Sex-specific effects of intermittent submaximal fatiguing handgrip plus blood flow restriction on upper limb neuromuscular characteristics during a repetitive pointing task

Carson Graham
Department of Kinesiology Physical Education
McGill University
Montreal, Quebec, Canada
December 2024

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

TABLE OF CONTENTS

ABSTRACT

The goal of this Master's project was to investigate the sex-specific effects of a fatiguing handgrip task, and blood flow restriction (BFR), on repetitive arm motion. The motivation for this thesis was to better understand combined effects of both interventions, which could eventually help improve workplace injury prevention approaches. This research is particularly relevant given the higher prevalence of neck and shoulder work-related musculoskeletal disorders (WMSDs) in females, which are thought to be linked to sex differences in fatigue responses. These differences may be due to variations in blood flow, which could affect local and central fatigue mechanisms, and ultimately contribute to injury risk. Ten female and eleven male healthy participants performed three 30-second repetitive pointing tasks (RPTs) (pre-fatigue, post-fatigue, and recovery). The fatiguing protocol was an intermittent submaximal handgrip task, until the participant was unable to meet the target force (50% of maximum grip strength) for three consecutive contractions. Each participant completed a control session without BFR and an intervention session with 50% BFR applied to the upper arm during the handgrip task. Muscle activation (electromyography) was recorded during the handgrip and each RPT. Muscle thickness (ultrasound), and forearm and upper arm circumferences were recorded after each of the 3 RPT sequences. Both sexes had similar time to fatigue during the handgrip task, under both conditions. However, females exhibited greater forearm muscle activation and greater decreases in median power frequency (MdPF) in the flexor carpi radialis and brachioradialis muscles. Post-fatigue, forearm circumference and muscle thickness increased significantly in both sexes. Females demonstrated greater forearm muscle thickness changes, while males showed more consistent increases in biceps brachii thickness under BFR. During the RPTs, males displayed significant increases in MdPF of upper arm muscles (e.g., middle deltoid and pectoralis major) from pre- to post-fatigue, suggesting proximal compensation

for forearm fatigue. In contrast, females showed persistent fatigue effects in forearm muscles and no significant increases in upper arm MdPF post-fatigue. Forearm fatigue led to sex differences in neuromuscular strategies during repetitive pointing tasks. Males compensated for localized forearm fatigue with increased activation of proximal muscles, while females exhibited sustained forearm fatigue, reflecting limited compensation. These sex-specific responses to localized fatigue highlight how fatigue in one region can influence activation patterns in subsequent tasks, potentially impacting workplace performance and injury risk, which could have impact on sex-specific recommendations for post-work recovery strategies.

RÉSUMÉ

L'objectif de ce projet de maîtrise était d'examiner les effets spécifiques au sexe d'une tâche de préhension fatigante et de la restriction du flux sanguin (RFS) sur les mouvements répétitifs du bras. Cette recherche visait à mieux comprendre les effets combinés de ces deux interventions, dans le but d'améliorer les approches de prévention des blessures professionnelles. Ce sujet est particulièrement pertinent en raison de la prévalence accrue des troubles musculo-squelettiques liés au travail (TMS) au niveau du cou et des épaules chez les femmes, souvent attribuée à des différences sexuelles dans les réponses à la fatigue. Ces différences pourraient être dues à des variations du flux sanguin, influençant les mécanismes de fatigue locale et centrale, et contribuant ainsi au risque de blessure. Dix femmes et onze hommes en bonne santé ont réalisé trois tâches répétitives de pointage de 30 secondes (TRP) (pré-fatigue, post-fatigue et récupération). Le protocole de fatigue consistait en une tâche intermittente de préhension sous-maximale jusqu'à ce que le participant ne puisse plus maintenir la force cible (50 % de la force maximale de préhension) pendant trois contractions consécutives. Chaque participant a complété une session témoin sans RFS et une session interventionnelle avec une RFS de 50 % appliquée sur le haut du bras pendant la tâche de préhension. L'activation musculaire (électromyographie) a été enregistrée pendant la tâche de préhension et chaque séquence de TRP. L'épaisseur musculaire (échographie) ainsi que les circonférences de l'avant-bras et du haut du bras ont été mesurées après chaque séquence de TRP. Les deux sexes ont montré un temps de fatigue similaire lors de la tâche de préhension, quelle que soit la condition. Cependant, les femmes ont affiché une activation musculaire plus importante des muscles de l'avant-bras et une diminution plus marquée de la fréquence médiane de puissance (FMdP) dans les muscles flexor carpi radialis et brachioradialis. Post-fatigue, la circonférence de l'avant-bras et l'épaisseur musculaire ont significativement

augmenté chez les deux sexes. Les femmes ont montré des augmentations plus importantes de l'épaisseur musculaire de l'avant-bras, tandis que les hommes présentaient des augmentations plus soutenues de l'épaisseur du biceps brachii sous RFS. Lors des TRP, les hommes ont affiché des augmentations significatives de la FMdP des muscles proximaux du bras (p. ex., le deltoïde moyen et le grand pectoral) entre les phases pré- et post-fatigue, suggérant une compensation proximale pour la fatigue de l'avant-bras. En revanche, les femmes ont montré des effets de fatigue persistants dans les muscles de l'avant-bras et aucune augmentation significative de la FMdP des muscles proximaux du bras post-fatigue. La fatigue de l'avant-bras a entraîné des différences sexuelles dans les stratégies neuromusculaires pendant les tâches répétitives de pointage. Les hommes ont compensé la fatigue locale de l'avant-bras par une activation accrue des muscles proximaux, tandis que les femmes ont présenté une fatigue soutenue de l'avant-bras, reflétant une compensation limitée. Ces réponses spécifiques au sexe face à la fatigue localisée mettent en évidence l'impact potentiel de la fatigue régionale sur les schémas d'activation lors des tâches suivantes, ce qui pourrait influencer les performances professionnelles et le risque de blessure, ce qui pourrait contribuer à des recommandations adaptées au sexe en matière de stratégies de récupération post-travail.

ACKNOWLEDGMENTS

I would like to begin by expressing my sincere gratitude to my supervisor, Dr. Julie Côté, for her guidance and support throughout my degree. Julie created an environment that encouraged collaboration, problem-solving, and independence, skills I will take with me into my career and life. I am especially grateful for her open-minded approach to research, which gave me the freedom to explore a topic I am passionate about. Julie's patience, thoughtful advice, and encouragement have been instrumental in helping me grow as both a researcher and individual. I will always be thankful for the opportunities I had in the BOS lab and the lessons I learned under her supervision.

To my research assistant, Pruthvi Patel, and the entire BOS lab team—thank you for being such an integral part of this journey. Pruthvi, your dedication, time, and hard work on building and perfecting protocols, recruiting participants, and collecting data were invaluable. You not only helped me navigate the challenges of data collection but made the process so enjoyable. I would also like to thank Erika Renda for her mentorship and guidance in teaching me data collection methods, understanding timelines, and processing data, your insights and support made a huge difference. To the rest of the BOS lab team, thank you for always being there, whether it was troubleshooting, offering encouragement, or building friendships along the way. I am grateful for each of you.

Finally, to my family, I cannot thank you enough for your sacrifices and for always being there for me to help me chase any of my goals. To my mum, dad and my grandma, as I've grown, I've come to truly appreciate the hard work you've done, not only support me, but also my sisters, and my nieces. The drive and confidence you instilled in me have been the foundation of everything I've accomplished. Your support, whether it was over the phone, in person, or simply

felt through your love and care, has meant the world to me. I am forever grateful for everything you've done.

CONTRIBUTIONS OF AUTHORS

Carson Graham, the candidate, was responsible for research design, setup, recruitment, data collection, analysis, writing and any other steps necessary for the completion of the research study and submission of the thesis as per McGill University requirements.

Julie N. Côté, Ph.D., Full Professor, Department of Kinesiology and Physical Education, McGill University, the candidate's supervisor, was actively involved in every step and decision made regarding the research study and completion of thesis submission.

Pruthvi Patel., assisted with the setup, recruitment and data collection.

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

Abbreviation	Meaning
ANOVA	Analysis of Variance
BFR	Blood flow restriction
CMD	Central motor drive
CNS	Central nervous system
EMG	Electromyography
MdPF	Median power frequency
MVIC	Maximal voluntary isometric contraction
RMS	Root mean squared
RPT	Repetitive pointing task
WMSD	Work-related musculoskeletal disorder

Muscle Abbreviation	Name
AD	Anterior Deltoid
BB	Biceps Brachii
BR	Brachioradialis
FCR	Flexor Carpi Radialis
MD	Middle Deltoid
PD	Posterior Deltoid
PEC	Pectoralis Major
UT	Upper Trapezius

INTRODUCTION

Work-related musculoskeletal disorders (WMSDs) pose a significant risk to worker health and represent a substantial economic burden to employers (Canadian Institutes of Health Research, 2019). WMSDs can develop as a result of acute or chronic trauma from workplace tasks, affecting muscles, tendons, and nerves (CCOHS, 2024). Among these, injuries and disorders affecting the upper limb, particularly in the neck and shoulder regions, are of the most reported WMSDs, and disproportionately affect females (Alrowayeh et al., 2010). This disparity has been linked to sex differences in fatigue responses (Hunter, 2014).

Upper limb WMSDs are often associated with repetitive tasks performed over prolonged periods with insufficient recovery time (Colombini & Occhipinti, 2006). It is well-documented that females exhibit greater endurance during submaximal fatiguing tasks than males, even when matched for strength (Côté, 2012; Hunter et al., 2004). However, the sex difference in endurance is eliminated at higher contraction intensities or in conditions where blood flow is restricted (ischemia or occlusion) (Russ & Kent-Braun, 2003; Hunter et al., 2006). This suggests that the difference in fatigue resistance may be due to local responses within the muscle such as metabolic differences or fibre type composition (Simoneau & Bouchard, 1989; Hunter et al., 2009). The difference in blood flow or muscle perfusion can affect local fatigue mechanisms by influencing intra-muscular responses, and lead to inhibitory signals to central motor drive (CMD) (Amann & Dempsey, 2008).

