonlinear Analysis of Physiological Data, Springer**:** 251-269.
- Casamento-Moran, A., S. K. Hunter, Y.-T. Chen, M. H. Kwon, E. J. Fox, B. Yacoubi and E. A. Christou (2017). "Sex differences in spatial accuracy relate to the neural activation of antagonistic muscles in young adults." Experimental Brain Research: 1-12.
- Cavuoto, L. A. and R. K. Mehta (2013). The effects of obesity and workload on hand grip endurance. Proceedings of the Human Factors and Ergonomics Society Annual Meeting, SAGE Publications Sage CA: Los Angeles, CA.
- Cavuoto, L. A. and M. A. Nussbaum (2013). "Differences in functional performance of the shoulder musculature with obesity and aging." International Journal of Industrial Ergonomics **43**(5): 393-399.
- Cavuoto, L. A. and M. A. Nussbaum (2013). "Obesity-related differences in muscular capacity during sustained isometric exertions." Applied Ergonomics **44**(2): 254-260.
- Cavuoto, L. A. and M. A. Nussbaum (2014). "The influences of obesity and age on functional performance during intermittent upper extremity tasks." Journal of Occupational and Environmental Hygiene **11**(9): 583-590.
- D'Hondt, E., B. Deforche, I. De Bourdeaudhuij and M. Lenoir (2008). "Childhood obesity affects fine motor skill performance under different postural constraints." Neuroscience Letters **440**(1): 72-75.
- Daly, J. J., K. Sng, K. Roenigk, E. Fredrickson and M. Dohring (2007). "Intra-limb coordination deficit in stroke survivors and response to treatment." Gait & Posture **25**(3): 412-418.
- Davids, K., S. Bennett and K. M. Newell (2006). Movement system variability, Human Kinetics.
- Davids, K., P. Glazier, D. Araujo and R. Bartlett (2003). "Movement systems as dynamical systems." Sports Medicine **33**(4): 245-260.
- Delmonico, M. J., T. B. Harris, M. Visser, S. W. Park, M. B. Conroy, P. Velasquez-Mieyer, R. Boudreau, T. M. Manini, M. Nevitt and A. B. Newman (2009). "Longitudinal study of muscle strength, quality, and adipose tissue infiltration." The American Journal of Clinical Nutrition **90**(6): 1579-1585.

- Ding, J., S. B. Kritchevsky, A. B. Newman, D. R. Taaffe, B. J. Nicklas, M. Visser, J. S. Lee, M. Nevitt, F. A. Tylavsky and S. M. Rubin (2007). "Effects of birth cohort and age on body composition in a sample of community-based elderly." The American Journal of Clinical Nutrition **85**(2): 405-410.
- Ditor, D. S. and A. Hicks (2000). "The effect of age and gender on the relative fatigability of the human adductor pollicis muscle." Canadian Journal of Physiology and Pharmacology **78**(10): 781-790.
- Drøyvold, W., T. Nilsen, Ø. Krüger, T. Holmen, S. Krokstad, K. Midthjell and J. Holmen (2006). "Change in height, weight and body mass index: Longitudinal data from the HUNT Study in Norway." International Journal of Obesity **30**(6): 935-939.
- Eksioglu, M. (2011). "Endurance time of grip-force as a function of grip-span, posture and anthropometric variables." International Journal of Industrial Ergonomics **41**(5): 401-409.
- Enoka, R. M., E. A. Christou, S. K. Hunter, K. W. Kornatz, J. G. Semmler, A. M. Taylor and B. L. Tracy (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. and J. Duchateau (2008). "Muscle fatigue: what, why and how it influences muscle function." The Journal of Physiology **586**(1): 11-23.
- Falla, D. and D. Farina (2007). "Periodic increases in force during sustained contraction reduce fatigue and facilitate spatial redistribution of trapezius muscle activity." Experimental Brain Research **182**(1): 99-107.
- Fedorowich, L., K. Emery, B. Gervasi and J. N. Côté (2013). "Gender differences in neck/shoulder muscular patterns in response to repetitive motion induced fatigue." Journal of Electromyography and Kinesiology **23**(5): 1183-1189.
- Fethke, N. B., D. Anton, J. E. Cavanaugh, F. Gerr and T. M. Cook (2007). "Bootstrap exploration of the duration of surface electromyography sampling in relation to the precision of exposure estimation." Scandinavian Journal of Work, Environment & Health: 358-367.

