Sex-specific effects of localized muscle fatigue on muscle activation during a multi-joint repetitive task

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July 21th, 2020

A thesis submitted to McGill University in partial fulfillment of the requirement of the degree of Master of Science

CONTRIBUTION OF AUTHORS

Erika Renda, the candidate, was responsible for data processing, data analysis, writing and other steps related to the completion of the research study and submission of the thesis as per University requirements.

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Caroline Paquette, Ph.D., Assistant Professor, Department of Kinesiology and Physical Education, McGill University and David Pearsall, Ph.D., Associate Professor, Department of Kinesiology and Physical Education, were members of the candidate's supervisory committee.

ACKNOWLEDGEMENTS

I would like to thank Dr. Julie Côté. I am extremely grateful for all the help and guidance you have provided me throughout my Master's. I appreciate all the time you put in helping me complete this project.

I would like to thank Chen Yang. I am extremely grateful for all the assistance you provided me throughout my Master's. I really appreciated the help and the laughter you provided me when I was extremely stressed.

I would like to thank all the individuals in the BOS lab for the time I've spent with you over the year and a half. I have learnt something from each one of you. I also would like to thank you for all the laughter we've had while in the lab.

Lastly, I would like to thank my family and friends who have put up with me while I was stressed throughout this year and a half.

ABSTRACT

The aim of this Master's project was to explore sex-specific effects of localized muscle fatigue on muscle activation during a multi-joint repetitive task. Participants without history of upper body injuries, lower back pain, musculoskeletal or cardiovascular impairments underwent 3 separate fatiguing protocols which aimed to fatigue the elbow, shoulder and trunk. Before and after each fatiguing protocol the participants performed a 30 second repetitive pointing task in the horizontal plane while electromyographical (EMG) data was recorded from arm, shoulder and trunk muscles. The results indicate that in comparison to men, women vary in bicep activation from trial to trial when either the shoulder or elbow are fatigued in order to continue to perform the task. However, men require a higher muscle activation of upper trapezius activity to perform the task in comparison to women when the shoulder is fatigued. Thus, the results illustrate that males and females compensate differently during a repetitive pointing task when their elbows and shoulders are locally fatigued.

RÉSUMÉ

L'objectif de ce projet de Maîtrise était d'explorer les effets spécifiques au sexe de la fatigue musculaire localisée sur l'activation musculaire lors d'une tâche répétitive multi-articulaire. Les participants sans antécédents de blessures au haut du corps, de douleurs lombaires, de troubles musculo-squelettiques ou cardiovasculaires ont subi 3 protocoles de fatigue distincts qui visaient à fatiguer le coude, l'épaule et le dos. Avant et après chaque protocole de fatigue, les participants ont effectué une tâche de pointage répétitif de 30 secondes dans le plan horizontal tandis que les données électromyographies (EMG) étaient enregistrées à partir des muscles des bras, des épaules et du tronc. Les résultats indiquent qu'en comparaison avec les hommes, l'activation du biceps des femmes varie d'un essai à l'autre lorsque l'épaule ou le coude sont fatigués afin de continuer à effectuer la tâche. Cependant, les hommes ont besoin d'une activation musculaire plus élevée du trapèze supérieur pour effectuer la tâche par rapport aux femmes lorsque l'épaule est fatiguée. Ainsi, les résultats illustrent que les hommes et les femmes compensent différemment lors d'une tâche de pointage répétitive lorsque leurs coudes et leurs épaules sont localement fatigués.

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INTRODUCTION

Upper extremity musculoskeletal disorders (MSDs) are a significant problem in society. MSDs can affect muscles, nerves, tendons, joints, cartilages and/or spinal discs (Bernard, 1997). Research has shown that neck and upper limb MSDs are usually caused by forceful hand or arm exertions, repetitive movements of hands or arms, prolonged static posture, or vibrations (Ayoub & Wittels, 1989; Gerr et al., 1991; Piligian et al., 2000; Rempel et al., 1992; Bernard, 1997). Also, it has been reported that more women than men experience work-related MSDs (Schneider & Irastorza, 2010). It has been suggested that this may be due to differences in how the two sexes perform the same work tasks or in physiological differences when performing the same tasks in the same way (Côté, 2012; Lewis and Mathiassen, 2013). Moreover, sex differences during isometric and dynamic tasks can be due to differences in contractile properties, which are linked with muscle fiber size and composition (Simoneau & Bouchard, 1989). However, much remains unknown about the specific mechanisms underlying sex differences in the production of MSDs.

Research has shown that fatigue is another important risk factor for musculoskeletal disorders (Hunt et al., 1999; Oakman et al., 2012). Muscle fatigue can be defined as a decrease in the maximal force or power that one can produce after performing submaximal and/or dynamic contractions (Wang et al., 2018; Vollestad, 1997). Localised muscle fatigue, which refers to fatigue that is induced directly to a muscle or small group of agonist muscles, is also thought to increase the risk of developing a work-related MSD, although this link is difficult to prove (Lin, 2009; Rashedhi, 2016). Several studies have investigated how localized muscle fatigue affects the function of the fatigued muscle, either through changes in EMG such as increased amplitude, decreased frequency, increased variability, or impairments in the mechanical output of that muscle (Wang et al., 2018; Vollestad, 1997; Bigland-Ritchie et al., 1983; Gandevia, 2001; Srinivasan and Mathiassen, 2012). Similarly, several studies have investigated how fatigue induced by the repetition of multijoint movements, such as those performed in the workplace (e.g. hammering, inspecting and sorting objects on an assembly line), induce whole-body adaptations and change coordination strategies (Fuller et al., 2009). However, there is limited research on how localized muscle fatigue, for instance fatigue to the biceps muscles when holding a heavy weight, or to the low back when maintaining a forward flexed trunk posture, would affect the biomechanics of a subsequent whole-body task, although this regularly occurs in workplaces that encompass several work tasks performed in rotation. Moreover, whether there could be sex differences in how localized muscle fatigue affects whole-body tasks is unknown.

The objective of this Master's thesis was to evaluate sex-specific effects of localized muscle fatigue, induced at different arm and trunk joints, on electromyography characteristics across different joints involved in a multijoint repetitive arm task. We hypothesized that localized muscle fatigue would lead to compensations from muscles around the other joints involved in the repetitive multijoint task, and that these would be different across men compared to women.

LITERATURE REVIEW

Prevalence of injury and sex differences:

Upper extremity musculoskeletal disorders are a significant problem in society. Musculoskeletal Disorders (MSDs) can affect muscles, nerves, tendons, joints, cartilages and/or spinal discs (Bernard, 1997). According to the Government of Canada, in 2017, 15% of Canadians suffered from upper extremity work-related MSDs (Centre of Occupational Health, 2017). Also, in that same year, there were 251 625 total lost time claims, contributing to benefit costs of $7.5 billion (Association of Workers' Compensation Boards of Canada, 2019). Research has shown that neck and upper MSDs are usually caused by forceful hand and arm exertions, repetitive movements of hands and arms, prolonged static posture and vibrations (Ayoub & Wittels, 1989; Gerr et al., 1991; Piligian et al., 2000; Rempel et al., 1992; Bernard, 1997). Moreover, it has been shown that in a workplace, there is a relationship between shoulder injury and tasks involving repetitive performance while sustaining shoulder adduction and flexion (Hagberg & Kvarnstrom, 1984; Viiikari-Juntura, 1998). Research also showed that there was a significant positive association between musculoskeletal disorders and fatigue (Hunt et al., 1999; Oakman et al., 2012).

It has been consistently reported that a greater number of women experience work related MSDs (Schneider & Irastorza, 2010). According to Macpherson et al.'s (2018) study, more female time lost claims were due to musculoskeletal disorders. A systematic study conducted by Treaster & Burr (2011) determined that women had a significantly higher prevalence in many types of upper extremity musculoskeletal disorders in comparison to men, even when controlling for confounders such as age and work factors. It has been suggested that sex differences in MSD prevalence may be due to differences in how tasks are allocated to men and to women within the same job, in how the two sexes perform the same work tasks, in physiological effects when performing the same tasks in the same way, and more (Côté, 2012; Lewis and Mathiassen, 2013). At the biological level, sex differences during isometric and dynamic tasks can be due to differences in contractile properties, which are linked with muscle fiber size and composition (Simoneau & Bouchard, 1989). Another sex difference which can have an effect on the development of injury is muscle perfusion, as studies have shown that women have a lower increase in metabolite build-up following fatigue, which can impact their ability to recover (Hunter and Enoka, 2001). Another factor is that in certain muscles such as the trapezius, women have a smaller fiber cross-sectional area in comparison to men, thus they have a lower force-generating capacity (Lindman et al., 1990, 1991). Therefore, it is most likely that all of these factors play a role in a complex interaction to explain sex differences in musculoskeletal disorder occurrences, making it difficult to exactly identify the specific mechanisms by which sex differences in MSD may occur.

Muscle fatigue and electromyography:

Previous research used various definitions for muscle fatigue. It has been defined as a "failure to maintain the required or expected force" (Edwards, 1981; Dimitrova & Dimitrov, 2003), as well as "a feeling or sensation of weakness or muscle pain" (Gonzalez-Izal et al., 2012). However, in this thesis, we will use a definition of muscle fatigue taken from the literature on low-intensity tasks sustained for a period of time and stopped prior to exhaustion, whereby muscle fatigue is defined as a decrease in the maximal force or power one produces for submaximal contraction and/or dynamic contractions (Wang et al., 2018; Vollestad, 1997).

The force and power produced is dependent on the contractile mechanisms within the skeletal muscle fibre (Taylor et al., 2016). However, the chain of processes in the nervous system and the changes at any level of the pathway can impact the force or power generated. Force and power are also influenced by processes within the central nervous system that effect the neural drive to the muscle (Taylor et al., 2016). Muscle fatigue can be divided into central and peripheral fatigue (Gonzalez-Izal et al., 2012). Central fatigue is the reduction in force and power influenced by the reduction in neural drive to the muscle (Taylor et al., 2016). Central fatigue is usually associated with a decrease in voluntary activation of a muscle attributed to a decrease in motor unit recruitment and discharge rate (Gonzalez-Izal et al., 2012), whereas peripheral muscle fatigue is associated with change in neuromuscular transmission and action potential propagation as well as a reduction in contractile strength of the muscle fibers (Gonzalez-Izal et al., 2012). In general, muscle fatigue can be induced by various components such as metabolic, structural and energetic changes which occur in muscles (Cifrek et al., 2009). These changes can be due to a lack of oxygen and nutrients which are supplied through blood circulation. These changes could also be due to changes in efficiency of the nervous system (Cifrek et al., 2009, Gonzalez-Izal et al., 2012).