The impact of localized fatigue on non-fatigued muscles has also been observed in studies utilizing blood flow restriction (BFR). BFR intensifies local fatigue by limiting oxygen delivery and increasing metabolite accumulation which is detected by sensory fibres within the muscle that

send inhibitory signals to the central nervous system (Broxterman et al., 2018; Hammer et al., 2020). This is the same process that occurs during exercise where muscle contraction/exercise leads to local fatigue and results in increased intramuscular pressures, metabolite buildup and reduced oxygen availability (Hunter, 2018). BFR has been shown to exacerbate local fatigue and may also affect non-fatigued muscles, potentially due to CMD inhibition (Kennedy et al., 2014; Hammer et al., 2020; Zahiri et al., 2024; Wong et al., 2019).

Given the documented effects of BFR, sex differences in blood flow during fatiguing tasks may result in sex-specific effects on both local and central fatigue responses. These differences could influence muscle coordination during multi-joint tasks and impair task performance following fatiguing tasks. Such effects are particularly relevant in occupational settings, where workers frequently switch between tasks involving different muscle groups.

One task used to simulate occupational tasks is the repetitive pointing task (RPT), described in detail by Fuller et al. (2009). The RPT involves repetitive flexion and extension of the elbow while reaching between two target points, with the arm maintained at shoulder height in a standing position. Studies using this task have consistently demonstrated sex-specific responses in muscle activation and fatigue adaptations (Srinivasan et al., 2016; Renda et al., 2022; Fedorowich et al., 2013; Yoon et al., 2021). Furthermore, Renda et al. (2022) showed that even when localized fatigue was induced in various trunk and shoulder muscles prior to the RPT sex differences in compensation strategies prevailed. However, it is unclear if these differences in compensation strategies are influenced by sex differences in blood flow or localized fatigue effects on CMD.

The objective of this thesis was to investigate sex differences in muscle activation and compensatory strategies during a RPT performed before and after a fatiguing submaximal handgrip task, with and without BFR applied. By examining changes in muscle activation using electromyography and measures of muscle thickness and circumference, with their changes considered as byproxies for changes in their perfusion, we aimed to understand how BFR interacts with sex-specific local fatigue mechanisms and subsequent task performance with non-fatigued muscles. We hypothesized that forearm fatigue would result in sex-specific alterations in muscle recruitment strategies during the repetitive task. Additionally, we hypothesized that BFR would amplify fatigue responses and elicit distinct sex-specific effects. These findings aim to enhance understanding of the mechanisms underlying WMSDs and inform the development of targeted ergonomic and rehabilitation interventions

LITERATURE REVIEW

Work-Related Musculoskeletal Disorders

WMSDs are conditions caused by or significantly influenced by the work environment and the tasks performed. According to the Centers for Disease Control and Prevention (2020), these disorders either develop primarily due to work-related factors or are aggravated and prolonged by them. In North America, WMSDs account for approximately 29-35% of all occupational injuries and illnesses (Bhattacharya, 2014). In Canada, musculoskeletal disorders also impose a significant economic burden, estimated to be around $22 billion (Canadian Institutes of Health Research, 2019). These costs include healthcare expenses, lost productivity, and compensation claims. Given these significant health and economic impacts, research into ergonomic solutions is essential to mitigate this cost and protect employee's well-being. Approximately 34% of WMSDs occur in the neck/shoulder area, often as a result of prolonged, high-paced, repetitive tasks with a lack of recovery (Alrowayeh, et al., 2010; Colombini and Occhipinti, 2006). Muscle fatigue plays a significant role in the development of these disorders, as it develops with prolonged or repetitive use of a muscle group which can reduce functional capacity (Mantooth et al., 2018; Enoka and Duchateau, 2016).

Neuromuscular and Physiological Aspects of Upper Limb Fatigue

Fatigue is a complex phenomenon which is related to impairment in task performance and can increase the risk of developing musculoskeletal disorders (Hunter, 2014; Amann et al., 2008; van der Windt et al., 2000). A widely adopted framework by Enoka and Duchateau (2016) defines fatigue as a disabling symptom to cognitive and physical performance that arises from the interactions between performance fatigability and perceived fatiguability. Performance

fatiguability refers the measurable declines in force, power or endurance, while perceived fatiguability refers to subjective sensations such as effort or discomfort (Enoka & Duchateau, 2016). While the authors caution against using classifications such as "central" or "peripheral", these terms are useful descriptors when referring to mechanistic aspects of fatigue. Peripheral fatigue is a local response within the muscle, which is mediated by the activation of group III (mechanosensitive) and IV (metabosensitive) muscle afferents. When these sensory fibres detect mechanical strain, metabolite accumulation or reduced oxygen availability, inhibitory feedback is sent to the central nervous system, resulting in reductions in central motor drive (CMD) (Gandevia, 2001; Amann & Dempsey, 2008). This can account for an approximate 25% reduction in maximal force production during single-limb exercises (Gandevia, 2001). It has been hypothesized that this occurs to modulate planning and execution of motor tasks beyond the fatigued muscle group (Gandevia, 2001; Amann & Dempsey, 2008). The reduced CMD also may have a broader impact on multiple muscles in the system, and in some cases affect non-exercised muscles, a phenomenon also known as non-local muscle fatigue (Zahiri et al., 2024). In the workplace, complex multi-joint movements and shifts in muscle group activation are common. Fatigue-related alterations to the central nervous system can affect overall movement performance and control (Sadler and Cressman, 2019). Understanding how fatigue in different muscle groups may affect the performance of other muscle groups can help identify risk factors for injury, guiding interventions to improve worker safety and efficiency.

Non-Local Muscle Fatigue

Non-local muscle fatigue occurs when fatigue in one muscle group leads to a reduction in function in non-exercised muscles located contralaterally, ipsilaterally, inferior, or superior to the fatigued muscle group (Halperin, 2015; Kennedy, 2013). This phenomenon is thought to arise from

centrally mediated mechanisms such as reductions in CMD from inhibitory afferent signals. A study by Kennedy et al. (2013) demonstrated this by recording maximal voluntary contractions of the plantar flexors before and after a fatiguing handgrip task. The authors found that the ankle plantar flexors showed a reduction in voluntary activation following the fatiguing handgrip task. In single limb multi-joint tasks, the location of fatigued muscles also seems to have differing effects on muscle activation and movement coordination. Cowley and Gates (2017) found that proximal (shoulder flexor) muscle fatigue caused widespread changes in joint angles and range of motion, while distal (finger flexor) fatigue primarily altered movement timing, suggesting different neural responses depending on the fatigued muscle group. Furthermore, a study by Renda et al. (2022) found that localized fatigue in various upper limb and trunk muscles resulted in alterations to muscle activation patterns during a repetitive upper limb task recorded by electromyography (EMG), that varied by sex. Together, these findings emphasize that peripheral fatigue responses can have a broad influence on neuromuscular function, potentially affecting coordination and compensation strategies during multi-joint tasks.

Electromyography

EMG is a physiological measure commonly used in sports and occupational research to assess muscle fatigue (Farina et al., 2014). EMG records the summation of electrical signals from motor unit action potentials, detected either at the muscle site using intramuscular electrodes or by surface electrodes placed on the skin above the muscle (Farina et al., 2014). The obtained signal can then be processed to interpret the alterations in activity occurring at the target muscle. These alterations can be assessed as myoelectric manifestations of fatigue and allow researchers to quantify fatigue in different scenarios (Marco et al., 2017). The EMG signal can be presented in time (e.g., amplitude) and frequency (e.g., power frequency) domains. During low-intensity

exercise, fatigue is associated with recruitment of larger motor units to compensate for the decline in force-generating capacity of the fatigued muscle, reflected by increases in EMG amplitude (i.e., muscle activation, which is quantified using the signal's root-mean-square (RMS) value) (McManus et al., 2020). Additionally, fatigue can be assessed by observing changes in the median power frequency (MdPF) of the EMG signal. As fatigue progresses, there is typically a shift to lower frequencies in the power spectrum, resulting in a decrease in MdPF, reflecting a reduction in muscle conduction velocity and changes in muscle fiber type recruitment (Farina et al., 2014). Fatigue effects can be influenced by sex in ways that are reflected by the EMG signal. For example, women often have a greater proportion of Type I (slow-twitch) fibers, which are more resistant to fatigue, compared to Type II (fast-twitch) fibers (Hunter, 2014). Type I fibres are connected to have a lower recruitment threshold, so they are the first to be recruited and remain activated for prolonged periods of time during low-force efforts, whereas Type II fibres are higher threshold fibres and are more fatigable (Hagg, 1991).

Sex Differences in Muscular Fatigue

Studies have found that women are generally less fatigable than men during submaximal isometric contractions of similar relative intensity; however, the precise underlying mechanisms remain unclear (Enoka & Hunter, 2001; Hicks et al., 2001; Yoon et al., 2007). In a review of sex differences on performance fatigability, it was suggested that muscle morphology may play a key role in females' endurance (Hunter, 2014). Males tend to have greater muscle mass than women, thus, males produce greater absolute force per contraction at the same relative intensity. However, this results in greater metabolic demand and mechanical compression on the vascular bed, both of which lead to increased reliance on anaerobic pathways. The byproducts of anaerobic glycolysis such as lactate and protons are detected by the group III/IV afferents which send inhibitory

signalling causing CMD reductions, and potentially the earlier task termination in males (Gandevia, 2001; Hicks et al., 2001; Taylor et al., 2016). Furthermore, Yoon et al. (2007) found that the sex difference in endurance were the most apparent during low intensity contractions but were eliminated at higher intensities. However, fatigue resistance in women has also been shown to persist even when men and women are strength-matched (Hunter et al., 2004; Fulco et al., 1999), indicating that factors beyond muscle mass contribute to the sex difference.