- Field-Fote, E. C. and D. Tepavac (2002). "Improved intralimb coordination in people with incomplete spinal cord injury following training with body weight support and electrical stimulation." Physical Therapy **82**(7): 707-715.
- Frontera, W. R., V. A. Hughes, R. A. Fielding, M. A. Fiatarone, W. J. Evans and R. Roubenoff (2000). "Aging of skeletal muscle: a 12-yr longitudinal study." Journal of Applied Physiology **88**(4): 1321-1326.
- Frontera, W. R., V. A. Hughes, K. J. Lutz and W. J. Evans (1991). "A cross-sectional study of muscle strength and mass in 45-to 78-yr-old men and women." Journal of Applied Physiology **71**(2): 644-650.
- Fulco, C., P. Rock, S. Muza, E. Lammi, A. Cymerman, G. Butterfield, L. Moore, B. Braun and S. Lewis (1999). "Slower fatigue and faster recovery of the adductor pollicis muscle in women matched for strength with men." Acta Physiologica Scandinavica **167**(3): 233-240.
- Furness, P., J. Jessop and O. Lippold (1977). "Long-lasting increases in the tremor of human hand muscles following brief, strong effort." The Journal of Physiology **265**(3): 821-831.
- Gallagher, S. and M. C. Schall Jr (2017). "Musculoskeletal disorders as a fatigue failure process: Evidence, implications and research needs." Ergonomics **60**(2): 255-269.
- Gentier, I., E. D’Hondt, S. Shultz, B. Deforche, M. Augustijn, S. Hoorne, K. Verlaecke, I. De Bourdeaudhuij and M. Lenoir (2013). "Fine and gross motor skills differ between healthy-weight and obese children." Research in Developmental Disabilities **34**(11): 4043-4051.
- Granata, K. P., S. E. Wilson and D. A. Padua (2002). "Gender differences in active musculoskeletal stiffness. Part I.: Quantification in controlled measurements of knee joint dynamics." Journal of Electromyography and Kinesiology **12**(2): 119-126.
- Gunning-Dixon, F. M. and N. Raz (2000). The cognitive correlates of white matter abnormalities in normal aging: a quantitative review, American Psychological Association.
- Hamill, J., R. E. van Emmerik, B. C. Heiderscheit and L. Li (1999). "A dynamical systems approach to lower extremity running injuries." Clinical Biomechanics **14**(5): 297-308.

- Harbourne, R. T. and N. Stergiou (2009). "Movement variability and the use of nonlinear tools: principles to guide physical therapist practice." Physical Therapy **89**(3): 267.
- Hatzikotoulas, K., T. Siatras, E. Spyropoulou, I. Paraschos and D. Patikas (2004). "Muscle fatigue and electromyographic changes are not different in women and men matched for strength." European Journal of Applied Physiology **92**(3): 298-304.
- Heiderscheit, B. C., J. Hamill and R. E. van Emmerik (2002). "Variability of stride characteristics and joint coordination among individuals with unilateral patellofemoral pain." Journal of Applied Biomechanics **18**(2): 110-121.
- Hertz, R. and M. McDonald (2004). "Obesity in the United States Workforce." Pfizer Facts, United States of America.
- Hicks, A. L., J. Kent-Braun and D. S. Ditor (2001). "Sex differences in human skeletal muscle fatigue." Exercise and Sport Sciences Reviews **29**(3): 109-112.
- Hughes, R. E., M. E. Johnson, S. W. O'Driscoll and K.-N. An (1999). "Age-related changes in normal isometric shoulder strength." The American Journal of Sports Medicine **27**(5): 651-657.
- Hunter, S. K., A. Critchlow, I.-S. Shin and R. M. Enoka (2004). "Fatigability of the elbow flexor muscles for a sustained submaximal contraction is similar in men and women matched for strength." Journal of Applied Physiology **96**(1): 195-202.
- Hunter, S. K., A. Critchlow, I.-S. Shin and R. M. Enoka (2004). "Men are more fatigable than strength-matched women when performing intermittent submaximal contractions." Journal of Applied Physiology **96**(6): 2125-2132.
- Hunter, S. K. and R. M. Enoka (2001). "Sex differences in the fatigability of arm muscles depends on absolute force during isometric contractions." Journal of Applied Physiology **91**(6): 2686-2694.
- Jackson, J. A., S. E. Mathiassen and P. G. Dempsey (2009). "Methodological variance associated with normalization of occupational upper trapezius EMG using sub-maximal reference contractions." Journal of Electromyography and Kinesiology **19**(3): 416-427.
- Jaworowski, Å., M. Porter, A. M. Holmbäck, D. Downham and J. Lexell (2002). "Enzyme activities in the tibialis anterior muscle of young moderately active men and women: relationship with body composition, muscle cross-sectional area and fibre type composition." Acta Physiologica **176**(3): 215-225.