Muscle fatigue can be directly measured by assessing force, power and torque recordings. For instance, muscle fatigue has been shown to decrease joint range of motion, as well as maximal force and power capacity of a muscle (Enoka & Duchateau, 2008). In addition, surface electromyography (EMG) recordings can also be used to assess muscle fatigue (Gonzalez-Izal et al., 2012). Surface EMG recordings are manifestations of myoelectric signals, which themselves are electrical representations of the neuromuscular activity of muscle contraction (Jurell, 1998). The signal produced is dependent on the firing rate of the motor units, the shape and number of motor-unit action-potentials (MUAPs) and the number of synchronized MUAPs (Jurell, 1998). The MUAP is defined as the summation of action potentials from the muscle fibers which are innervated by a single motor unit (Jurell, 1998). The summation of the MUAP contributes to the amplitude and the frequency characteristics of the recorded signal (Jurell, 1998). The EMG signal thus reflects the activity of the motor units which are located near the electrode.

The influences of fatigue on all of these aforementioned parameters are dependent on the type of tasks which are performed (Barry & Enoka, 2007). Additionally, changes in motor units during fatiguing contractions can vary across populations depending on the characteristics of the task being performed (Barry & Enoka, 2007). Task dependency reflects that a muscle's motor output, such as how EMG outcomes change with fatigue, can vary according to various task-related factors such as subject motivation, muscle activation patterns, intensity and duration of activity and continuous or intermittent activity (Barry & Enoka, 2007). In addition, research has stated that task dependency may be one of the reasons for differences in study findings on fatigability between men and women. When performing fatiguing contractions or sustaining a contraction, women usually have a longer time to task failure in comparison to men (Barry & Enoka, 2007; Enoka & Duchateau, 2008). However, in many of these studies, the fatiguing load was adjusted to each individual's maximum capacity. Since the average man is most often stronger than the average woman, and therefore for the same relative load, the absolute load of men will be higher, they may experience a higher occlusion of blood flow and metabolic activity when performing a task of equivalent intensity. As a result, men must activate a greater muscle mass to exert the same relative force as women, which could accelerate their fatigue process, compared to women's (Barry & Enoka, 2007; Enoka & Duchateau, 2008). Lastly, this sex difference may also be due to the fact that women have a smaller reliance on glycolytic metabolism as compared to men (Barry & Enoka, 2007; Enoka & Duchateau, 2008).

Fatigue and characteristics of the electromyographical (EMG) signal:

Using EMG, muscle fatigue can be quantified by determining parameters in either the time or frequency domain, for instance root mean square (RMS) in the time domain, and mean power frequency (MnPF) in the frequency domain. The amplitude of EMG signals is affected by the number of active motor units, their discharge rates, and shape and propagation velocity of the intracellular action potentials (Gonzalez-Izal et al., 2012; Jurell, 1998). In submaximal contractions, when a muscle becomes fatigued, the EMG amplitude increases (Bigland-Ritchie et al., 1986). The mean power frequency is defined as the average frequency of the spectrum (Jurell, 1998). As a muscle becomes fatigued, the myoelectric power spectrum is expected to be compressed and move towards lower frequencies due to decreases in muscle fiber conduction velocities as well as in the increase duration of the motor unit action potential waveform (Jurell, 1998; Gonzalez-Izal et al., 2012; Cifrek et al., 2009). Jurell also determined that MnPF is the most reliable measure of spectral shifts (1998).

Motor variability:

Motor variability is defined as the variability in postures, movements and muscle activity between successive repetitions of the same task (Mathiassen, 2006; Madeleine, 2010; Srinivasan and Mathiassen, 2012). In literature, motor variability has been suggested to be a factor in determining susceptibility to developing fatigue, pain and musculoskeletal disorders (Madeleine 2010; Srinivasan and Mathiassen, 2012). According to Missenard et al., the central nervous system uses the most optimal strategy to ensure preservation of the task performance when experiencing muscle fatigue (2009). In order to preserve task performance, the central nervous system alters muscular activation which may cause movement to movement variability (Missenard et al., 2009). Motor variability can be quantified using kinematic and kinetic variables such as joint angles, velocities and torques (Preatoni et al., 2013). EMG measurements can also be used to evaluate variability in motor unit recruitment (Srinivasan and Mathiassen, 2012). Using EMG data, muscle activity variation can be quantified by calculating the standard deviation across the RMS data of the repeated task cycles, then normalizing it to the average RMS (Srinivasan and Mathiassen, 2012). It has been shown that as fatigue is induced through movement repetition, motor variability (including movement-to-movement variability in EMG parameters) usually increases in healthy individuals (Srinivasan and Mathiassen, 2012). However, this may vary depending on the task, the variable studied, and the mechanical role of the variable towards production of the task.

Repetitive motion-induced fatigue and sex differences:

Some previous studies have assessed how fatigue affects multijoint coordination, such as how repetitive motion-induced fatigue affects compensations across the body (Côté et al., 2002 & 2008; Fuller et al., 2009; Gates & Dingwell, 2008). These studies demonstrated that the manner in which the body compensates is task dependent. Côté et al. (2002)'s study assessed the effects of fatigue during a repetitive sawing task using kinematic measures in 30 healthy individuals. The participants performed repetitive sawing motions until reaching a task difficulty criterion of 8/10 on the Borg CR10 scale, while 30s of data was collected every minute. They determined that fatigue led to reductions in elbow motion amplitude, which was compensated by increasing trunk motion. A later study conducted by Côté et al. (2008) studied hammering in 30 healthy individuals, this time through quantification of muscle activity. They determined that there was an increased EMG activity in the trapezius, a prime shoulder stabilizer that likely became fatigued as a result of hammering, as well as in the external oblique, in this task, a prime trunk mover which was likely not fatigued but rather increased its activation to assist arm motion, indicating compensations by muscles distal to the area of fatigue (Côté et al., 2008).

Fatigue effects on compensations across the body were also assessed during a repetitive pointing task using EMG, kinematic and kinetic measures. Fuller et al. (2009) assessed the effects of the repetitive pointing task on the whole body as the arm became fatigued in 14 young healthy individuals. The pointing task involved the participant to repeatedly move their arm between two targets in the horizontal plane. They determined that the trapezius muscle activity significantly increased between the first to the last minute, further emphasizing the role of the trapezius as a shoulder stabilizer heavily involved during fatiguing repetitive arm tasks. They also determined that as an individual becomes fatigued, their shoulder elevates, and the abduction angle decreases. Additionally, their body's center of mass laterally shifted towards their non-moving arm. These results suggest compensatory strategies to decrease the load on the fatigued shoulder. However, it is not clear if the same results would be observed if fatigue is induced locally at the individual muscles involved in the repetitive task, nor whether these changes would occur similarly in men and women.

Sex differences have been observed in EMG variables during some tasks of repetitive motion-induced fatigue. Studies which assessed sex differences during dexterous work of screwing a bolt concluded that even though there were no sex differences in time to fatigue and proprioceptive outcomes, there were sex differences in EMG RMS and MnPF values (Minn et al., 2018 & Otto et al., 2019). They determined that men tended to have higher EMG MnPF values, whereas women tend to have higher EMG RMS values when they became fatigued. Indeed, Minn et al. (2018) determined that men had a higher MnPF in anterior deltoid, biceps brachii and triceps brachii and that women displayed higher RMS EMG in upper trapezius, anterior deltoid, lower trapezius, triceps brachii, extensor carpi ulnaris and flexor carpi radialis. They suggested that these results illustrate that men and women use their muscles differently to perform the task; however, the increase in RMS suggests that women require a higher muscular effort (Minn et al., 2018). They also suggest that this may have an influence on the prevalence rate of work-related neck/shoulder musculoskeletal disorder between sexes (Minn et al., 2018). Similar results were demonstrated in the Otto et al., (2019) study.

Two other studies assessed sex differences in EMG variables using the same repetitive pointing task as in Fuller et al. (2009). A study by Fedorowich et al. (2013) did not determine any sex differences in EMG RMS or EMG SD values during the repetitive pointing task. However, during this same task, Srinivasan et al. observed sex differences in EMG SD values (2016). They determined that the upper trapezius, anterior deltoid, biceps brachii and triceps brachii showed a significant increase in mean muscle activity with fatigue (Srinivasan et al., 2016). They also determined that men showed a higher increase in trapezius and anterior deltoid muscle with fatigue. Women, however, showed a higher increase in biceps brachii and triceps brachii EMG variability (Srinivasan et al., 2016). For this specific task, these results suggest that men increase the involvement of muscles which stabilize and move the shoulder, and that women rather increase the involvement of the muscles which stabilize the elbow and the prime mover muscles (Srinivasan et al., 2016). These results imply that men use a shoulder-based control strategy and that women use an elbow-based control strategy. In these studies, fatigue was induced by repetitions of the pointing task; however it is not clear if the same results would be observed if fatigue was induced locally at the individual muscles involved in the repetitive task, although the previous observation that men use a shoulder strategy and women use an elbow strategy suggest that inducing fatigue at different joints would indeed have different effects on men and women.

Localised fatigue and multijoint tasks:

Localised Muscle Fatigue (LMF) is a significant mechanism involved in the cause of work-related MSDs. Localised muscle fatigue occurs when fatigue is induced directly in one or a few agonist muscles (Lin, 2009). Like muscle fatigue, localized muscle fatigue, can be assessed using direct methods such as measurements of voluntary contractions and indirect methods which are based on changes in electromyography data (Alasim et al., 2019). Localized muscle fatigue may occur in the workplace for instance when a worker statically holds boxes, or holds the arm above shoulder height when accomplishing a dexterous manual task, fatiguing specific muscle groups in between repetitive whole-body movement tasks.

Previous studies using kinematic methods have determined that other joints compensate for localised muscle fatigue during multijoint movements (Cowley et al., 2017; Huffenus et al., 2005; Yang et al., 2019). Cowley and Gates assessed the effects of proximal and distal upper extremity muscle fatigue on repetitive multi-joint ratcheting movements by the change in kinematics of the trunk, shoulder, elbow and wrist (Cowley et al., 2017). Proximal muscle fatigue was defined as shoulder flexor fatigue, and distal fatigue was defined as finger flexor fatigue. They concluded that proximal fatigue had a significantly higher effect on the kinematics of the trunk, shoulder and elbow. On the other hand, distal fatigue caused significantly smaller kinematic changes in the trunk and wrist. Finally, they concluded that movement variability increased for proximal joints and not distal joints. Another study assessed the effects of distal fatigue and proximal fatigue on multijoint upper extremity throwing task by assessing kinematic and kinetic parameters (Huffenus et al., 2005). Distal fatigue was induced in the extensor digitorum communis and proximal fatigue was induced in the triceps brachii. They determined that in the distal fatigue condition, the elbow compensated by modifying its torque. For proximal fatigue, they concluded that the wrist compensated by increasing its contribution to the task (Huffenus et al., 2005). However, neither study assessed any EMG variables to determine the effects of LMF on the various joints.