Independent of muscle mass, women have a greater capacity for oxidative metabolism and a lower reliance on glycolytic pathways, which may delay metabolite accumulation and reduce activation of group III/IV afferents that inhibit central motor drive (Hicks et al., 2001; Hunter, 2014). Supporting this, females have been shown to exhibit lower glycolytic enzyme activity and greater lipid oxidation during endurance tasks (Kent-Braun et al., 2003; Hicks et al., 2001). Additionally, some studies report that women have a higher proportion of type I (fatigue-resistant) muscle fibers in certain muscle groups, which may further contribute to their enhanced fatigue resistance (Hunter, 2014). While these physiological and morphological factors provide a foundation for understanding sex differences in fatigue, it is important to understand how they may manifest in different tasks, particularly in tasks where sex differences in fatigue may play a role in performance and injury risk.

Sex-Specific Biomechanics of Occupational Neck/Shoulder Fatigue

To study neck and shoulder fatigue within the context of WMSDs, researchers have used various standardized experiments to simulate job tasks. One method commonly used to replicate typical workplace motions is the repetitive pointing task (RPT) (Fuller et al., 2009). This task involves the repetitive movement of the hand between two targets by flexing and extending the

elbow while maintaining the arm at shoulder height. Many authors have utilized this experimental design, with some variations, to investigate the mechanisms underlying fatigue from repetitive upper limb motions. Most studies using this protocol have identified significant changes in fatigued muscles, such as the deltoids, biceps, triceps, and trapezius. EMG RMS generally increases with fatigue that results from the performance of the RPT, particularly in the trapezius and deltoids; moreover, no significant difference in time to fatigue between males and females was recorded (Fedorowich et al., 2013; Yoon et al., 2021). However, adaptations in movement and muscle activity in response to fatigue did differ between sexes. For example, Srinivasan et al. (2016) found that while males and females showed no differences in movement-to-movement variability in EMG RMS at the start of the task, they exhibited different control strategies as fatigue progressed. Males increased variability in the trapezius and anterior deltoid, whereas females increased variability in the biceps and triceps. The authors suggest that this could be a task-specific response, related to the biomechanical demands of the task, whereby men tend to rely on a 'shoulder-based' compensation strategy, whereas females rely on an 'elbow-based' one (Srinivasan et al., 2016). Another possible explanation is that females defer mechanical loading down the kinetic chain to mitigate fatigue in the upper trapezius, which plays a stabilizing role in this task (Srinivasan et al., 2016). A study by Renda et al. (2022) sought to determine if these strategies persisted after inducing localized fatigue at different joints prior to the RPT. The authors found, consistent with previous studies, that males employed shoulder-based compensation strategies while females used elbow-based ones. This could also be related to females' tendency to recruit synergist muscles while males rely more on primary movers when adapting to fatigue (Anders et al., 2004).

Beyond biomechanical factors, physiological differences also contribute to the sex-specific fatigue compensation strategies. When performing low-to-moderate force sustained isometric contractions at the same percentage of maximal capacity, men generally experience more restricted blood flow due to greater intramuscular pressures consequent to their absolute higher muscle strength (Cote, 2012). This difference in muscle perfusion becomes especially apparent when comparing males and females in tasks involving muscles like the elbow flexors or handgrip muscles, where women tend to show greater endurance (Hunter et al., 2004). However, when contraction intensity is maximal, blood flow is similarly restricted in both sexes, and the performance gap between males and females narrows, suggesting that blood flow is a limiting factor (Hunter et al., 2006). Blood flow restriction can be observed via natural muscle swelling or external restriction, which can offer insights into how blood flow affects fatigue compensation strategies.

Blood Flow Restriction

BFR refers to the application of controlled external pressure, typically via a pneumatic cuff to partially restrict arterial inflow and occlude venous outflow during exercise (Gepfert et al., 2019). When applied during low-load resistance training, BFR can induce muscle hypertrophy and strength gains comparable to high-load exercise (Hughes et al., 2017; Loenneke et al., 2012). The proposed mechanisms include greater metabolic stress, increased recruitment of fast-twitch fibers, and elevation of anabolic signaling pathways (Loenneke et al., 2010).

Although BFR has been used to date mainly as a training modality, more recently studies have been exploring BFR as a laboratory-controlled condition to investigate fatigue mechanisms. BFR amplifies both peripheral and central fatigue by increasing the accumulation of metabolites,

reducing oxygen availability, and creating mechanical compression in the muscle (Broxterman et al., 2018; Hammer et al., 2020; Russ & Kent-Braun, 2003). As such, these physiological changes can result in increased EMG RMS, a measure reflecting greater neuromuscular activation, and decreases in EMG MdPF, indicative of muscle fatigue. Recently, Olmos et al. (2024) further demonstrated that BFR increases neural excitation and motor unit firing rates during moderate load contractions, even when the task is not taken to failure. In a study by Hammer et al. (2020), the researchers examined voluntary activation and force output of a fatigued muscle with and without restricting blood flow during rhythmic isometric handgrip exercise. They found that reductions in both measures occurred when fatigued, with even greater reductions when blood flow was restricted. Interestingly, after removing BFR, the results were similar to those of the control group, suggesting that BFR was the limiting factor on force output (Hammer et al., 2020).

In a study by Kennedy et al. (2014), BFR exacerbated the fatigue response (increased discomfort, reduced force output) and caused greater reductions in voluntary activation, indicating an underlying neuromuscular mechanism. Additionally, they found that these effects were not limited to the exercised muscle but also affected the more proximal non-fatigued muscles. These findings suggest that the application of BFR can exacerbate fatigue responses in the active muscles as well as non-local muscles and provide a research design to help advance the understanding of how fatigue affects the entire neuromuscular system. Importantly BFR may help understand sex differences in fatigue responses. Russ and Kent-Braun (2003) demonstrated that sex differences in muscle fatigue that exist under normal conditions are eliminated with BFR, suggesting that a sex difference in the variables that can be manipulated with BFR may play a significant role in explaining the mechanisms of sex differences in fatigue.

Knowledge Gaps

Despite extensive research on WMSDs, significant knowledge gaps remain, particularly regarding sex differences in fatigue and the relationship between localized fatigue and the response of non-fatigued muscles of the same limb. It is currently unclear if the application of BFR during the fatiguing task would result in a sex difference during the RPTs. Renda et al. (2022) demonstrated that localized fatigue during a multi-joint repetitive task leads to sex-specific compensatory strategies, with different patterns of muscle activation and coordination in males and females. However, is unclear how these compensatory strategies manifest under conditions like BFR, which can increase localized fatigue. The combination of distal and proximal fatigue effects and sex-specific responses to BFR could significantly influence overall muscle activation and coordination patterns during multi-joint tasks, thereby contributing to the risk of WMSDs.

Objectives/Hypotheses

In our study, which investigates the effects of a fatiguing handgrip task with and without BFR on subsequent RPTs, we aim to reveal potential sex differences in how forearm fatigue impacts muscle activation during a repetitive pointing task. By examining changes in muscle activation, we can gain insights into the fatigue response employed by males and females under different fatigue conditions. This research will enhance the understanding of WMSDs and inform the development of effective interventions to improve worker health and productivity. We hypothesized that males would exhibit greater recruitment in the more proximal muscles (e.g., deltoids, pectoralis major and upper trapezius), while females would show increased recruitment of the elbow and forearm muscles (e.g., biceps brachii, flexor carpi radialis and brachioradialis) following the fatiguing handgrip. Additionally, BFR was expected to exacerbate fatigue responses in both sexes.

RESEARCH ARTICLE

Sex-Specific Effects of Intermittent Submaximal Fatiguing Handgrip Plus Blood Flow Restriction on Upper Limb Neuromuscular Characteristics During a Repetitive Pointing Task

Carson Graham, Pruthvi Patel & Julie N. Côté

Department of Kinesiology and Physical Education, McGill University
Montreal, Quebec H2W 1S4, Canada

Correspondence to: Carson.graham@mail.mcgill.ca

1. Introduction

Fatigue is a complex concept which can be defined by the subjective feelings of discomfort and exertion (perceived fatiguability) and the measurable functional declines in contractile function and muscle activation (performance fatiguability) (Enoka & Duchateau, 2016). In occupational settings, fatigue can contribute to the development of work-related musculoskeletal disorders (WMSDs). WMSDs of the neck and shoulder region are commonly reported, and are more prevalent among females, potentially due to sex differences in fatigue responses (Hunter, 2014; Côté, 2012). Studies indicate that females often show greater fatigue resistance in sustained and intermittent isometric submaximal contractions, such as those involving the elbow and finger flexors (Hunter, 2014). However, this varies with task type, muscle group(s) involved, and contraction intensity (Hunter, 2014). For example, females exhibit more endurance during submaximal handgrip and elbow flexor tasks, but this difference diminishes when contraction intensities are maximal (Enoka & Hunter, 2001; Yoon et al., 2007; West et al., 1995). This may be related to males' larger muscle mass and higher absolute contraction forces, creating greater intramuscular pressure and leading to an accelerated local fatigue response relative to females. During maximal contractions, blood flow is restricted similarly, possibly explaining the lack of endurance difference at these intensities (Hicks et al., 2001; Hunter et al., 2004).