- Kankaanpää, M., D. Laaksonen, S. Taimela, S.-M. Kokko, O. Airaksinen and O. Hänninen (1998). "Age, sex, and body mass index as determinants of back and hip extensor fatigue in the isometric Sørensen back endurance test." Archives of Physical Medicine and Rehabilitation **79**(9): 1069-1075.
- Kennel, M. B., R. Brown and H. D. Abarbanel (1992). "Determining embedding dimension for phase-space reconstruction using a geometrical construction." Physical Review A **45**(6): 3403.
- Kent-Braun, J. A. and A. V. Ng (1999). "Specific strength and voluntary muscle activation in young and elderly women and men." Journal of Applied Physiology **87**(1): 22-29.
- Kent-Braun, J. A., A. V. Ng, J. W. Doyle and T. F. Towse (2002). "Human skeletal muscle responses vary with age and gender during fatigue due to incremental isometric exercise." Journal of Applied Physiology **93**(5): 1813-1823.
- Kern, P. A., R. B. Simsolo and M. Fournier (1999). "Effect of weight loss on muscle fiber type, fiber size, capillarity, and succinate dehydrogenase activity in humans 1." The Journal of Clinical Endocrinology & Metabolism **84**(11): 4185-4190.
- Lannersten, L., K. Harms-Ringdahl, K. Schüldt, J. Ekholm and S. M. S. Group (1993). "Isometric strength in flexors, abductors, and external rotators of the shoulder." Clinical Biomechanics **8**(5): 235-242.
- Larsson, L. and J. Karlsson (1978). "Isometric and dynamic endurance as a function of age and skeletal muscle characteristics." Acta Physiologica **104**(2): 129-136.
- Lipsitz, L. A. and A. L. Goldberger (1992). "Loss of'complexity'and aging: Potential applications of fractals and chaos theory to senescence." Jama **267**(13): 1806-1809.
- Madeleine, P. (2010). "On functional motor adaptations: from the quantification of motor strategies to the prevention of musculoskeletal disorders in the neck-shoulder region." Acta Physiologica **199**(s679): 1-46.
- Madeleine, P. and T. Madsen (2009). "Changes in the amount and structure of motor variability during a deboning process are associated with work experience and neck–shoulder discomfort." Applied Ergonomics **40**(5): 887-894.
- Maffiuletti, N. A., M. Jubeau, U. Munzinger, M. Bizzini, F. Agosti, A. De Col, C. L. Lafortuna and A. Sartorio (2007). "Differences in quadriceps muscle strength and fatigue

between lean and obese subjects." European Journal of Applied Physiology **101**(1): 51-59.

- Marmon, A. R., M. A. Pascoe, R. S. Schwartz and R. M. Enoka (2011). "Associations among strength, steadiness, and hand function across the adult life span." Medicine & Science in Sports & Exercise **43**(4): 560-567.
- Mathiassen, S. E. (2006). "Diversity and variation in biomechanical exposure: what is it, and why would we like to know?" Applied Ergonomics **37**(4): 419-427.
- Mathiassen, S. E., T. Möller and M. Forsman (2003). "Variability in mechanical exposure within and between individuals performing a highly constrained industrial work task." Ergonomics **46**(8): 800-824.
- Maughan, R., M. Harmon, J. Leiper, D. Sale and A. Delman (1986). "Endurance capacity of untrained males and females in isometric and dynamic muscular contractions." European Journal of Applied Physiology and Occupational Physiology **55**(4): 395-400.
- Mehta, R. K. and A. E. Shortz (2014). "Obesity-related differences in neural correlates of force control." European Journal of Applied Physiology **114**(1): 197-204.
- Narici, M., M. Bordini and P. Cerretelli (1991). "Effect of aging on human adductor pollicis muscle function." Journal of Applied Physiology **71**(4): 1277-1281.
- Newcomer, B., D. Larson-Meyer, G. Hunter and R. Weinsier (2001). "Skeletal muscle metabolism in overweight and post-overweight women: an isometric exercise study using 31P magnetic resonance spectroscopy." International Journal of Obesity **25**(9): 1309.
- Newell, K. M. and D. M. Corcos (1993). Variability and motor control, Human Kinetics Publishers Champaign, IL.
- Newell, K. M. and A. B. Slifkin (1998). "The nature of movement variability." Motor behavior and human skill: A multidisciplinary perspective: 143-160.
- Nicolay, C. W. and A. L. Walker (2005). "Grip strength and endurance: Influences of anthropometric variation, hand dominance, and gender." International Journal of Industrial Ergonomics **35**(7): 605-618.
- Pethick, J., S. L. Winter and M. Burnley (2015). "Fatigue reduces the complexity of knee extensor torque fluctuations during maximal and submaximal intermittent isometric contractions in man." The Journal of Physiology **593**(8): 2085-2096.