Another study assessed fatigue location effects on body compensation in the same repetitive pointing task used in the current thesis, through analyses of kinematics and inter-joint coordination (Yang et al., 2019). They determined that localised elbow, shoulder and trunk fatigue increased trunk lateral flexion variability. Additionally, fatigue at different locations lead to different kinematic changes. Shoulder and elbow fatigue induced angular changes in all three joints, whereas trunk fatigue increased angular standard deviation of the shoulder and the elbow (Yang et al., 2019).

EMG characteristics have also been used to assess the impact of localised fatigue during a repetitive multijoint task. These studies evaluated the coordination and co-contraction of the fatigued muscles involved in those tasks (Gorelick et al., 2003; Gate & Dingwell, 2010). Gorelick et al. (2003) assessed the effects of muscle fatigue produced by a generalized fatiguing protocol and a localised fatiguing protocol on the coordination of multiple joints during a manual handling task, consisting in a weighted stoop lift, using electromyographic techniques. Ten male participants were recruited to participate in this study. They determined that the protocol which locally fatigued the muscles of the trunk altered the neuromuscular coordination, which may ultimately lead to back injury (Gorelick et al., 2013). A study conducted by Gates and Dingwell (2010) assessed co-contraction during a repetitive upper extremity task. In order to fatigue the shoulder muscles, 20 healthy individuals performed a lift task. Once they were fatigued, they had to complete a saw-like task. They determined that localized fatigue did not have a significant effect on co-contraction of the muscles involved in the task. They suggested that participants used a feedback correction strategy to compensate for fatigue rather than cocontraction (Gates and Dingwell, 2010). Since the effects of muscle fatigue are task dependent, it is not clear how the activity patterns of the muscles around the various joints involved in a multijoint repetitive pointing task would adapt when localized fatigue is induced. More importantly, it is completely unknown if men and women would respond similarly to localized muscle fatigue when performing multijoint tasks, as no studies have assessed this sex difference previously.

Summary:

In summary, it has been shown that muscle fatigue induced during repetitive movements in a multijoint task leads the body to compensate by increasing the involvement of muscles at the various joints involved and/or shifts in body placement. However, less studies have used EMG approaches to investigate adaptations to localized fatigue induced at different body parts during a repetitive task. Finally, no study to our knowledge has evaluated sex differences therein.

RESEARCH ARTICLE

Sex-specific effects of localized muscle fatigue on muscle activation during a multi-joint repetitive task

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Abstract:

The objective of this study was to measure sex-specific effects of localized muscle fatigue on muscle activation during a multi-joint repetitive pointing task (RPT). Seventeen young adults (8 males) were recruited. Electromyographical electrodes were placed on: upper trapezius, pectoralis major, anterior and middle deltoid, biceps and triceps brachii, and left and right erector spinae. Subjects held a light weight in their hand and performed the RPT at 1 Hz for 30 seconds before and after localized fatigue tasks, which consisted of one shoulder, one elbow and one lower back isometric fatiguing protocols until exhaustion in randomized order. Activation amplitude (RMS), variability (SD) and mean power frequency (MnPF) were calculated for each of the pre-fatigue and post-fatigue RPT trials. There were sex x fatigue location interaction effects on upper trapezius RMS ($p=0.038$), with males' upper trapezius RMS more affected by shoulder fatigue, and in biceps brachii SD ($p = 0.023$), with females' biceps brachii SD more affected by shoulder fatigue. Results demonstrate that males and females compensate differently during a repetitive pointing task when their elbows and shoulders are locally fatigued, which could have implications on sex-specific workplace injury risks.

Introduction:

The majority of daily living activities performed by the average individual includes repetitive movements of their dominant upper extremity. Unfortunately, repetitive movements may lead to the development of Musculoskeletal Disorders (MSDs) (Kilbom, 1994). According to the Government of Canada, in 2017, 15% of Canadians suffered from upper extremity work-related MSDs, thus creating an economic burden (Centre of Occupational Health, 2017). It has been consistently reported that more women than men experience work related MSDs (Schneider

& Irastorza, 2010). In 2017 alone, there were over 250 000 total lost time claims, thus creating benefit costs of $7.5 billion (Association of Workers' Compensation Boards of Canada, 2019). Additionally, a majority of female time lost claims were due to musculoskeletal disorders (Macpherson, Lane, Collie & McLeod, 2018).

Previous research which evaluated the development of MSDs determined that muscle fatigue is one of the factors for its development (Iridiastadi & Nussbaum, 2006). Muscle fatigue can be defined as a decrease in the maximal force or power one produces for submaximal contraction and/or dynamic contractions (Wang et al., 2018; Vollestad, 1997). Localised muscle fatigue, fatigue that is induced directly in one or a few agonistic muscles, can increase the risk of developing a work-related MSD (Lin, 2009; Rashedhi, 2016). Localized muscle fatigue can be assessed using direct (e.g. force measurement) or indirect methods such as those based on changes in a muscle's electromyogram (EMG) (Alasim et al., 2019). Studies of fatigue using EMG have generally shown increases in amplitude, indicative of increased recruitment of motor units to continue to meet the task demands in the presence of fatigue, as well as compression of the power spectrum and move towards lower frequencies (Jurell, 1998; Gonzalez-Izal et al., 2012; Cifrek et al., 2009), and increased EMG variability (Srinivasan and Mathiassen, 2012). In addition, studies have identified that motor output becomes more variable with fatigue, which includes findings of increased movement-to-movement variability in EMG amplitude with fatigue (Srinivasan and Mathiassen, 2012).

Many studies addressing the link between fatigue and MSDs have investigated fatigue induced by repetitive upper limb tasks. They determined that as people perform a repetitive upper limb task, the main agonist joint and muscles generally reduce their mechanical contribution to the task, but that other joints and muscles compensate and increase their contributions so that the task can be maintained (Côté et al., 2002; Fuller et al., 2009). Moreover, some of these studies identified sex differences in how men and women adapt their joint movements and muscle activities during repetitive motion-induced fatigue (Bouffard et al., 2018).

Only a few studies investigated the impact of localized muscle fatigue (i.e. induced by localized efforts of individual muscles involved in a task) on patterns of whole-body tasks. Some investigated the kinematic changes of multiple joints during a multijoint task after localised muscle fatigue was induced. These studies determined that generally, the fatigued joint decreased its contribution to the task, whereas the other joints involved in the task compensated by increasing their torque to contribute to the task (Cowley & Gates, 2017; Huffenus et al., 2005; Yang et al., 2019). Additionally. the degree of kinematic change and motor variability was shown to be different depending if the proximal or distal upper extremity was fatigued (Cowley & Gates, 2017; Huffenus et al., 2005; Yang et al., 2019).

Studies which assessed the impact of localised muscle fatigue using EMG measures evaluated the coordination and co-contraction of the fatigued muscles involved in those tasks (Gorelick et al., 2003; Gate & Dingwell, 2010). Gorelick et al. determined that fatigued muscles alter their neuromuscular coordination (2003). However, Gates and Dingwell determined that localized fatigue did not have a significant effect on co-contraction on the muscles involved in the task (2010). Since less studies have used EMG approaches to investigate adaptations to localized fatigue induced at different body parts during a repetitive task, it is not clear how the activity patterns of the muscles around the various joints would adapt when localized fatigue is induced. More importantly, it is completely unknown if men and women would respond similarly to localized muscle fatigue when performing multijoint tasks, as no studies have assessed this sex difference previously. Therefore, the objective of this study was to evaluate the sex-specific effects of localized fatigue at different arm and trunk joints on electromyography characteristics across different joints involved in a multijoint, standing repetitive arm task. We hypothesized that localized muscle fatigue at different joints would lead to compensation from muscles around the other joints during a repetitive multijoint task. Additionally, we hypothesized that there would be sex differences in these compensation strategies.

Methods:

2.1 Participants

Seventeen right-handed healthy young adults (8 men, 9 women; age: men = 23.75 ± 2.28 yrs, women = 22.33 ± 2.11 yrs, P = 0.23; height: men = 179.13 ± 5.30 cm, women = 166.89 cm ± 7 cm, P = 0.0018; weight: men = 71.54 ± 5.17 kg, women = 55.91 ± 7.35kg, P = 0.00028) were recruited as a convenience sample to participate in this study. Printed and electronic advertisements were posted on notice boards to recruit participants between June 2017 to August 2017. All participants recruited were McGill University students. Participants were excluded if they had any prior employment experience in manual material handling. Individuals who had lower back pain, upper body injuries, or musculoskeletal or cardiovascular impairments in the last 6 months prior to the data collection were also excluded. Participants signed a written informed consent form prior to participating. The study was approved by the Research Ethics Board of the Centre for Interdisciplinary Research in Rehabilitation (CRIR) of Greater Montreal. It was conducted in accordance with The Helsinki Declaration.

2.2 Experimental Protocol

The participant was given a brief introduction of the process once the informed consent form was signed. Before placement of the electrodes, the skin surface over the muscles of interest was shaved and cleaned with alcohol, to decrease impedance. Bipolar Ag/AgCl, 10 mm- diameter surface electrodes (Ambu©,Denmark) were placed parallel to the muscle fibers on the skin overlaying each of the following muscles: Upper Trapezius (midpoint between the acromion and C7 spinous process), Pectoralis Major (3 cm below and proximal to the coracoid process), Anterior Deltoid (vertically below the lateral end of the clavicle), Biceps Brachii (midpoint between the acromioclavicular and elbow joint), Middle Deltoid (2 to 3 cm under the acromion), Triceps Brachii (Midpoint and 2 cm medial of the line between posterior crista of the acromion and the olecranon), Left Lumbar Erector Spinae (2-3 cm lateral to the spine of L1) and Right Lumbar Erector Spinae (2-3 cm lateral to the spine of L1). Electrodes were placed on the right side of the body. A reference electrode was placed on C7. Placement of the electrodes was done following the SENIAM guidelines (Hermens et al., 2000). Electrodes and wires were secured on the skin using surgical tape.

Two, 5-second (ramp up – hold – ramp down) maximal voluntary isometric contractions (MVICs) were performed and electromyography (EMG) data was measured for each muscle (see Table 1). The MVICs guidelines from Hermens et al. (2000) were followed. One minute of rest was given between MVICs. Once the MVICs were obtained, the participant rested for 10 minutes. To avoid interrater variability, the same assessor was responsible for the MVIC protocol for each participant.