Local fatigue, also commonly referred to as peripheral fatigue, involves responses within the working muscle(s). It is mediated by the firing of group III and IV muscle afferents, which are activated by detecting variables such as mechanical compression, reduced oxygen availability, and metabolite buildup (ie., lactate and protons) within the working muscle (Amaan et al 2013; Tornero-Aguilera et al, 2022). These sensory fibres send inhibitory signals to the central nervous system which results in a reduction in central motor drive (CMD) and subsequently voluntary

activation. Sex differences in peripheral fatigue responses may also contribute to sex differences in endurance (Gandevia, 2001; Amann & Dempsey, 2008; Hunter, 2014). The greater intramuscular pressure in males reduces metabolic clearance and oxygen availability while increasing mechanical compression. These conditions are detected by the sensory afferents, leading to inhibitory signalling to the central nervous system and reductions to CMD. This mechanism may help explain how contraction intensity influences the observed sex differences in endurance. However, when males and females are matched for strength, the endurance difference persists (Hunter et al., 2004; Fulco et al., 1999), suggesting that factors beyond muscle mass contribute to the local fatigue response. These could include differences in muscle morphology, perfusion and metabolic efficiency leading to peripheral fatigue and CMD reductions (Hicks et al., 2001; Russ & Kent-Braun, 2003; Hunter, 2014). The reduction in CMD not only limits the capacity of the fatigued muscle but can also influence the performance and activation of non-fatigued muscles (Martin & Rattey, 2006; Kennedy et al., 2014). Studies have demonstrated these effects through the application of external blood flow restriction (BFR). BFR has been shown to amplify both peripheral fatigue and CMD reduction effects, leading to impaired voluntary activation (Hammer et al., 2020; Kennedy et al., 2014). Naturally occurring BFR during muscle contractions and experimentally applied BFR can similarly intensify local fatigue, and these effects have been observed to extend to non-exercised muscles, further impacting neuromuscular activation and performance (Gandevia, 2001; Hammer et al., 2020; Hunter et al., 2004; Kennedy et al., 2014; Zahari et al., 2024). Despite the growing use of BFR in research and rehabilitation, the limited representation of females in these studies leaves a significant knowledge gap regarding potential sex differences in fatigue responses and BFR (Wong et al., 2019; Counts et al., 2018).

Other factors beyond muscle mass linked to sex differences in local fatigue responses include muscle fiber composition and metabolic efficiency, with females typically having a greater proportion of type I fibers, as well as a superior ability to utilize oxygen (Wüst et al., 2008; Hicks et al., 2001).Type I fibers, have a greater oxidative capacity and lower recruitment threshold, and can remain active for prolonged periods, whereas type II fibers rely on glycolytic pathways, making them better suited for producing greater force over shorter durations (Hunter, 2014; Simoneau & Bouchard, 1989). Females' greater oxidative capacity may prolong their ability to use oxygen within the muscle before shifting to anaerobic glycolysis, thus preventing the accumulation of metabolic byproducts (Russ & Kent-Braun, 2003; Hicks et al., 2001).These differences are reflected in electromyography (EMG) recordings: females tend to exhibit lower median power frequency (MdPF) during submaximal fatiguing tasks, reflecting sustained recruitment of fatigue-resistant type I fibers, while males show higher activation amplitudes, indicative of greater motor unit recruitment and reliance on higher-threshold type II fibers to sustain force production (Farina et al., 2014; McManus et al., 2020). Furthermore, females typically display less movement-to-movement variability in muscle activation, which may indicate a lesser ability to redistribute muscle fiber recruitment amongst non-fatigued motor units, and potentially an increased risk of strain during prolonged activity (Côté, 2012). These differences in recruitment and activation patterns could influence performance and injury risk, especially in multi-joint tasks.

The repetitive pointing task (RPT) has been widely used to simulate repetitive occupational tasks, revealing sex-specific compensation strategies during fatigue (e.g., Fuller et al., 2009; Yoon et al., 2021; Renda et al., 2022). Specifically, males tend to rely on a "shoulder-based" strategy, increasing recruitment of stabilizing and moving muscles in the shoulder, such as the upper

trapezius and anterior deltoid, while females adopt an "elbow-based" strategy, emphasizing muscles like the biceps and triceps (Srinivasan et al., 2016). This sex-specific difference in motor control strategies may reflect inherent differences in muscle properties and task demands. Males, with greater relative upper body strength, rely more heavily on shoulder muscles as primary movers, while females, potentially aiming to mitigate fatigue in the upper trapezius, distribute mechanical load to elbow flexors and extensors, reducing reliance on the shoulder (Anders et al., 2004; Srinivasan et al., 2016).

These differing strategies may have important implications for injury risk. Females' reliance on an elbow-based strategy could reduce strain on the upper trapezius but increase overuse risk in the biceps and triceps during prolonged tasks. Conversely, males' reliance on shoulder muscles might predispose them to shoulder-specific injuries, such as rotator cuff strain. This divergence in motor strategies could partially explain the higher prevalence of neck-shoulder WMSDs in females, as prolonged reliance on synergist muscles in repetitive tasks may reduce the system's ability to distribute mechanical loads efficiently, increasing strain over time (Côté, 2012; Srinivasan et al., 2016).

Non-local muscle fatigue, where the fatigue affects non-exercised muscles, impacts multi-joint performance (Zahari et al., 2024). For instance, Kennedy et al. (2014) showed that fatiguing the finger flexors reduced torque in non-fatigued elbow flexors, with BFR exacerbating these effects. These findings suggest that sex-specific local BFR responses can trigger CMD changes that can extend fatigue across muscle groups, such that sex differences in local fatigue responses, modulated by blood flow, may affect more than just the working muscles.

The present study had three primary objectives: 1) Compare muscle activation during the RPT before and after a submaximal fatiguing handgrip task; 2) Identify sex differences in muscle activation and compensatory strategies; and 3) Examine BFR effects on the handgrip task and subsequent RPT. We hypothesized that 1) males would show greater reliance on more proximal muscles, while females would have increased elbow/forearm muscle activation post-handgrip; 2) BFR would amplify fatigue responses in both sexes; and 3) these amplified responses would affect males' and females' EMG activation differently during the RPT.

2. Methods

2.1. Participants

Twenty-four healthy right-handed adults (12 males, 12 females) were recruited. Participants were excluded if they had consumed alcohol within 24 hours or caffeine within 12 hours prior to the visit, and if they had any known musculoskeletal impairments or symptoms that could affect upper extremity endurance. Participants signed a written informed consent form prior to participation. This study was approved by the McGill Faculty of Medicine Institutional Review Board. It was conducted in accordance with the ethical principles stated in the Declaration of Helsinki (2013) as well as the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans (2014).

2.2. Instrumentation

2.2.1. Limb circumference and muscle thickness measurements

Limb circumference and muscle thickness were measured at three time points: pre-fatigue, post-fatigue, and post-recovery. Limb circumference measurements were recorded in centimeters using a flexible measuring tape. Muscle thickness assessments were performed using brightness-

mode ultrasonography (Logiq S7, GE Healthcare, Chicago, IL, USA) with a 12 MHz probe (38 mm scanning length). All measurements were taken by the same assessor. Probe placements for each muscle and the sites for circumference measurements are summarized in Table 1.

Table 1. Muscle thickness and limb circumference measurement sites.

Muscle	Position	Measurement location
Upper Trapezius	Seated with arms at sides	Transversely at midpoint between C6 and acromion
Biceps Brachii	Seated with arms at sides	Transversely superior to electrode placement
Flexor Carpi Radialis	Arms supported at 90° in supine position	Anterior forearm, 30% proximal between styloid process and head of the ulna
Flexor Digitorum Profundus/Flexor Digitorum Superficialis	Arms supported at 90° in supine position	Anterior forearm, 30% proximal between styloid process and head of the radius
Circumference	Position	Measurement location
Forearm	Seated with arms at sides	30% distance from the antecubital fossa to the styloid process of the radius
Upperarm	Seated with arms at sides	60% distance from the acromion to the distal biceps brachii insertion

2.2.2. Muscle Activity

Surface EMG signals were collected using bipolar wireless surface EMG electrodes (Trigno Avanti, Delsys, USA; 20 mm inter-electrode distance, 10 mm diameter, Ambu, Denmark). Prior to electrode placement the skin was shaven and abraded with alcohol to ensure proper signal conductivity. Electrodes were then positioned according to the guidelines detailed in table 2. The

electrodes were placed on the skin overlaying the target muscles, then secured with surgical tape. EMG signals were recorded using Vicon Nexus 2.8.0 software (VICON Motion Systems Ltd, Oxford, UK) at a sampling rate of 2000 Hz with a common-mode rejection ratio of 80 dB. The system's operating bandwidth ranged from 10–500 Hz with a per-channel gain of 2000. Data were collected during the maximum voluntary isometric contraction (MVIC) trials, from the first 30 seconds and last 30 seconds of the handgrip task, and for each 30-second RPT trial

Table 2. Electrode placements as per guidelines detailed in Barbero et al., 2012.

Muscle	Landmarks	Electrode Placement (relative to % of line between landmarks)
Upper Trapezius	Distal clavicle to 6th cervical vertebrae	44%
Pectoralis Major	Acromial angle to xiphoid process	30% (Female), 45% (Male)
Anterior Deltoid	Coracoid process to deltoid tuberosity	8%
Middle Deltoid	Acromion to lateral epicondyle	17%
Posterior Deltoid	Acromion to center of glenoid cavity	47% + >2cm lateral
Biceps Brachii	Acromion to distal insertion biceps brachii tendon	On the muscle belly, < 62%
Brachioradialis	Styloid process to midpoint between epicondyles	32%
Flexor Carpi Radialis	Medial epicondyle to radial styloid process	13%

2.3. Maximal Voluntary Contractions & Grip Strength

After electrode placement, the participant performed 2, 5-second MVICs against manual resistance, in postures and directions indicated in Table 3, while EMG data was collected, and received 1-minute rest between trials. Afterwards, the participant completed 3 grip strength trials using a digital handgrip dynamometer (MDSystems, DynX, 12-0455) with visual feedback on a computer monitor. The monitor was positioned at eye level on an adjustable desk at arm length from the seated participant.