- Pincus, S. M. (1994). "Greater signal regularity may indicate increased system isolation." Mathematical Biosciences **122**(2): 161-181.
- Preatoni, E., M. Ferrario, G. Donà, J. Hamill and R. Rodano (2010). "Motor variability in sports: a non-linear analysis of race walking." Journal of Sports Sciences **28**(12): 1327-1336.
- Rantanen, T., K. Masaki, D. Foley, G. Izmirlian, L. White and J. Guralnik (1998). "Grip strength changes over 27 yr in Japanese-American men." Journal of Applied Physiology **85**(6): 2047-2053.
- Richman, J. S. and J. R. Moorman (2000). "Physiological time-series analysis using approximate entropy and sample entropy." American Journal of Physiology-Heart and Circulatory Physiology **278**(6): H2039-H2049.
- Riley, M. A. and M. T. Turvey (2002). "Variability and determinism in motor behavior." Journal of Motor Behavior **34**(2): 99-125.
- Rissanen, A., M. Heliövaara and A. Aromaa (1988). "Overweight and anthropometric changes in adulthood: a prospective study of 17,000 Finns." International Journal of Obesity **12**(5): 391-401.
- Roepstorff, C., M. Thiele, T. Hillig, H. Pilegaard, E. A. Richter, J. F. Wojtaszewski and B. Kiens (2006). "Higher skeletal muscle α2AMPK activation and lower energy charge and fat oxidation in men than in women during submaximal exercise." The Journal of Physiology **574**(1): 125-138.
- Rosenstein, M. T., J. J. Collins and C. J. De Luca (1993). "A practical method for calculating largest Lyapunov exponents from small data sets." Physica D: Nonlinear Phenomena **65**(1-2): 117-134.
- Samani, A., D. Srinivasan, S. E. Mathiassen and P. Madeleine (2015). "Nonlinear metrics assessing motor variability in a standardized pipetting task: Between-and within-subject variance components." Journal of Electromyography and Kinesiology **25**(3): 557-564.
- SATO, H. and J. OHASHI (1989). "Sex differences in static muscular endurance." Journal of Human Ergology **18**(1): 53-60.
- Schulte, P. A., G. R. Wagner, A. Ostry, L. A. Blanciforti, R. G. Cutlip, K. M. Krajnak, M. Luster, A. E. Munson, J. P. O’Callaghan and C. G. Parks (2007). "Work, obesity, and occupational safety and health." American Journal of Public Health **97**(3): 428-436.

- Shortz, A. E. and R. K. Mehta (2013). Neural And Muscular Alterations in Healthy and Obese During Intermittent Static Exertions. IIE Annual Conference. Proceedings, Institute of Industrial Engineers-Publisher.
- Simoneau, J.-A. and C. Bouchard (1989). "Human variation in skeletal muscle fiber-type proportion and enzyme activities." American Journal of Physiology-Endocrinology And Metabolism **257**(4): E567-E572.
- Srinivasan, D. and S. E. Mathiassen (2012). "Motor variability in occupational health and performance." Clinical Biomechanics **27**(10): 979-993.
- Srinivasan, D., K. E. Sinden, S. E. Mathiassen and J. N. Côté (2016). "Gender differences in fatigability and muscle activity responses to a short-cycle repetitive task." European Journal of Applied Physiology **116**(11-12): 2357-2365.
- Stanek, K. M., S. M. Grieve, A. M. Brickman, M. S. Korgaonkar, R. H. Paul, R. A. Cohen and J. J. Gunstad (2011). "Obesity is associated with reduced white matter integrity in otherwise healthy adults." Obesity **19**(3): 500-504.
- Staron, R. S., F. C. Hagerman, R. S. Hikida, T. F. Murray, D. P. Hostler, M. T. Crill, K. E. Ragg and K. Toma (2000). "Fiber type composition of the vastus lateralis muscle of young men and women." Journal of Histochemistry & Cytochemistry **48**(5): 623-629.
- Stenholm, S., T. B. Harris, T. Rantanen, M. Visser, S. B. Kritchevsky and L. Ferrucci (2008). "Sarcopenic obesity-definition, etiology and consequences." Current Opinion in Clinical Nutrition and Metabolic Care **11**(6): 693.
- Stergiou, N. (2004). Innovative analyses of human movement, Human Kinetics Publishers.
- Svendsen, J. H. and P. Madeleine (2010). "Amount and structure of force variability during short, ramp and sustained contractions in males and females." Human Movement Science **29**(1): 35-47.
- Takala, E.-P. (2002). "Static muscular load, an increasing hazard in modern information technology." Scandinavian Journal of Work, Environment & Health: 211-213.
- Tetteh, E. G., N. Latif, J. D. McGlothlin and J. Peters (2009). "Impacts of frequency and posture on body mass index in manual handling tasks." Human Factors and Ergonomics in Manufacturing & Service Industries **19**(4): 329-343.