Table 1. Muscle Maximum Voluntary Isometric Contractions (MVICs) positions.

Muscles	Posture	Direction of effort
Upper Trapezius	Participant shrugged their shoulders upwards	Primary researcher applied pressure downwards
Pectoralis Major	Participant pressed their hands together, with elbows at 90 degrees flexion and shoulders in neutral position	N/A
Anterior Deltoid	Participant performed shoulder abduction while the shoulder is in slight flexion, humerus in slight medial rotation	Primary researcher applied pressure on the arm in direction of adduction and slight extension
Middle Deltoid	Participant performed shoulder abduction while elbow in 90 degrees flexion and fist in neutral position	Primary researcher applied downward pressure at the distal end of the humerus
Biceps Brachii	Participant performed arm supination and elbow in 90 degrees flexion	Primary researcher provided pressure as participant attempted a bicep curl
Triceps Brachii	Participant performed shoulder abduction with elbow in flexion at 90 degrees	Participant attempted to extend forearm while primary researcher applied pressure
Left and Right Erector Spinae	Lifting trunk from a prone position	N/A

Then, the participant was familiarized to the experimental movement task, consisting of a repetitive pointing task (RPT). This part of the study is described in detail in Yang et al. (2019). Briefly, the RPT involved the participant to repetitively move their arm between a proximal and a distal target, which were aligned with the participant's midline, at shoulder height while in a standing position. For this study, the rate of the pointing task was synchronized with a metronome at 1 second per cycle which allowed for two movements (one forward, one backward) per second. This rhythm was maintained using auditory feedback heard each time the touch-sensitive targets were touched. For this protocol, in order to imitate a real-life assembly line, the participant held a light weight (12 cm x 7.5 cm x 1 cm, 0.7 kg females and 1.4 kg for males) while performing the RPT task.

The participant received 10 minutes of rest after practicing the RPT for a few trials. Following the rest period, the participant performed 30s of the repetitive pointing task (RPT) which represented the non-fatigued RPT (NFRPT). Before and after NFRPT, exertion levels experienced at the shoulder, elbow and lower back muscles were assessed using a Borg CR10 scale (Borg, 1982). Following the NFRPT, the participant performed a series of fatiguing protocols to individually fatigue the shoulder, elbow and trunk, in randomized order. Immediately after each fatiguing protocol, the participant performed the 30-second RPT (SFRPT for shoulder fatigued RPT, EFRPT for elbow fatigued RPT, TFRPT for trunk fatigued RPT). After each post-fatigue RPT, the participant was given at least 30 minutes to rest while sitting on a chair to passively recover (Davidson, 2004). Every 5 minutes, the participant was asked to rate the fatigue of each targeted muscle using the Borg CR10 scale (Borg, 1982). The recovery period continued until the participant's Borg CR10 score matched that of the one recorded prior to the NFRPT.

The three fatiguing protocols were conducted in series of intermittent static tasks. The shoulder fatiguing protocol aimed to fatigue the anterior muscular structure around the shoulder joint. The participant held a weight inserted in the wrist band (12 cm x 7.5 cm x 1 cm, 0.7 kg for females and 1.4 kg for males) with their shoulder positioned at 90 degrees flexion and 45 degrees horizontal abduction, for 1 minute per set, and 10 seconds of rest between each set. The elbow fatiguing protocol aimed to fatigue the extensor muscles (triceps brachii). Fatigue was produced by the participant extending their elbow at 145 degrees while isometrically pulling a Thera-Band (black color, 3.31 kg of resistance at 100% elongation), with 1 minute per set and 10 seconds of rest between each set. The aim of the lower back fatiguing protocol was to fatigue the erector lumbar spinae muscles. The participant extended their low back 30 degrees from an unsupported prone position until their trunk was aligned with their hips, knees and ankles. This position was held for 30 seconds per set and they received 10 seconds of rest between each set.

Figure 1. Shoulder, elbow and lower back fatiguing protocol postures

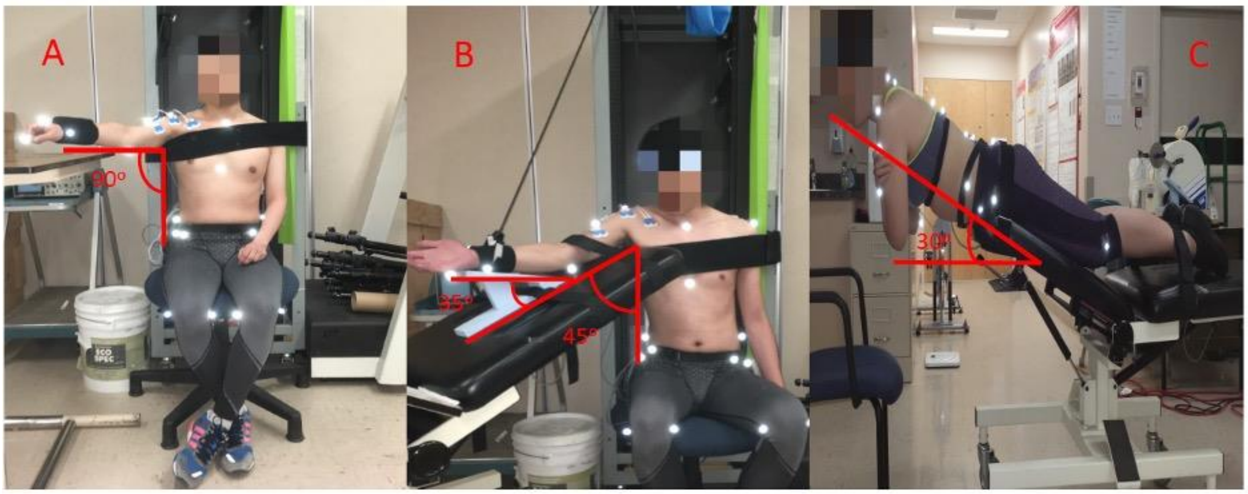


Figure A represents the shoulder fatiguing protocol, figure B represents the elbow fatiguing protocol and figure C represents the lower back fatiguing protocol

The Borg CR10 scale score of the targeted muscles was also asked and recorded at the end of each fatiguing protocol. Each protocol was terminated when 1) the participant rated Borg CR10 score 10 for 3 consecutive times or 2) the position could not be maintained for 1 minute (30 seconds for the lower back protocol) 3 consecutive times. The participant was not aware of these termination criteria.

2.3 Data acquisition

Surface EMG signals were collected during each MVIC trial, and from the 30s RPT trials (TeleMyo 900, Noraxon USA Inc.; 1080 Hz). The TeleMyo data acquisition system had an operating bandwidth of 10- 500 Hz, an effective common mode rejection ratio of 130 dB at 60 Hz, had at least 85 dB throughout the operating bandwidth and had a fixed per-channel gain of

2000. The data was digitally converted using a 16-bit A/D board over a ± 10 V range and stored for further analysis. Once recorded, all EMG (RPT and MVIC) data was then visually screened for heartbeat contamination. No EMG data contained evident heartbeat signals. The RPT data was filtered using a zero-lag, 2nd order Butterworth bandpass filter of 10 – 450 Hz. The data was then partitioned into forward and backward movement phases. The maximum RMS from the moving RMS average of each MVIC for each muscle were visually selected to ensure that values represented true maximum voluntary RMS, and not a random twitch or glitch. The greatest maximum RMS value was then used to normalize the EMG data for each RPT trial. To calculate the RMS, the RPT EMG data was rectified. A RMS value was determined for each of the 30 forward movement phases, therefore providing 30 RMS values for each muscle. The RMS values were averaged together to obtain a mean RMS value to represent the EMG RMS for that muscle for each condition. The Fast Fourier transform was applied to the filtered RPT EMG data in order to obtain the mean power frequency (MnPF). The MnPF was calculated for each trial over the 1s windows therefore obtaining 30 MnPF values. The MnPF was also averaged together to obtain a mean MnPF value to represent the MnPF for that muscle for each condition. The variability was quantified by calculating the standard deviation (SD) of all the EMG RMS values recorded during each forward movement phase. One SD value was obtained for each muscle in each condition.

2.4 Statistical Analysis

Generalized estimating equations (GEE) were used to assess the effects of fatigue condition (NFRPT, SFRPT, EFRPT and TFRPT), sex (female, male) and the interaction between fatigue location and sex on EMG variables (RMS, SD and MnPF). The GEE approach was applied secondary to it being able to obtain higher power with a smaller sample size in comparison to the repeated measures analyses of variance (RM-ANOVA), less restrictive assumptions than RM-ANOVA as well as it helps to estimate the overall average effects per group (Ma et al., 2012; Naseri et al., 2016). In order to apply pair-wise comparisons, the Least Significance Difference tests were applied between condition (NFRPT, SFRPT, EFRPT and TFRPT) and sex for each of the EMG variables (RMS, SD and MnPF). The significance level was $p < 0.05$. Statistics were conducted in SPSS (SPSS Statistics v24, IBM Corp., US). To correct for type one errors, the Benjamini-Hochberg procedure was implemented since it outputs greater power in comparison to Bonferroni technique (Thissen et al., 2002).

Results:

3.1 MnPF

There were interaction effects of sex x condition on left erector spinae MnPF (Wald chi-square = 11.19, p = 0.011) (Figure 2). For males, there was lower left erector spinae MnPF in TFRPT compared to all 3 conditions (NFRPT: p < 0.001 EFRPT: p < 0.001; SFRPT: p < 0.001. For females, there was lower left erector spinae MnPF in TFRPT compared to EFRPT (p =0.028) and SFRPT (p= 0.024).

Main effects of fatigue location for mean power frequency were found in upper trapezius, pectoralis major, anterior deltoid, middle deltoid, triceps brachii and right erector spinae (Table 2).