Table 3. Maximal voluntary isometric contractions positions.

Muscle	Posture	Direction of Effort
Upper Trapezius	Seated; arm abducted at 90°	Elevation of the shoulders
Pectoralis Major	Seated; arm abducted ~30°	Adduction of the arm
Anterior Deltoid	Seated; arm along the body, elbow flexed	Elevation of the arm
Middle Deltoid	Seated; arm abducted at 45°, elbow flexed	Abduction of the shoulder
Posterior Deltoid	Seated; abducted at 90°, elbow flexed	Retropulsion of the arm, against elbow resistance
Biceps Brachii	Seated; arm flexed at 90°	Forearm flexion.
Brachioradialis	Seated; forearm flexed at 90°	Flexion of the forearm
Flexor Carpi Radialis	Seated; elbow flexed at 90°	Wrist flexion to radial side
Handgrip	Seated; arm along body	Grip dynamometer device

2.4. Experimental Task

For our repetitive task we used the RPT, described in length in Fuller et. al (2009). Briefly, the RPT consists of the standing participant repetitively moving their arm in a horizontal plane at shoulder height between a proximal and a distal target (length: 6 cm, radius: 0.5 cm, response time: 130 ms, Quantum Research Group ltd), aligned with the participant's midline, at a frequency of 1 Hz following the beat of a metronome. The participant first completed the non-fatigued RPT (NFRPT) for 30 seconds. Immediately following this, the participant was instructed to sit down

and then begin the fatiguing handgrip task, which was performed at 50% of their peak handgrip MVIC. Once the fatigue criteria were met, the participant returned to the RPT position and performed the 30-second fatigued RPT (FRPT). Once complete, the participant was seated and asked to rest with both arms on their lap and to remain in this position for 10 minutes of static rest. Finally, they returned to the RPT position and completed the 30-second recovered RPT (RRPT).

Prior to the fatigue task, an inflatable cuff was placed on the dominant upper arm at the midpoint of the biceps brachii, with the bladder aligned with the brachial artery. In the intervention session, the cuff was inflated to 50% of the participant's resting systolic blood pressure during the fatiguing handgrip task and removed immediately upon task termination. In the control session, the cuff remained at 0 mmHg and was removed at the end of the task.

For the fatigue protocol, the participant was seated with both arms in a neutral position at their sides, feet flat on the ground, and facing a monitor that provided real-time feedback on the force exerted on the dynamometer. Holding the handgrip dynamometer in their right hand, they were instructed to squeeze until a bar on the screen reached the target zone, while focusing on using their forearm muscles and keeping their elbow straight to avoid engaging the upper arm muscles. The task followed a 1.5-second contraction cycle (1.5s contraction followed by 1.5s rest),

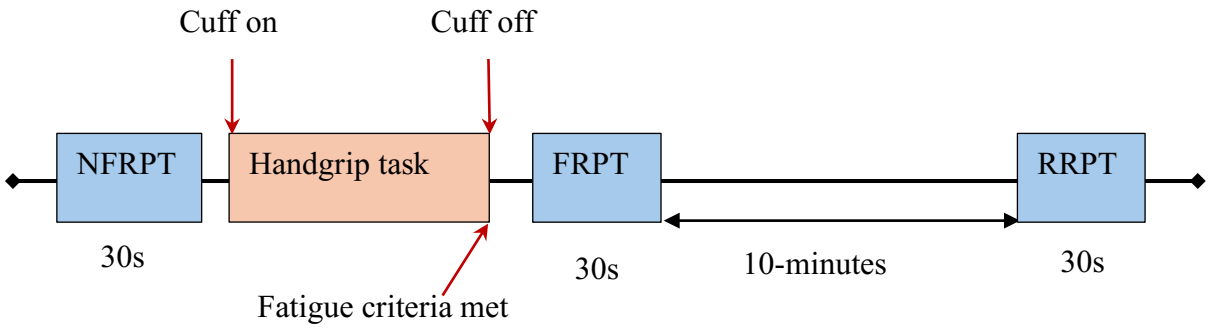

Fig.1. Experimental task timeline.

timed with a metronome, and continued until the participant failed to meet the target force for three consecutive squeezes. The participant was unaware of this termination criterion. See (fig. 1) for details on the experimental task timeline.

2.5. Data analysis

Time to fatigue was calculated as the amount of time (seconds) the handgrip was performed until the fatigue criterion was met. Custom programs in MATLAB (The MathWorks, Inc., Natick, MA, USA) were used for data analysis. The data was digitally converted using a 16-bit A/D board over a ±10 V range and stored for further analysis. No evident heartbeat signals were present in the EMG data, and the EMG data showed no artifacts or power line interference.

The EMG data collected was filtered using a zero-lag, 4^{th} order Butterworth bandpass filter (10-450 Hz). The filtered data collected during the three RPTs were partitioned into 15 forward, and 15 backward reaches using the signal from the touch-sensitive targets.

For data analysis, the average EMG data from the 15 forward reaches of each RPT were calculated and used in the statistical analysis. Power in the frequency spectrum was calculated for each forward reach, and the median value across these reaches was extracted as the MdPF. RMS values were calculated over 15, 1-second non-overlapping windows from the pre-fatigue fatigued, and recovered conditions for each muscle signal, using only the forward reaches. The average of these 15 RMS values was used as the representative mean muscle activation amplitude value (expressed as a fraction of MVIC values).

All muscle thickness measurements were conducted using ImageJ (version 1.54j, National Institutes of Health, USA). Muscle thickness for the Biceps Brachii (BB) and Upper Trapezius

(UT) was measured by calculating the vertical distance between the echogenic fascial layers (Yoon et al., 2021). The measurements for the Flexor Carpi Radialis (FCR), Flexor Digitorum Superficialis (FDS), and Flexor Digitorum Profundus (FDP), all were captured from the same ultrasound image. The FCR thickness was measured from the radial bone to the superficial fascia, while the FDS and FDP were measured together as a single unit from the bone to the echogenic fascia between them (Abe et al., 2022). Limb circumference measures were recorded in centimeters at the three time points (pre-fatigue, post-fatigue, and recovery) and prepared for subsequent statistical analysis.

2.6. Statistical analysis

Repeated measures analysis of variance (ANOVAs) to examine the main and interaction effects of fatigue, blood flow restriction, and sex on time to fatigue, muscle thickness, limb circumference and EMG characteristics. The within-subject factors included session (control vs. intervention) and time (pre-fatigue, post-fatigue, and recovered), while the between-subject factor was sex.

Post-hoc pairwise comparisons were performed using Bonferroni correction to control for Type I errors. Descriptive statistics were calculated and reported as means and standard deviations. Pearson correlation coefficients were used to examine the relationships between grip strength and time to fatigue. All statistical analyses were conducted using SPSS software (version 29.0, IBM Corp., Armonk, NY, USA). Statistical significance was set at $p < 0.05$ for all tests.

3. Results

A total of 24 participants (n=12 females) were initially recruited for this study. Three datasets (2 females and 1 male) were excluded due to malfunctioning equipment, resulting in a

final sample size of 21 participants (n=10 females, n=11 males). Table 4 provides their demographic data.

Table 4. Participant Demographics: mean and standard deviation (SD) of male and female participants [95% CI] of participant characteristics.

Characteristic	Male	Female	Diff. [95% CI]	p-value
Age (years)	22.91(3.26)	22.84(3.26)	-0.063 [-2.70, 2.58]	= 0.96
Height (cm)	183.64(10.71)	161.15(5.64)	-22.48 [-29.56, -15.40]**	<0.001
Weight (kg)	79.24(12.18)	61.87(13.2)	-20.64 [-29.06, -12.22]**	<0.001

Note: Significance is indicated by * ($p<0.05$) and ** ($p<0.001$), using Bonferroni correction.

Repeated measures analysis showed no significant effect of condition ($p = 0.3$) or sex ($p = 0.99$) on time to fatigue. In the control condition, females' mean time was 352.70 ± 90.45 s and 483.50 ± 250.57 s in the intervention condition. Males' mean time was 342.07 ± 162.54 s in the control and 389.36 ± 164.12 s in the intervention. Females had significantly lower peak grip strength (25.94 ± 6.14 kg) compared to males (43.07 ± 7.81 kg, $p < 0.001$). No significant correlations were found between grip strength and time to fatigue in any condition. (Table 5).

Table 5. Correlations between grip strength and time to fatigue for each sex during the control and intervention sessions.

Sex	Control	Intervention
Females	r=0.20 (p = 0.58)	r=-0.28 (p = 0.38)
Males	r=0.42 (p = 0.3)	r=0.45 (p = 0.16)

Note: Values are means with standard errors in brackets. Bonferroni correction applied; $p = 0.005$ (*) and $p < 0.001$ (**).

3.1. Forearm and upper arm circumference

There was a significant effect of sex on forearm and upper arm circumference at all time points. Males had a larger forearm circumference than females ($p < 0.001$). Forearm circumference increased by significantly from pre- to post-fatigue ($p < 0.001$) and decreased from post-fatigue to recovery ($p = 0.009$). No significant changes were observed in upper arm circumference, and there were no other significant effects.

3.2. Muscle thickness (Ultrasound)

3.2.1. Biceps Brachii muscle thickness

There was a significant Time × Sex × Condition interaction for BB thickness ($p = 0.005$) (fig.2). In the control session, females showed a 0.45 ± 1.44 cm increase from pre- to post-fatigue ($p = 0.03$) and a 0.28 ± 0.07 cm decrease from post-fatigue to recovery ($p = 0.004$), with no significant difference between pre-fatigue and recovery ($p = 0.51$). No significant differences were found at any time points in the intervention session for females or in the control session for males.