- Tracy, B. L., K. S. Maluf, J. L. Stephenson, S. K. Hunter and R. M. Enoka (2005). "Variability of motor unit discharge and force fluctuations across a range of muscle forces in older adults." Muscle & Nerve **32**(4): 533-540.
- van Dieën, J. H., H. H. Oude Vrielink and H. M. Toussaint (1993). "An investigation into the relevance of the pattern of temporal activation with respect to erector spinae muscle endurance." European Journal of Applied Physiology and Occupational Physiology **66**(1): 70-75.
- van Emmerik, R. E. and E. E. van Wegen (2000). "On variability and stability in human movement." Journal of Applied Biomechanics **16**(4): 394-406.
- WHO (2016). "Obesity and overweight." Fact sheet No. 311; World Health Organization.
- Yassierli, M. A. Nussbaum, H. Iridiastadi and L. A. Wojcik (2007). "The influence of age on isometric endurance and fatigue is muscle dependent: a study of shoulder abduction and torso extension." Ergonomics **50**(1): 26-45.
- Yoon, T., B. S. De-Lap, E. E. Griffith and S. K. Hunter (2008). "Age-related muscle fatigue after a low-force fatiguing contraction is explained by central fatigue." Muscle & Nerve **37**(4): 457-466.

APPENDICES

APPENDIX A

International Physical Activity Questionnaire

INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE

We are interested in finding out about the kinds of physical activities that people do as part of their everyday lives. The questions will ask you about the time you spent being physically active in the **last 7 days**. Please answer each question even if you do not consider yourself to be an active person. Please think about the activities you do at work, as part of your house and yard work, to get from place to place, and in your spare time for recreation, exercise or sport.

Think about all the **vigorous** activities that you did in the **last 7 days**. **Vigorous** physical activities refer to activities that take hard physical effort and make you breathe much harder than normal. Think *only* about those physical activities that you did for at least 10 minutes at a time.

1. During the **last 7 days**, on how many days did you do **vigorous** physical activities like heavy lifting, digging, aerobics, or fast bicycling?

   _____ **days per week**

   ☐ No vigorous physical activities → ***Skip to question 3***

2. How much time did you usually spend doing **vigorous** physical activities on one of those days?

   _____ **hours per day**

   _____ **minutes per day**

   ☐ Don't know/Not sure

Think about all the **moderate** activities that you did in the **last 7 days**. **Moderate** activities refer to activities that take moderate physical effort and make you breathe somewhat harder than normal. Think only about those physical activities that you did for at least 10 minutes at a time.

3. During the **last 7 days**, on how many days did you do **moderate** physical activities like carrying light loads, bicycling at a regular pace, or doubles tennis? Do not include walking.

   _____ **days per week**

   ☐ No moderate physical activities → ***Skip to question 5***

4. How much time did you usually spend doing **moderate** physical activities on one of those days?

_____ **hours per day**

_____ **minutes per day**

☐ Don't know/Not sure

Think about the time you spent **walking** in the **last 7 days**. This includes at work and at home, walking to travel from place to place, and any other walking that you have done solely for recreation, sport, exercise, or leisure.

5. During the **last 7 days**, on how many days did you **walk** for at least 10 minutes at a time?

_____ **days per week**

☐ No walking → ***Skip to question 7***

6. How much time did you usually spend **walking** on one of those days?

_____ **hours per day**

_____ **minutes per day**

☐ Don't know/Not sure

The last question is about the time you spent **sitting** on weekdays during the **last 7 days**. Include time spent at work, at home, while doing course work and during leisure time. This may include time spent sitting at a desk, visiting friends, reading, or sitting or lying down to watch television.

7. During the **last 7 days**, how much time did you spend **sitting** on a **week day**?

_____ **hours per day**

_____ **minutes per day**

☐ Don't know/Not sure

This is the end of the questionnaire, thank you for participating.