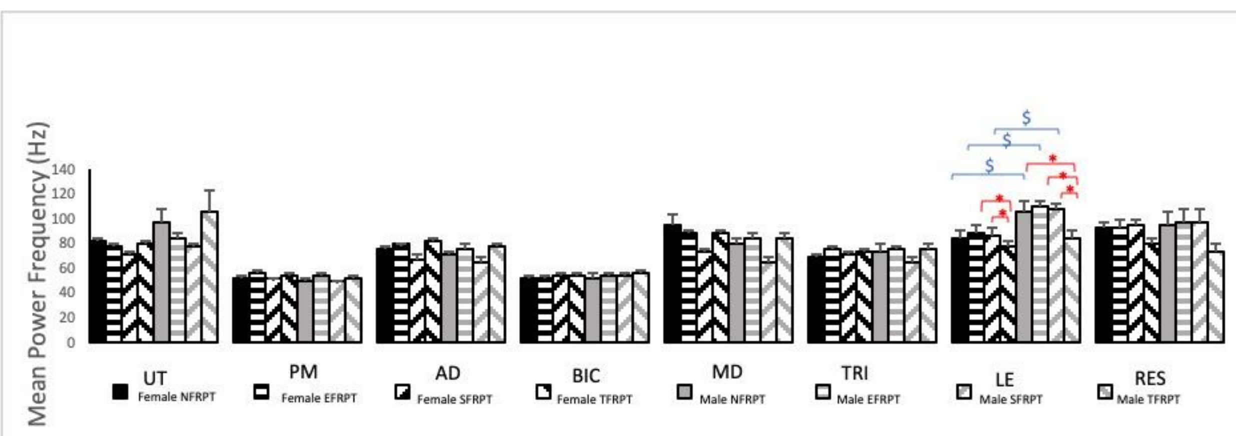
Table 2. Main effects of fatigue location for mean power frequency

Muscle	Main effect	Condition
Upper Trapezius	Wald Chi-Square = 20.87 p < 0.001	SFERT 6.77 Hz smaller than EFRPT, p < 0.001 SFRPT 15.32 Hz smaller than NFRPT, p = 0.011

Pectoralis Major	Wald Chi-Square =10.01, p = 0.018	SFRPT 4.49 Hz smaller than EFRPT, p =0.0031
Anterior Deltoid	Wald Chi-Square = 49.86, p < 0.001	SFRPT 12.09 Hz smaller than EFRPT, p < 0.001 SFRPT 6.95 Hz smaller than NFRPT, p = 0.0037; SFRPT 13.93Hz smaller than TFRPT, p < 0.001
Middle Deltoid	Wald Chi-Square = 87.60, p < 0.001	SFRPT 16. 28 Hz smaller than EFRPT, p < 0.001; SFRPT 18.54 Hz smaller than NFRPT, p < 0.001; SFRPT 17.75 Hz smaller than TFRPT, p < 0.001
Triceps Brachii	Wald Chi-Square = 8.12, p = 0.04	SFRPT 6.77 Hz smaller than EFRPT, p = 0.0086; SFRPT 6.06 Hz smaller than TFRPT, p = 0.0065
Left Erector Spinae	Wald Chi-Square = 55.63, p < 0.001	TFRPT 17.42 Hz smaller than EFRPT, p < 0.001; TFRPT 14.28 Hz smaller than NFRPT, p < 0.001; TFRPT 15.39 Hz smaller than SFRPT, p < 0.001
Right Erector Spinae	Wald Chi-Square = 59.25, p < 0.001	TFRPT 18.76 Hz smaller than EFRPT, p < 0.001; TFRPT 17.14 Hz smaller than NFRPT, p < 0.001; TFRPT 19.67 Hz smaller than SFRPT, p < 0.001

Results also show some main Sex effects. Females have a lower left erector spinae MnPF in comparison to males when performing the RPT task under the non-fatigued, shoulder fatigued and elbow fatigued conditions (EFRPT: 21.41 Hz smaller, $p = 0.011$; NFRPT: 21.00 Hz smaller, $p = 0.036$; SFRPT: 6.78 Hz smaller, $p = 0.012$) (Figure 2).

Figure 2. GEE of Mean Power Frequency before, and after protocols of localized muscle fatigue.



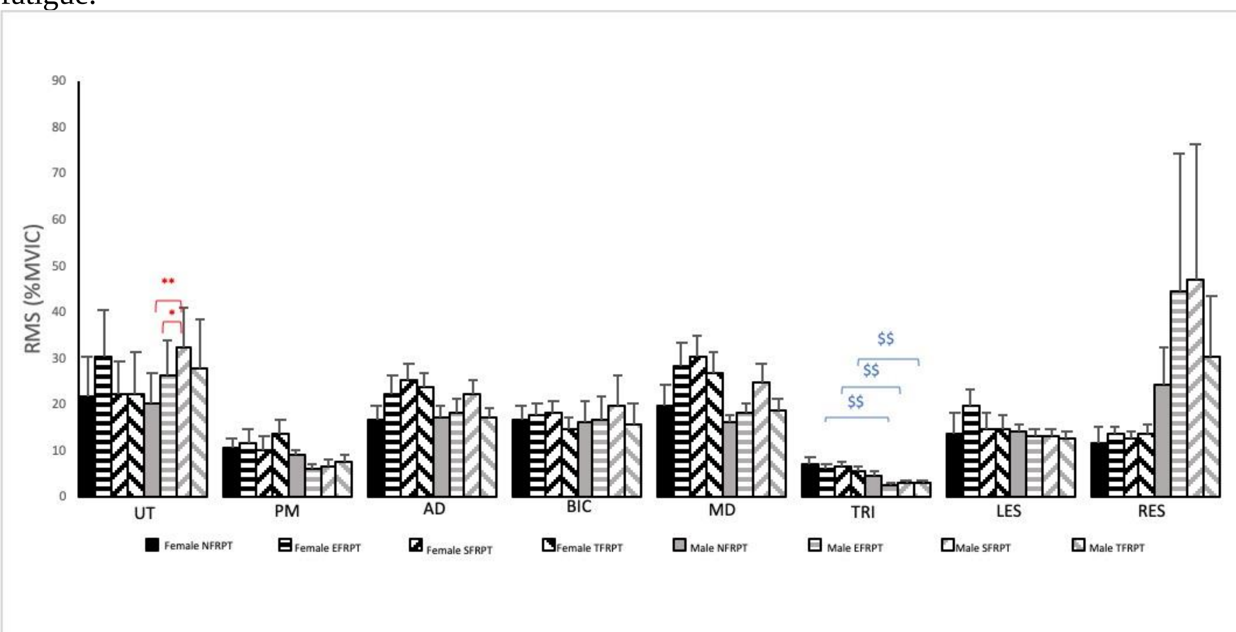
Upper Trapezius (UT), Pectoralis Major (PM), Anterior Deltoid (AD), Biceps Brachii (BIC), Middle Deltoid (MD), Triceps Brachii (TRI), Left Erector Spinae (LES), Right Erector Spinae

(RES). Non-fatigued repetitive pointing task (NFRPT), elbow fatigued repetitive pointing task (EFRPT), shoulder fatigued repetitive pointing task (SFRPT) and trunk fatigued repetitive task (TFRPT). The brackets with the * represent the interaction effects sex x condition type. The brackets with the $ represent the main Sex effect. The error bars represent the standard error.
* indicates that there is a statistically significant p- value between 0.01 and 0.05.
** indicates that there is a statistically significant p-value at or under 0.01
$ indicates that there is a statistically significant p- value between 0.01 and 0.05.
$$ indicates that there is a statistically significant p-value at or under 0.01.

3.2 EMG RMS

There were interaction effects of sex x condition on upper trapezius RMS (Wald chi-square = 8.41, p = 0.038) (Figure 3). Males had higher upper trapezius RMS activity during SFRPT compared to both EFRPT (p = 0.018) and NFRPT (p = 0.0067).

Figure 3. GEE of Muscle activation amplitude before, and after protocols of localized muscle fatigue.



Upper Trapezius (UT), Pectoralis Major (PM), Anterior Deltoid (AD), Biceps Brachii (BIC), Middle Deltoid (MD), Triceps Brachii (TRI), Left Erector Spinae (LES) and Right Erector Spinae (RES). Non-fatigued repetitive pointing task (NFRPT), elbow fatigued repetitive pointing task (EFRPT), shoulder fatigued repetitive pointing task (SFRPT) and trunk fatigued repetitive task (TFRPT). The brackets with the * represent the interaction effects sex x condition type. The brackets with the $ represent the main Sex effect. The error bars represent the standard error.
* indicates that there is a statistically significant p- value between 0.01 and 0.05.
** indicates that there is a statistically significant p-value at or under 0.01
$ indicates that there is a statistically significant p- value between 0.01 and 0.05.

$$ indicates that there is a statistically significant p-value at or under 0.01.

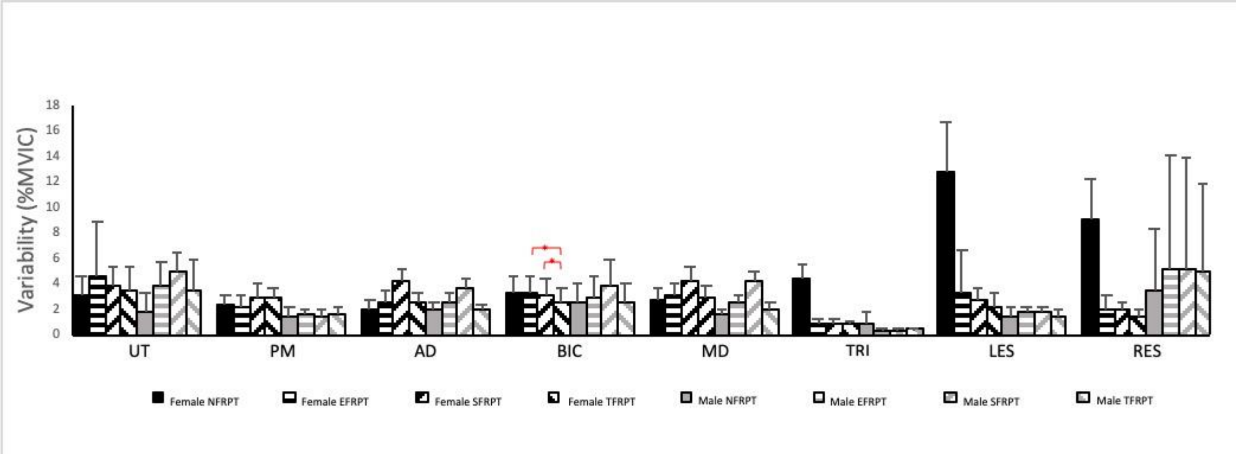
There were main effects of fatigue location on the RMS of anterior deltoid (Wald Chi-Square = 8.78, $p = 0.032$) and middle deltoid (Wald Chi-Square = 28.76, $p < 0.001$). There was greater anterior deltoid RMS at SFRPT and TFRPT than at NFRPT (SFRPT: 6.80 %MVIC, $p = 0.0032$; TFRPT: 3.51 %MVIC, $p = 0.039$). As for the middle deltoid, RMS was significantly greater in SFRPT than in all 3 other conditions (NFRPT: 9.71 %MVIC greater, $p < 0.001$, EFRPT: 4.07 %MVIC greater, $p = 0.047$, TFRPT: 4.74 %MVIC greater, $p = 0.0032$).