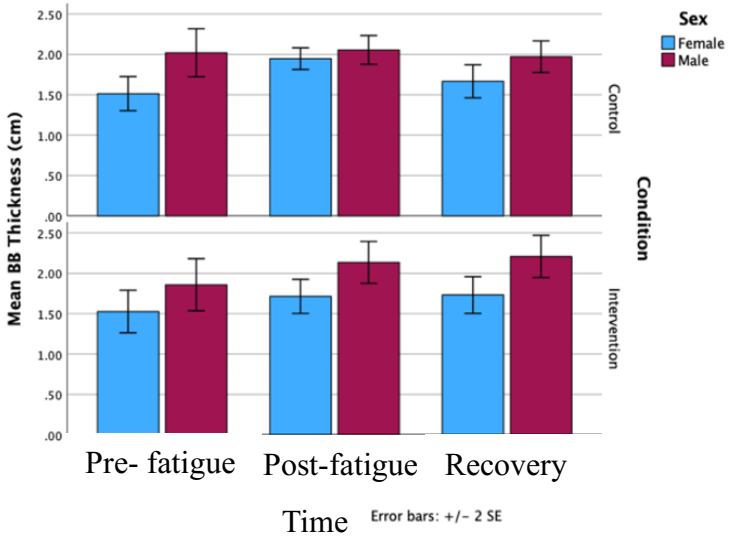

Figure. 2. Biceps Brachii thickness measured by ultrasound after each RPT. Significant three-way interaction (Sex × Condition × Time) ($p = 0.005$).

In the intervention, males showed a 0.38 ± 0.13 cm increase from pre- to post-fatigue ($p = 0.04$) and a 0.47 ± 0.12 cm increase from pre-fatigue to recovery ($p = 0.01$), with no significant change from post-fatigue to recovery ($p = 1.00$). All muscle thickness results are indicated in Table 6.

3.2.2. Flexor Carpi Radialis thickness

No significant interactions were observed on FCR thickness, however, time and sex had significant effects ($p < 0.001$). Males had a significantly greater FCR thickness relative to females ($p < 0.001$). FCRT increased by 0.31 ± 0.08 cm from pre- to post-fatigue ($p = 0.01$) and decreased by 0.14 ± 0.05 cm from post-fatigue to recovery ($p = 0.03$).

3.2.3. Flexor Digitorum Profundus and Flexor Digitorum Superficialis thickness

No significant interactions were found on FDP and FDS thickness. However, there were significant main effects of time ($p = 0.01$) and sex ($p = 0.003$). FDS increased by 0.15 ± 0.04 cm from pre- to post-fatigue ($p = 0.004$), with no significant difference between post-fatigue and recovery ($p = 0.16$)

3.2.4. Upper Trapezius muscle thickness

There were no significant interactions on UT thickness. However, there was a significant main effect of sex. Males had a mean UT thickness of 1.55 ± 0.06 cm, while females had 1.02 ± 0.07 cm ($p < 0.001$).

Table 6. Muscle Thickness (cm) for each sex measured using ultrasound B-mode after each RPT: pre-fatigue, post-fatigue, and recovered.

Sex	Muscle	Pre-fatigue (cm)	Post-fatigue (cm)	Recovered (cm)	Pre/Post (cm)	Difference	Post/Rec Difference (cm)	
Male	BB	1.97(0.11)	2.07(0.10)	2.06(0.12)	-0.10(0.11)	p = 1.00	0.00(0.07)	p = 1.00

Sex	Muscle	Pre-fatigue (cm)	Post-fatigue (cm)	Recovered (cm)	Pre/Post (cm)	Difference	Post/Rec Difference (cm)
	FCR	2.40(0.11)	2.68(0.09)	2.59(0.09)	-0.28(0.10)	* **p = 0.04**	0.09(0.05) p = 0.43
	FDP/FDS	3.24(0.05)	3.39(0.04)	3.28(0.08)	-0.15(0.06)	p = 0.07	0.11(0.08) p = 0.48
	UT	1.52(0.07)	1.60(0.08)	1.52(0.06)	-0.08(0.05)	p = 0.29	0.08(0.05) p = 0.40
Female	BB	1.54(0.08)	1.83(0.08)	1.71(0.10)	-0.29(0.09)	* **p = 0.02**	0.12(0.18) p = 0.18
	FCR	1.65(0.15)	1.99(0.12)	1.80(0.12)	-0.34(0.13)	p = 0.07	0.19(0.07) p = 0.07
	FDP/FDS	2.96(0.44)	3.12(0.04)	3.02(0.07)	-0.16(0.05)	* **p = 0.03**	0.10(0.07) p = 0.49
	UT	1.02(0.08)	1.08(0.09)	0.97(0.07)	-0.06(0.05)	p = 0.85	0.10(0.06) p = 0.32

Note: Values are means with standard errors in brackets. Bonferroni correction applied; p = 0.005 (*) and p < 0.001 (**).

3.3. Repetitive pointing task electromyography

3.3.1. RPT EMG Median power frequency (MdPF)

A significant 3-way interaction was found for the FCR EMG MdPF (p=0.03) (Fig. 3). Further examination through pairwise comparisons revealed differences in the fatigue response between sexes and across conditions. In the control session, females had a significant decrease in FCR MdPF of 7.45±2.66 Hz from pre-fatigue to post-fatigue (p = 0.05). Females had no significant difference from post-fatigue to recovered (p = 0.21) In the intervention session, females had no significant difference between pre-fatigue and post-fatigue (p = 0.76), or post-fatigue and recovered (p = 1.00). In the control session, males had no significant difference pre-fatigue and post-fatigue (p = 1.00), or post-fatigue and recovered (p = 0.27). In the intervention session, males had a significant decrease in FCR MdPF from pre-fatigue to post-fatigue of 23.91±8.89 Hz (p = 0.04). Males in the intervention had no significant difference between post-fatigue and recovered (p = 0.06).

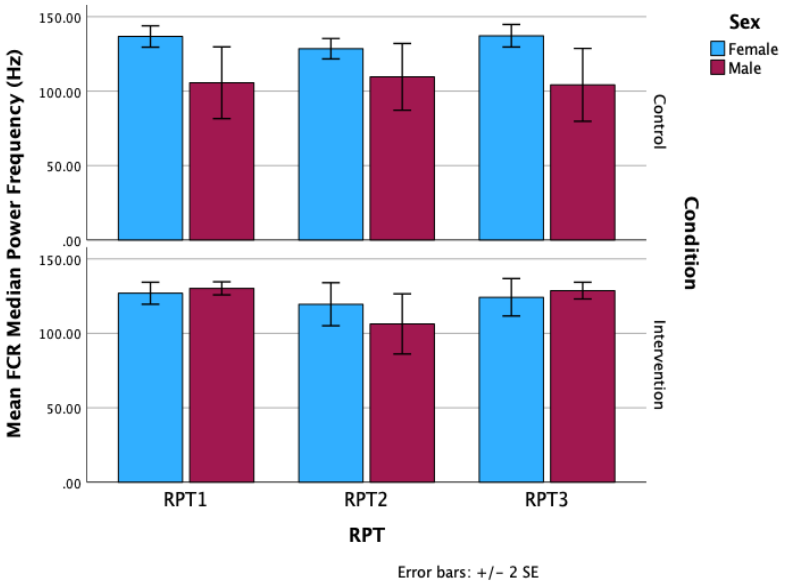

Figure. 3. Significant three-way interaction (Sex × Condition × Time) on Flexor Carpi Radialis MdPF (Hz) during the RPTs (p = 0.03).

A significant time×sex interaction was found for the middle deltoid (MD) (p=0.003) (Fig. 4) and the pectoralis major (PEC) EMG MdPF (p=0.03) (Fig. 5). Pairwise comparisons for the MD revealed that males have a significant increase in MdPF from pre-fatigue to post-fatigue (p<0.001). The difference for males between post-fatigue and recovered was not significant (p=0.100). Females had no significant difference in MD MdPF between any time points (p=1.00). Pairwise comparisons for the PEC MdPF revealed males had a significant increase in MdPF from pre-fatigue to recovered of 4.71±1.66 Hz (p=0.04). There was not a significant difference between pre-fatigue to post-fatigue (p = 0.08). Females did not have a significant difference in PEC MdPF between any of the time points (p=1.00).

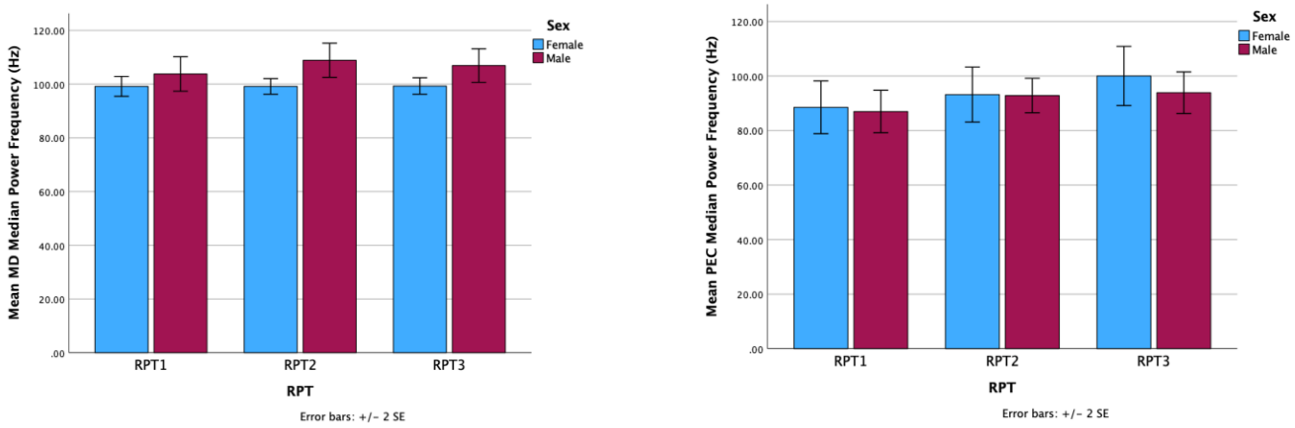

Figure. 4., **Figure. 5.** Time×sex interaction on Middle deltoid (p= 0.003) and Pectoralis Major (p= 0.032) MdPF (Hz) during the RPTs.