Results also show some main Sex effects. In reference to the MVICs measured, women activate their triceps brachii more when performing the RPT task under all 3 fatigued conditions in comparison to men (Figure 3). It was determined that women had a greater triceps brachii activation in comparison to men in the EFRPT (3.60 %MVIC greater, $p= 0.0012$), SFRPT (3.63 %MVIC greater, $p= 0.0027$) and TFRPT conditions (2.91 %MVIC greater, $p = 0.007$) (Figure 2).

3.3 EMG SD

There were interaction effects of sex x condition for biceps brachii SD (Wald chi-square = 9.48, $p = 0.023$ (Figure 4). For biceps brachii SD, for females, there was greater variability in SFRPT and EFRPT compared to TFRPT ($p = 0.035$ and $p =0.018$, respectively).

Figure 4. GEE of muscle activation variability before, and after protocols of localized muscle fatigue.



Upper Trapezius (UT), Pectoralis Major (PM), Anterior Deltoid (AD), Biceps Brachii (BIC), Middle Deltoid (MD), Triceps Brachii (TRI), Left Erector Spinae (LES) and Right Erector Spinae (RES). Non-fatigued repetitive pointing task (NFRPT), elbow fatigued repetitive pointing task (EFRPT), shoulder fatigued repetitive pointing task (SFRPT) and trunk fatigued repetitive task (TFRPT). The brackets represent the interaction effects sex x condition type. The error bars represent the standard error.
* indicates that there is a statistically significant p- value between 0.01 and 0.05.
** indicates that there is a statistically significant p-value at or under 0.01

There were main effects of fatigue location on activation variability in upper trapezius (Wald Chi-Square = 26.37, $p < 0.001$), anterior deltoid (Wald Chi-Square = 16.86, $p < 0.001$), middle deltoid (Wald Chi-Square = 26.01, $p < 0.001$) and right erector spinae (Wald Chi-Square = 14.19, $p = 0.0026$). The activation variability was significantly greater in upper trapezius in SFRPT and EFRPT in comparison to NFRPT (1.87 greater, p <0. 001 and 1.85 greater, p = 0.0024, respectively). The activation variability was significantly greater in anterior deltoid in SFRPT in comparison to all three conditions (NFRPT: 1.85 greater, p<0. 001, EFRPT: 1.35 greater, p = 0.0081, TFRPT: 1.60 greater, p <0. 001). Additionally, under the SFRPT condition, middle deltoid had a greater activation variability in comparison to all 3 conditions (NFRPT: 2.11 greater, p= 0. 0014, EFRPT: 1.40 greater, p = <0. 001, TFRPT: 1.80 greater, p < 0. 001). The activation variability in right erector spinae was significantly greater in SFRPT in comparison to TFRPT condition (0.37 greater, $p = 0.001$). Finally, there were no main Sex effects on any of the SD variables.

Discussion:

The hypotheses of this study were that localized fatigue at different joints would lead to changes in the activation of muscles around the other joints during the repetitive pointing task as well as there would be sex differences in compensation strategies. The main findings of our study were 1) in most fatiguing conditions, the shoulder agonists increase their activation 2) Men have a shoulder-based compensation strategy 3) Women have an elbow-based compensation strategy.

4.1 Sex differences

To our knowledge this is the first study which assessed sex differences in effects of localized fatigue induced at different body parts on arm and trunk muscle activity during a repetitive upper limb multi-joint task. Previously, there were studies which evaluated fatigability and motor control while performing the same repetitive pointing task, and others which assessed sex differences (Srinivasan et al., 2016; Fedorowich et al, 2013; Lomond et al., 2010). These previous studies denoted that the task significantly affects the activation of upper trapezius, supraspinatus, middle deltoid and biceps brachii muscles (Lomond et al., 2010; Fedorowich et al., 2013). Regarding sex differences, Fedorowich et al. determined that there were no significant sex differences in EMG RMS and EMG SD during the same repetitive pointing task (2013). However, Srinivasan et al., concluded that there were sex differences in variability, but not in amplitude, during this same experimental task. They determined that men had a higher EMG variability in upper trapezius and women had greater EMG variability in biceps brachii when fatigued. This difference could have been explained by a larger sample size in the Srinivasan study. However, results between these two studies and the present one can be explained by the fact that different kinds of fatigue were induced (maximal, statically induced, localized muscle fatigue in the present study, vs repetitive whole-limb induced in the previous two).

Biomechanically, the RPT task in the forward direction requires the participants to adduct their shoulder and extend their elbow in the horizontal plane. Therefore, the prime movers for this task are the anterior deltoid (shoulder) and the triceps brachii (elbow). During the RPT task, the upper trapezius works as a stabilizer for the shoulder and the biceps brachii works as the stabilizer for the forearm. The results indicated that males require a higher degree of upper trapezius activity to perform the task in comparison to females when the shoulder muscle was fatigued but not when the elbow or lower back muscle were fatigued, indicating that men require a higher degree of stabilization in the shoulder in comparison to women when the shoulder movers are locally fatigued. Similar results were seen in the Srinivasan et al., (2016) study. They evaluated sex differences in fatigability while performing the same repetitive pointing task until fatigue, although in those studies fatigue was not identified by exhaustion but rather by scoring 8/10 on the Borg CR10 scale. However, none of the specific joints required for the task were locally fatigued. Their results indicated that men require a higher involvement of the shoulder stabilizing muscles when fatigued, concluding that men use a more shoulder- based compensatory strategies when their upper extremity becomes fatigued. Another study conducted by Anders et al. (2004) also showed that men have a more shoulder-based compensatory strategy when they become fatigued. They assessed muscle activity while men performed push-ups (isometric shoulder exercise) which determined that men have a higher tendency to activate shoulder muscles while performing the task in comparison to women who showed higher muscle activation of the synergist muscles (Anders et al., 2004). A possible reason for this is that men have a bigger fiber cross-sectional area in upper trapezius muscle in comparison to women even though they have similar fiber type composition (Lindman et al., 1990&1991), supporting that men have a higher force-generating capacity in comparison to women (Meyland et al., 2014). Men may also require higher contribution from the trapezius muscle to stabilize the shoulder joint, since men's arms are likely to be longer and heavier, placing a higher torque on the shoulder joint when it moves in a horizontal plane, as in the current study. However, the exact effect of arm anthropometric load alone has never been studied, to our knowledge, and therefore this hypothesis would require verification from experimental and-or modeling studies.

Our results also indicated an interaction of sex and condition on biceps brachii SD. For females, there was greater variability in SFRPT and EFRPT compared to TFRPT. These results indicate that women require elbow stabilizers when either the shoulder or elbow are fatigued in order to continue to perform the task compared to when the trunk is fatigued. Previous studies also had similar results. Srinivasan et al. (2016) determined that women exhibited a greater increase in biceps variability when fatigued during the same repetitive task. Therefore, they concluded that women require an elbow-based control strategy when the arm is fatigued in order to continue to perform the task. They also suggested that when the upper trapezius is fatigued, women may implement a motor control strategy which defers the mechanical loading of the trapezius muscle down the kinetic chain, the elbow, to migrate the fatigue in the upper trapezius (Srinivasan et al., 2016). Other studies also concluded that men and women also have different patterns in stabilization and mobilization execution of a task (Otto et al., 2018). Since the elbow joint is the dynamic joint in the RPT, the women may have a higher variability in biceps brachii activation as a result of having weaker upper extremity strength. Therefore, women may compensate by changing the amount of activation of the elbow task stabilizer, biceps brachii, from trial to trial in order to perform the task. These previous results identify mechanisms that may explain how men and women have different ways of compensating for fatigue in a multi-joint task when the structures around the shoulder and the elbow are fatigued. Thus, our findings support our hypothesis that men and women use different compensatory strategies.

Our results also show that there was a main effect of sex on RMS of the triceps brachii muscle when performing the RPT under all 3 fatigue conditions, showing that women activate their triceps muscles more than men, no matter the condition, in order to perform the task until completion. A significantly higher triceps brachii RMS for 3 conditions may be because women tend to use more muscle activity which is closer to their maximal capacity (Haward and Griffin, 2002). However, this result may also be due to the sex differences in the ability to fully activate muscles during the MVIC procedure. It has been suggested that females are less likely to achieve maximal activation when performing MVIC (Dotan & Falk, 2010). This would lead to a smaller RMS value for the MVIC (denominator) therefore leading to a higher normalized EMG RMS value. This hypothesis, although in need of further validation, is supported by recent studies showing a significant impact on the EMG normalization procedure on sex differences in experimental EMG studies (Cid et al., 2020).

4.2 Localized shoulder fatigue

Under the SFRPT condition, muscle activation was greater in middle deltoid in comparison to the other conditions, and in anterior deltoid in comparison to NFRPT condition. Additionally, the MnPF was smaller in anterior deltoid and middle deltoid in SFRPT in comparison to the other three conditions. This demonstrates that when the shoulder muscles are fatigued, the prime movers mainly increased their muscle activation, likely by recruiting more and bigger motor units to keep up with the required pace and maintain the elevated arm posture and the movement performance. These results confirm the kinematic results presented in the Yang et al. study, which determined by kinematic measures that shoulder fatigue impacts the shoulder horizontal abduction and abduction angles which are actions influenced by anterior deltoid and middle deltoid (2019). Our results were further supported by the Bouffard et al. (2018) study, which concluded that the humerothoracic angle decreased when fatigued. The muscles most involved in the humeral elevation are the deltoids.

Additionally, SD was greater in anterior deltoid and middle deltoid in SFRPT in comparison to the other three conditions. The increase in variability suggests that these muscles may be searching for new movement patterns to preserve task performance in the presence of fatigue at that joint. These results are also in line with those of Yang et al. (2019), who presented kinematic data showing that when the shoulder is fatigued, it increases its movement variability in shoulder horizontal abduction, which is an action influenced by anterior deltoid (Yang et al., 2019). The increase in middle deltoid variability may be due to the fact that when fatigued, the shoulder may be slightly abducted in order to continue to perform the task. However, this was not shown with the kinematic data. The increase in activation variability in upper trapezius in comparison to NFRPT suggests that when the shoulder is fatigued, the change in movement variability may require variable amounts of stabilization from the shoulder.

Right erector spinae greater variability in SFRPT in comparison to TFRPT suggests that while performing the RPT under shoulder fatigue, the participants would consistently alter the movement of their trunk. This result aligns with the results obtained in Yang et al., (2019) study.

They determined with kinematic measures that SFRPT caused greater variability in trunk rotation angles (Yang et al., 2019), suggesting attempts to search for ways to use movement of the unfatigued proximal joint, the trunk, to contribute to the arm task. Such compensations from the trunk have also been shown to occur in other studies using the same experimental task (Fuller et al., 2009, 2011, 2013), and suggest a strategy to engage a joint that otherwise would not be required to move, now as a mover, which may represent an efficient strategy, since a change of a few degrees in trunk motion may represent a good mechanical advantage towards movement of the arm endpoint (Fuller et al., 2013).

4.3 Localized elbow fatigue

In the EFRPT trial, one of the prime movers (triceps brachii) was locally fatigued. Under this condition, the middle deltoid muscle activation was significantly greater in comparison to NFRPT. The action of the middle deltoid is to abduct the shoulder, suggesting that when the triceps are fatigued, the shoulder compensates by further abducting the shoulder in order to perform the task. Additionally, upper trapezius variability in this condition is greater than compared to NFRPT, suggesting that the task's shoulder stabilizer is recruited to compensate from trial to trial movement. These interpretations are supported by the results obtained in Yang et al., (2019) study, that assessed the kinematic changes when localized fatigue is induced at the shoulder, elbow and trunk joints during the same repetitive pointing task (2019). Their results showed that the EFRPT condition led to a greater shoulder abduction angle (Yang et al., 2019), which could indeed be achieved by increasing variability in the elbow joint.

4.4 Localized trunk fatigue

In the TFRPT trial, the left and right erector spinae, which act as posture stabilisers, were fatigued. Under this condition, the muscle activation amplitudes in anterior deltoid and middle deltoid were significantly greater in comparison to NFRPT. A reason for this may be that since the trunk muscles are fatigued, the trunk is likely stiffened, reducing its motion, as demonstrated by reduced trunk axial rotation during the RPT after trunk fatigue in Yang et al. (2019). With less trunk motion, a compensatory strategy would be to further engage the shoulder movers (evidenced by increased activation of the anterior deltoid and middle deltoid) to move the arm from one target to the other. Their results also indicate that there are higher variabilities of shoulder horizontal abduction angle, suggesting that the shoulder produces movement corrections in order to continue to execute the task (Yang et al., 2019). This aligns with Huffenus et al.'s study which also determined that the distal joints (shoulder) compensate for the proximal joint (trunk), although they used kinematic outcomes to support this point (2006).

One of the limitations of this study was the small sample size. A greater sample size would potentially lead to the determination of other sex main effects and interaction effects. Another possible limitation would be the movement of surface EMG electrodes while performing the RPT. For the surface electrodes to adhere to the skin surface, double sided tape was used. Additionally, to further secure the electrode to the skin surface, tape was placed over the electrode onto the skin. Even though the electrode was doubly taped, movement of the various joints may cause some shift in the electrodes, thereby potentially leading to motion artefacts, as well as cross-talk from muscle activity from the surrounding muscles. Lastly, the use of voluntary contractions to normalize EMG data could have led to a limitation due to variations between individuals' ability to reach true maximal efforts.

It would be of interest in future studies to include the assessment of muscle activity of the wrist joint, since previous research has identified compensations from the wrist when the structures around the elbow joint are fatigued (Huffenus et al., 2005). Additionally, it would be interesting to record lower extremity EMG in order to determine if they also increase their muscle activity when upper extremity joints are fatigued.

In conclusion, one's body compensations differ depending on which joint is locally fatigued during everyday tasks such as the repetitive pointing task. However, in each fatigued condition, the shoulder agonists, namely the anterior and middle deltoid, compensate by increasing their involvement in the task. Finally, the sex differences demonstrated by the results stress the importance that work injury prevention strategies should be sex-specific.

CONCLUSION

Previous studies used EMG to investigate how fatigue induced by the repetition of multijoint movements, induces whole-body adaptations and change coordination strategies (Fuller et al., 2009). However, there is limited research on how localized muscle fatigue induces whole-body adaptations and change in coordination strategies. To our knowledge this is the first study to assess sex differences in how localized muscle fatigue affects whole-body tasks. Our results determined that women and men use different strategies to compensate for localised muscle fatigue. For men when their shoulder structures are locally fatigued, they require higher muscle activation of the shoulder stabilizer for this task (e.g. upper trapezius). On the other hand, for females, when their shoulder and elbow (separately) were locally fatigued, they showed greater variability in the elbow stabilizer, biceps brachii, in order to maintain task performance. Also, one's body compensation differs depending on which joint is locally fatigued during the repetitive pointing task. However, in each fatigued condition, the shoulder agonists, anterior and middle deltoid, compensate by increasing their involvement in the task. These results however can only be generalised to a healthy population of young adults; more research is required to determine if these results can be generalised to other age groups. In addition, since research has previously shown that fatigue adaptations are task-specific, extrapolation of our findings to tasks that majorly differ in nature and objectives should be done with caution. In conclusion, our results support the notion that sex differences in work-related injury patterns may originate from differences in how muscles are used to produce a task, and stress the importance that work injury prevention strategies should be sex-specific.

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APPENDICIES

Appendix 1: Consent Form

Biomechanical Modeling of Posture and Movement Coordination: Fatigue, Gender and Aging effects.

CRIR Centre de recherche interdisciplinaire en réadaptation du Montréal métropolitain

Consent form

Hôpital juif de réadaptation Jewish Rehabilitation Hospital

1 - Title of project

Biomechanical Modeling of Posture and Movement Coordination: Fatigue, Gender and Aging effects.

2 - Researchers in charge of project

Julie Côté, Ph.D., Associate Professor, Department of Kinesiology and Physical Education, McGill University, (514) 398-4184 ext. 0539, (450) 688-9550, ext. 4813

Kim Emery, M.Sc., research assistant, Jewish Rehabilitation Hospital research center, (450) 688-9550 ext. 4827

Chen Yang, Ph.D. Student in Kinesiology, Department of Kinesiology and Physical Education, McGill University, (514) 804-0425

Maxana Weiss, Master Student in Kinesiology, Department of Kinesiology and Physical Education, McGill University, (438) 497-8608

3 - Preamble/Introduction

We are asking you to participate in a research project involving the analysis of your movements when you are fatigued. Before agreeing to participate in this project, please take the time to study and carefully consider the following information.

This consent form explains the aim of this study, the procedures, advantages, risks and drawbacks, as well as the persons to contact, if necessary.

This consent form may contain words that you do not understand. We invite you ask any question that you deem useful to the researcher and the others members of the staff assigned to the research project and ask them to explain any word or information which is not clear to you.

4 - Project description and objectives

The objectives of this research are to describe the time sequence of within- to between muscle changes occurring with repetitive motion-induced fatigue, and to assess the effects of fatigue on postural and proprioceptive characteristics. This project also aims at assessing gender differences in these fatigue responses. 30 healthy subjects will be recruited for this project and will perform a laboratory assessment protocol. The long-term objective of this project is to better understand how humans coordinate posture and repetitive arm motion and how fatigue affects this coordination. This research

Research protocol approved by the Committee for research ethics of the CRIR establishments, on xx/xx/2017 1 will provide knowledge and tools to identify, treat and prevent musculoskeletal disorders.

5 - Nature and duration of participation

The research project to which I am invited to participate aims at understanding how we coordinate posture and repetitive arm motion and how fatigue may affect this coordination. The experimental procedure takes place at the research center of the Jewish Rehabilitation Hospital. I am asked to participate in one experimental session that will last from two to three hours. The session involves four phases: Phase 1: preparation (30 minutes), Phase 2: pre-fatigue tests (30 minutes), Phase 3: fatigue procedure (30-90 minutes), Phase 4: post-fatigue tests (30 minutes).

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During Phase 1, locations of surface electrodes and markers will be marked on my skin using a make-up pen. Surface electrodes will be applied on the skin over my neck, trunk and dominant upper limb muscles in order to measure their activity. Reflective markers will be fixed on the skin over my neck, trunk, and arms in order to record their positions. None of these procedures is invasive.

During Phase 2, I will be asked to fill out questionnaires and complete baseline reference efforts, baseline strength measures, and a baseline measure of repetitive movements with my dominant arm.

During Phase 3, I will be asked to complete a fatiguing protocol which will require efforts of my back or dominant arm until exhaustion. I will be asked my perceived level of exertion every minute on a scale of 10.

During Phase 4, I will perform the same tests as those performed in Phase 2.

6 - Advantages associated with my participation

I will not personally benefit from any advantage by participating in this study. However, I will contribute to the advancement of knowledge of human movement and musculoskeletal disorders.

7 - Risks associated with my participation

None of the techniques used are invasive. I understand that my participation in this project does not put me at any medical risk.

8 - Personal inconvenience

The duration of the experimental session (approximately 2-3 hours) may represent an inconvenience for me. The possibility that some small

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regions (8, 3x3 cm each) of the skin over my neck, back and arm muscles have to be shaven before placing the electrodes might also represent an inconvenience for me. Although it is hypo-allergenic, the adhesive tape used to fix the electrodes on my skin may occasionally produce some slight skin irritation. Should this happen, a hypo-allergic lotion will be applied on my skin to relieve skin irritation. Also, I will experience some fatigue towards the end of the protocol, which may cause some tenderness, stiffness and/or pain in the upper body area during and/or following the session. These symptoms should dissipate within 48 hours following the completion of the protocol. A clinician will be present at all times during the experimental sessions.

9 - Access to my medical file

No access to my medical file is required for this study.

10 - Confidentiality

All the personal information collected for this study will be codified to insure confidentiality. Information will be kept under locking key at the research center of the Jewish Rehabilitation Hospital by one of the persons responsible for the study for a period of five years following the end of the study. Only the people involved in the project will have access to this information. If the results of this research project are presented or published, nothing will allow my identification. After this five-year period, data will be destroyed.

11 - Questions concerning the study

The researchers present during the testing should answer my questions concerning the project in a satisfactory manner.

12 - Withdrawal of subject from study

Participation in the research project described above is completely voluntary. I have the right to withdraw from the study at any moment. If ever I withdraw from the study, all documents concerning myself will be destroyed.

13 - Responsibility

By accepting to enter this study, I do not surrender to my rights and do not free the researchers, sponsor or the institutions involved from their legal and professional obligations.

14 - Monetary compensation

No monetary compensation will be given to me for participation in this protocol.

15 - Contact persons

If I need to ask questions about the project, signal an adverse effect and/or an incident, I can contact at any time Julie Côté, Ph.D., or Kim Emery, M.Sc., at the numbers indicated on the 1st page. I may also contact M. Michael Greenberg, local commissioner for the quality of services at the JRH, at (450) 688-9550, extension 232.

Also, if I have any questions concerning my rights regarding my participation to this research project, I can contact Mme. Anik Nolet, Research ethics co-ordinator of CRIR at (514) 527-4527 ext. 2643 or by email at anolet.crir@ssss.gouv.qc.ca

CONSENT

I declare to have read and understood the project, the nature and the extent of the project, as well as the risks and inconveniences I am exposed to as described in the present document. I had the opportunity to ask all my questions concerning the different aspects of the study and to receive explanations to my satisfaction.