There was a significant sex by condition interaction was found for the posterior deltoid (PD) (p= 0.04) (Fig. 6). In the control session males mean was 94.36±3.49 Hz and in the intervention the mean was 85.96±4.17 Hz (p = 0.04). Females did not show a significant difference in PD MdPF between the control or intervention (p = 0.46).

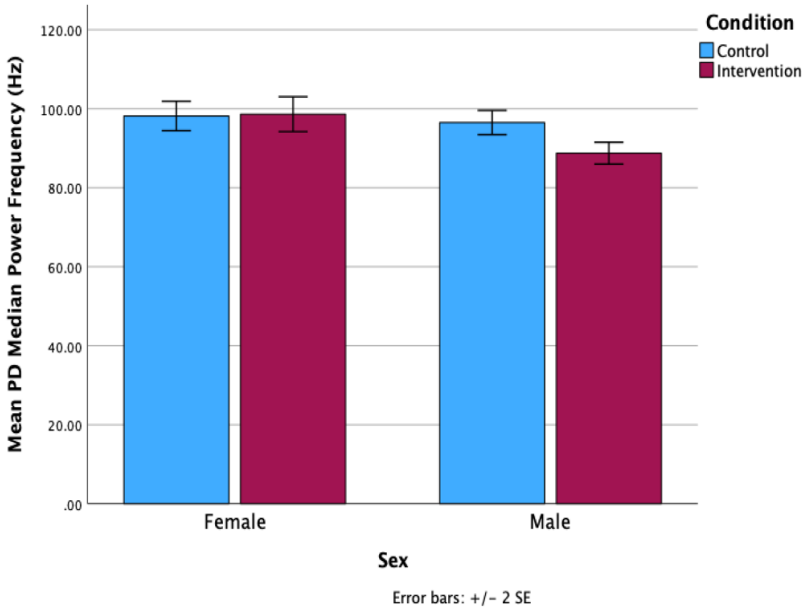

Figure. 6. Significant Sex×Condition interaction on Posterior deltoid MdPF (Hz) during the RPTs (p= 0.04).

Significant main effects for time were found in the UT (p = 0.04) and BB (p < 0.001). UT MdPF increased by 2.57 ± 0.7 Hz from pre- to post-fatigue (p = 0.01) with no significant change post-fatigue to recovery (p = 0.63). BB MdPF increased by 2.98 ± 0.81 Hz from pre- to post-fatigue (p = 0.01) with no significant change from post-fatigue to recovery (p = 0.36). For sex, significant differences were found in UT (p = 0.01) and AD (p = 0.05), with males having higher UT MdPF (114.3 ± 4.95 Hz) than females (93.87 ± 4.43 Hz, p = 0.007) and higher AD MdPF (114.2 ± 3.3 Hz) than females (104.6 ± 2.96 Hz, p = 0.05).

3.3.2. RPT EMG root mean squared (RMS)

There was a significant time×sex interaction on the PD EMG RMS (p=0.020) (Fig. 7). Males showed a significant increase in RMS from pre-fatigue to post-fatigue (p = 0.02) and had no significant difference between post-fatigue and recovered (p=1.00). Females did not have a significant difference in PD RMS between any of the time points. There were no other significant interactions for RMS. All EMG RMS values are indicated in Table 7.

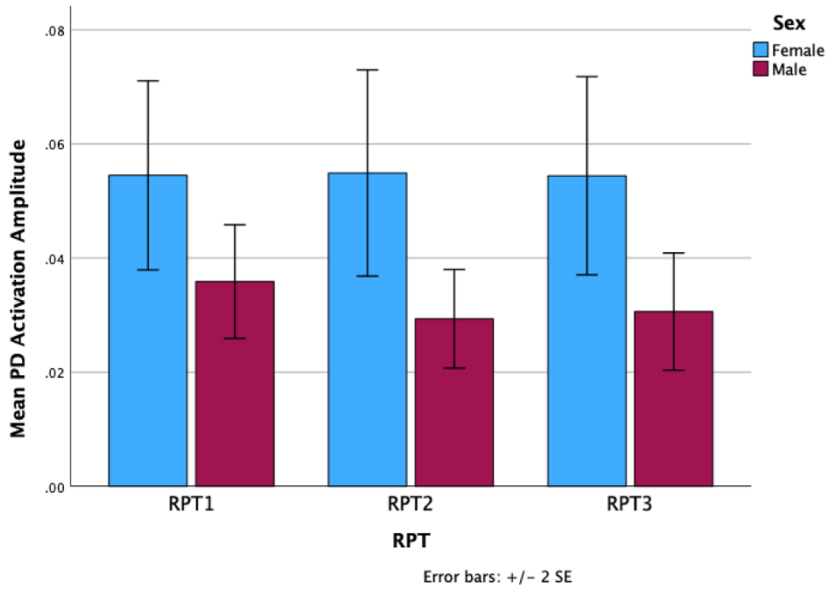

Figure. 7. Time×sex interaction on Posterior deltoid RMS (p= 0.020) during the RPTs. Values are represented as a fraction of MVIC values.

There were significant main effects for sex for four out of the eight muscles RMS. Females' mean UT RMS was 0.18 ± 0.02 and males mean was 0.11 ± 0.02 (p=0.04). Females' mean MD RMS was 0.15 ± 0.11 and males was 0.13 ± 0.02 (p=0.02). Females' mean PEC RMS was 0.07 ± 0.01 and males mean was 0.02 ± 0.01 (p=0.02). Females' mean BB RMS was 0.28 ± 0.08 and males mean was 0.10 ± 0.03 (p<0.001).

There were significant main effects of time for two of the eight muscles. For the UT RMS, time was significant (p=0.050). Pre-fatigue mean was 0.15 ± 0.01, post-fatigue mean was 0.15 ±

0.02, and recovered was 0.14 ± 0.02. However, post-hoc analyses revealed that there were no significant pairwise differences between pairs of time points. For the BR RMS, the time effect was also significant (p=0.04). The pre-fatigue mean was 0.04 ± 0.01, post-fatigue mean was 0.03 ± 0.00, and recovered mean was 0.04 ± 0.01. The mean difference between each time point was not significant.

Table 7. The Effect of the Fatiguing Handgrip on the EMG RMS of the Forearm and Shoulder Muscles During the Repetitive Pointing Tasks. Values are expressed as a fraction of MVIC values.

Muscle.	Sex	Pre-fatigue	Post-fatigue	Recovered	Pre/Post Difference	Post/Recovered Difference
PD	Male	0.04(0.01)	0.03(0.01)	0.03(0.01)	0.01(0.00) *** p = 0.024**	-0.00(0.00) p = 1.00
	Female	0.05(0.01)	0.05(0.01)	0.05(0.01)	0.00(0.00) p = 1.00	-0.00(0.00) p = 1.00
BB	Male	0.10(0.04)	0.10(0.03)	0.11(0.04)	0.01(0.01) p = 1.00	-0.01(0.01) p = 0.85
	Female	0.28(0.03)	0.28(0.03)	0.29(0.03)	0.00(0.01) p = 1.00	-0.01(0.01) p = 0.26
AD	Male	0.11(0.03)	0.11(0.03)	0.11(0.03)	-0.01(0.01) p = 1.00	0.00(0.01) p = 1.00
	Female	0.19(0.03)	0.18(0.03)	0.19(0.03)	0.02(0.01) p = 0.21	-0.01(0.01) p = 1.00
MD	Male	0.11(0.01)	0.10(0.02)	0.10(0.02)	0.01(0.01) p = 0.59	-0.00(0.01) p = 1.00
	Female	0.15(0.01)	0.15(0.01)	0.16(0.01)	-0.00(0.00) p = 1.00	-0.00(0.00) p = 1.00
UT	Male	0.12(0.02)	0.12(0.02)	0.10(0.03)	0.01(0.01) p = 1.00	0.02(0.01) p = 0.54
	Female	0.19(0.02)	0.18(0.02)	0.17(0.02)	0.00(0.01) p = 1.00	0.01(0.01) p = 0.56
PEC	Male	0.02(0.02)	0.02(0.01)	0.02(0.01)	0.01(0.01) p = 1.00	0.00(0.00) p = 1.00
	Female	0.08(0.02)	0.07(0.01)	0.06(0.01)	0.02(0.01) p = 0.69	0.00(0.00) p = 0.36
FCR	Male	0.02(0.00)	0.02(0.01)	0.02(0.00)	0.00(0.00) p = 1.00	0.01(0.00) p = 0.41
	Female	0.01(0.00)	0.01(0.01)	0.01(0.00)	0.00(0.00) p = 1.00	0.00(0.00) p = 1.00
BR	Male	0.03(0.01)	0.02(0.00)	0.03(0.01)	0.00(0.01) p = 1.00	-0.01(0.01) p = 1.00
	Female	0.05(0.01)	0.03(0.00)	0.05(0.01)	0.01(0.00) * p = 0.027	-0.01(0.01) p = 0.062

Note: Values are means with standard errors in brackets. Bonferroni correction applied; p = 0.005 (*) and p < 0.001 (**).

Table 8 The Effect of the Fatiguing Handgrip on the EMG MdPF (Hz) of the Forearm and Shoulder Muscles During the Repetitive Pointing Tasks.