I, undersigned, voluntarily accept to participate in this study. I can withdraw at any time without any prejudice. I certify that I have received enough time to take my decision.

A signed copy of this information and consent form will be given to me.

NAME OF PARTICIPANT (print): ________________________________

SIGNATURE OF PARTICIPANT: ________________________________

SIGNED IN ______________________, **on** __________________, **20**_____.

COMMITMENT OF RESEARCHER

I, undersigned, __________________________________ **, certify**

(a) having explained to the signatory the terms of the present form ;

(b) having answered all questions he/she asked concerning the study;

(c) having clearly told him/her that he/she is at any moment free to withdraw from the research project described above; and

(d) that I will give him/her a signed and dated copy of the present document.

____

Signature of person in charge of the project or representative

SIGNED IN __________________, **on** __________________________ **20**__.

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Appendix 2: Formulaire de consentement

CRIR Centre de recherche interdisciplinaire en réadaptation du Montréal métropolitain

Formulaire de consentement

Hôpital juif de réadaptation Jewish Rehabilitation Hospital

1 - Titre du projet

Modélisation biomécanique de la coordination entre la posture et le mouvement : effets de la fatigue, du genre et de l'âge.

2 - Responsable(s) du projet

Julie Côté, Ph.D., professeure agrégée, département de kinésiologie et d'éducation physique, université McGill, (514) 398-4184 poste 0539, (450) 688-9550, poste 4813

Kim Emery, M.Sc., assistante de recherche, centre de recherche de l'hôpital juif de réadaptation, (450) 688-9550 poste 4827

Chen Yang, étudiant au doctorat en kinésiologie, département de kinésiologie et d'éducation physique, université McGill, (514) 804-0425

Maxana Weiss, étudiante à la maîtrise en kinésiologie, département de kinésiologie et d'éducation physique, université McGill, (438) 497-8608

3 - Préambule/Introduction

Nous vous demandons de participer à un projet de recherche qui implique l'analyse de vos mouvements lorsque vous êtes fatigué. Avant d'accepter de participer à ce projet de recherche, veuillez prendre le temps de comprendre et de considérer attentivement les renseignements qui suivent.

Ce formulaire de consentement vous explique le but de cette étude, les procédures, les avantages, les risques et inconvénients, de même que les personnes avec qui communiquer au besoin.

Le présent formulaire de consentement peut contenir des mots que vous ne comprenez pas. Nous vous invitons à poser toutes les questions que vous jugerez utiles au chercheur et aux autres membres du personnel affecté au projet de recherche et à leur demander de vous expliquer tout mot ou renseignement qui n'est pas clair

4 - Description du projet et de ses objectifs

Les objectifs de cette recherche sont de décrire la séquence des changements intra- et inter-musculaires, ainsi que de mesurer les changements posturaux et proprioceptifs occasionnés par la fatigue due au mouvement répétitif. De plus, le projet vise à évaluer les différences de réponse à la fatigue entre les hommes et les femmes. 30 sujets en santé seront recrutés et participeront à un protocole d'évaluation en laboratoire. L'objectif à long terme de cette recherche est de mieux comprendre comment l'humain coordonne sa posture avec les mouvements répétitifs du bras, et comment la fatigue influence cette coordination. Cette étude permettra aussi d'accroître les connaissances et d'identifier des outils pour la prévention et le traitement des blessures musculo-squelettiques.

5 - Nature et durée de la participation

Le projet de recherche auquel je suis invité(e) à participer vise à comprendre comment nous coordonnons notre posture et nos mouvements répétitifs du bras et comment la fatigue peut influencer cette coordination. La procédure expérimentale sera effectuée au centre de recherche de l'hôpital juif de réadaptation. On me demande de participer à une séance expérimentale d'une durée approximative de 2 à 3 heures. Chaque séance comportera quatre phases : Phase 1 : préparation (30 minutes), Phase 2 : tests pré-fatigue (30 minutes), Phase 3 : procédure de fatigue (30-90 minutes) et Phase 4 : tests post-fatigue (30 minutes).

Durant la Phase 1, les emplacements des électrodes de surface et des marqueurs seront marqués sur ma peau à l'aide d'un crayon à maquillage. Des électrodes de surface seront fixées sur la peau des muscles de ma colonne et de mon bras dominant afin de mesurer leur activité. Des marqueurs réfléchissants seront fixés sur la peau de mon cou, de ma colonne et de mes bras afin d'enregistrer leurs déplacements. Aucune de ces procédures n'est effractive.

Lors de la Phase 2, on me demandera de remplir des questionnaires et de compléter des efforts de référence, des mesures de force et des mesures de mouvements répétitifs avec mon bras dominant.

Lors de la Phase 3, on me demandera de compléter un protocole de fatigue qui consistera en des efforts de mon dos ou de mon bras dominant jusqu'à épuisement. À la fin de chaque minute, je devrai identifier mon niveau d'effort perçu, sur une échelle de 0 à 10.

Lors de la Phase 4, on me demandera de refaire les tests effectués lors de la Phase 2.

6 - Avantages pouvant découler de ma participation

Je ne retirerai personnellement aucun avantage à participer à cette étude. Toutefois, j'aurai contribué à l'avancement des connaissances portant sur le mouvement humain et les blessures musculo-squelettiques.

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7 - Risques pouvant découler de ma participation

Aucune des procédures décrites n'est effractive. Je comprends que ma participation à cette recherche ne me fait courir aucun risque médical.

8 - Inconvénients personnels

La durée de la séance expérimentale (environ deux à trois heures) peut représenter un inconvénient pour certaines personnes. La possibilité que quelques petites surfaces (8, 3x3 cm chaque) de la peau sur les muscles de mon cou, mon dos et de mon bras doivent être rasées avant d'y apposer les électrodes peut aussi représenter un inconvénient pour moi. Bien qu'il soit hypo-allergène, le ruban adhésif utilisé pour maintenir les électrodes sur la peau peut occasionnellement provoquer de légères irritations de la peau. Le cas échéant, une lotion hypo-allergène sera appliquée pour soulager l'irritation cutanée. Aussi, je vais ressentir de la fatigue vers la fin de la séance expérimentale, ce qui pourrait occasionner de la sensibilité, de la raideur et/ou de la douleur dans la région du haut du corps durant et/ou après la séance. S'ils se manifestent, ces symptômes devraient disparaître dans les 48 heures suivant la fin du protocole expérimental. Un clinicien sera présent en tout temps pendant les séances expérimentales en cas de complications.

9 - Accès à mon dossier médical

Aucun accès à mon dossier médical n'est requis pour cette étude.

10 - Confidentialité

Tous les renseignements personnels recueillis à mon sujet au cours de l'étude seront codifiés afin d'assurer la confidentialité. Ces données seront conservées au centre de recherche de l'Hôpital juif de réadaptation et gardées sous clé par un responsable de l'étude pour une période de cinq ans suivant la fin de l'étude. Après cette période, les données seront détruites. Seuls les membres de l'équipe de recherche y auront accès. En cas de présentation des résultats de cette recherche sous forme écrite ou orale, rien ne pourra permettre de m'identifier.

11 - Questions concernant cette étude

Les chercheurs présents lors de la collecte des données s'engagent à répondre de façon satisfaisante à toutes mes questions concernant le projet de recherche.

1110

12 - Retrait de la participation du sujet

Ma participation au projet de recherche décrit ci-dessus est tout à fait libre et volontaire. Il est entendu que je pourrai, à tout moment, mettre un terme à ma participation. En cas de retrait de ma part, les documents électroniques et écrits me concernant seront détruits.

13 - Clause de responsabilité

En acceptant de participer à cette étude, je ne renonce à aucun de mes droits ni ne libère les chercheurs, le commanditaire ou les institutions impliquées de leurs obligations légales et professionnelles.

14 - Indemnité compensatoire

Aucune compensation financière ne me sera offerte pour ma participation à cette étude.

15 - Personnes ressources

Si je désire poser des questions sur le projet ou signaler des effets secondaires, je peux rejoindre en tout temps Julie Côté, Ph.D. ou Kim Emery, M.Sc., aux numéros indiqués à la 1ère page. Je peux également contacter Monsieur Michael Greenberg, commissaire locale à la qualité des services de l'HJR, au (450) 688-9550 poste 232.

De plus, si j'ai des questions sur mes droits et recours ou sur ma participation à ce projet de recherche, je peux communiquer avec Me Anik Nolet, coordonnatrice à l'éthique de la recherche des établissements du CRIR au (514) 527-4527 poste 2643 ou par courriel à l'adresse suivante: anolet.crir@ssss.gouv.qc.ca

CONSENTEMENT

Je déclare avoir lu et compris le présent projet, la nature et l'ampleur de ma participation, ainsi que les risques auxquels je m'expose tels que présentés dans le présent formulaire. J'ai eu l'occasion de poser toutes les questions concernant les différents aspects de l'étude et de recevoir des réponses à ma satisfaction.

Je, soussigné(e), accepte volontairement de participer à cette étude. Je peux me retirer en tout temps sans préjudice d'aucune sorte. Je certifie qu'on m'a laissé le temps voulu pour prendre ma décision.

Une copie signée de ce formulaire d'information et de consentement doit m'être remise.

NOM DU SUJET ____

SIGNATURE ____

Signé à _________________________, **le** __________, **20**_____.

ENGAGEMENT DU CHERCHEUR

Je, soussigné (e), ________________________________ **, certifie**

(a) avoir expliqué au signataire les termes du présent formulaire;

(b) avoir répondu aux questions qu'il m'a posées à cet égard;

(c) lui avoir clairement indiqué qu'il reste, à tout moment, libre de mettre un terme à sa participation au projet de recherche décrit ci-dessus;

et (d) que je lui remettrai une copie signée et datée du présent formulaire.

____

Signature du responsable du projet ou de son représentant

Signé à __________________, **le** ______________ **20**__.

Appendix 3: Borg CR10 Scale (English)

Rating	Description
0	Nothing at all
0.5	Extremely weak (just noticeable)
1	Very weak
2	Weak (light)
3	Moderate
4	Somewhat strong
5	Strong (heavy)
6	
7	Very strong
8	
9	
10	Extremely strong
•	Maximal

Appendix 4: Borg CR10 Scale (French)

Note	Description
0	Rien
0.5	Très très faible
1	Très faible
2	Faible
3	Modéré
4	Un peu dur
5	dur
6	
7	Très dur
8	
9	
10	Très très dur
•	Maximal