Muscle	Sex	Pre-fatigue	Post-fatigue	Recovered	Pre/Post Difference	Post/Recovered Difference
PD	Male	89.76(3.55)	90.59(3.43)	90.13(3.44)	0.13(1.38) p = 1.00	-1.17(0.87) p = 1.00
	Female	97.80(2.90)	97.66(2.80)	98.83(2.81)	0.13(1.38) p = 1.00	-1.17(0.85) p = 0.6
BB	Male	106.40(2.97)	111.10(3.22)	109.46(2.91)	-4.70(1.28) *** p = 0.01**	1.64(0.71) p = 0.11
	Female	98.11(2.30)	99.38(2.49)	99.51(2.26)	-1.27(0.99) p = 0.67	-0.13(0.55) p = 1.00
AD	Male	114.43(3.46)	114.56(3.3)	114.62(3.68)	-1.13(2.05) p = 1.00	-0.06(1.5) p = 1.00
	Female	102.85(3.1)	105.79(2.95)	105.16(3.29)	-2.95(1.83) p = 0.38	0.63(1.34) p = 1.00
MD	Male	103.10(3.97)	108.04(3.78)	106.41(3.71)	-4.94(1.03) ** p <0.001	1.64(0.70) p = 0.10
	Female	100.29(3.55)	100.26(3.39)	100.34(3.32)	0.03(0.92) p = 1.00	-0.08(0.63) p = 1.00
UT	Male	110.75(4.82)	113.60(4.94)	118.54(6.09)	-2.84(1.04) *** p = 0.04**	-4.95(4.04) p = 0.71
	Female	91.63(4.31)	93.94(4.42)	96.05(5.45)	-2.30(0.93) p = 0.74	-2.12(3.61) p = 1.00
PEC	Male	83.42(4.76)	89.79(4.60)	88.13(4.99)	-6.36(2.59) p = 0.08	1.65(2.08) p = 1.00
	Female	93.69(4.76)	91.62(4.60)	93.52(4.99)	2.07(2.59) p = 1.00	-1.90(2.08) p = 1.00
FCR	Male	118.83(6.36)	107.24(6.54)	113.32(5.46)	11.59(3.56) *** p = 0.02**	-6.08(4.23) p = 0.53
	Female	131.45(4.74)	124.02(4.87)	130.51(4.07)	7.43(2.65) * p = 0.05	-6.49(3.16) p = 0.19
BR	Male	119.43(3.85)	119.04(2.99)	122.28(4.62)	0.40(2.55) p = 1.00	-3.24(2.64) p = 0.55
	Female	138.03(3.56)	136.26(2.77)	141.66(4.28)	1.77(2.36) p = 1.00	-5.41(2.45) p = 0.12

Note: Values are means with standard errors in brackets. Bonferroni correction applied; p = 0.005 (*) and p < 0.001 (**).

3.4. Handgrip electromyography

3.4.1. Handgrip EMG RMS

A significant three-way interaction was found on AD EMG RMS during the handgrip task (p=0.02) (Fig.8). In the control session, females showed no significant difference in RMS from the first 30s to the last 30s (p=0.73). However, in the intervention session, females had a significant increase in RMS from the first 30s to the last 30s (p=0.04). Males showed no significant difference between the first and last 30s in the control (p=0.77) or intervention sessions (p=0.65).

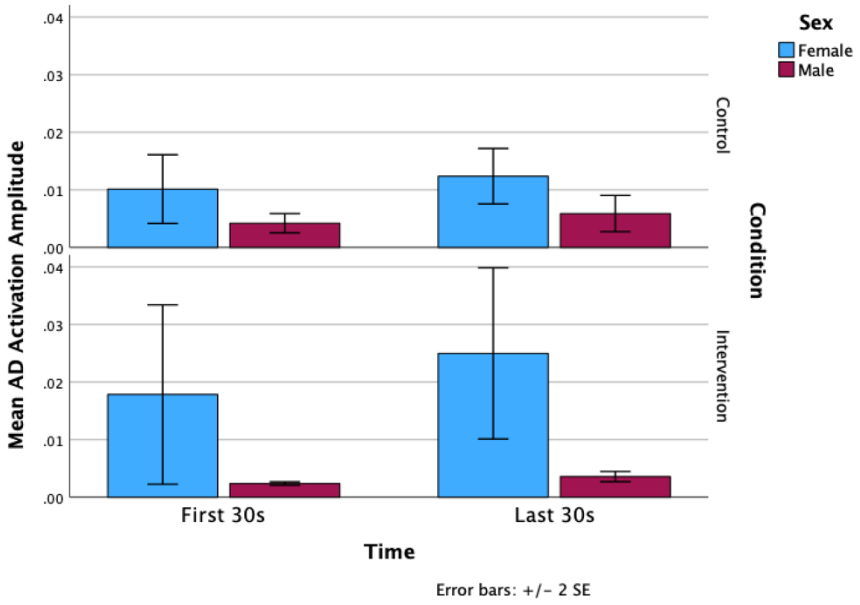

Figure.8. Three-way interaction on AD EMG RMS (p=0.015) during the handgrip task. Values are expressed as a fraction of MVIC values.

There was a significant time×sex interaction on PEC EMG RMS during the handgrip task (p=0.005) (Fig.9.). Females exhibited a significant increase in PEC RMS from the first 30s to the last 30s (p<0.001), while males showed no significant change (p=0.52).

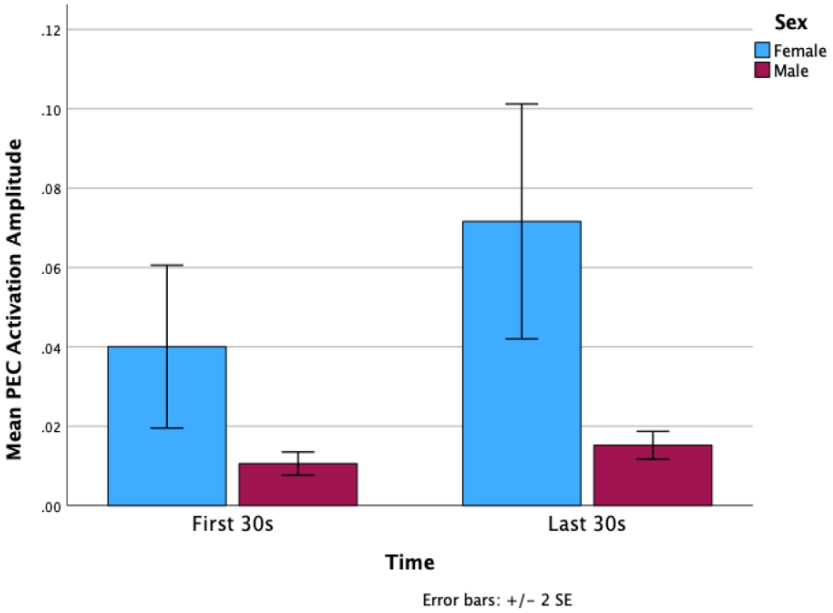

Figure.9. Time×sex interaction on PEC EMG RMS (p=0.005) during the handgrip task. Values are expressed as a fraction of MVIC values.

A significant main effect of time on EMG RMS was found in four of eight muscles. RMS increased from the first to the last 30s in PD ($p = 0.025$), BB ($p = 0.009$), FCR ($p = 0.048$), and PEC ($p < 0.001$). No significant effects of time were found for UT, AD, MD, and BR. A significant main effect of sex on EMG RMS was found for four of the eight muscles. Females had significantly greater mean RMS than males in the AD, FCR, BR, and PEC. No significant main effects of sex were found for the PD, BB, UT, and MD.

Table 9. EMG RMS during the first and last 30 seconds of the fatiguing handgrip task. Values are expressed as a fraction of MVIC values.

Muscle	Sex	First 30s	Last 30s	Difference
PD	Male	0.01 (0.003)	0.02 (0.007)	-0.00 (0.006) p = 0.49
	Female	0.02 (0.003)	0.03 (0.006)	-0.02 (0.005) *** p = 0.009**
BB	Male	0.01 (0.006)	0.03 (0.012)	-0.02 (0.010) p = 0.154
	Female	0.02 (0.004)	0.05 (0.009)	-0.02 (0.007) *** p = 0.008**
UT	Male	0.02 (0.013)	0.02 (0.006)	-0.01 (0.012) p = 0.61

Muscle	Sex	First 30s	Last 30s	Difference
	Female	0.05 (0.012)	0.03 (0.006)	0.02 (0.011) p = 0.06
AD	Male	0.00 (0.005)	0.00 (0.005)	-0.00 (0.003) p = 0.7
	Female	0.01 (0.004)	0.02 (0.004)	-0.00 (0.002) p = 0.27
MD	Male	0.01 (0.003)	0.01 (0.005)	-0.00 (0.005) p = 0.69
	Female	0.02 (0.003)	0.02 (0.004)	-0.01 (0.004) p = 0.15
FCR	Male	0.07 (0.014)	0.09 (0.026)	-0.02 (0.015) p = 0.22
	Female	0.12 (0.015)	0.15 (0.028)	-0.03 (0.016) p = 0.09
BR	Male	0.12 (0.023)	0.10 (0.021)	0.02 (0.026) p = 0.47
	Female	0.16 (0.020)	0.20 (0.018)	-0.03 (0.023) p = 0.19
PEC	Male	0.01 (0.008)	0.01 (0.014)	-0.00 (0.006) p = 0.52
	Female	0.04 (0.007)	0.07 (0.011)	-0.03 (0.005) **** p <0.001**

Note: Values are means with standard errors in brackets. Bonferroni correction applied; p = 0.005 (*) and p < 0.001 (**).

3.4.2. Handgrip MdPF EMG

There were no significant interactions for muscles' EMG MdPF during handgrip tasks, but significant main effects of time were found for six out of eight muscles. MdPF decreased from the first to the last 30s in PD (103 ± 3 Hz to 92 ± 2 Hz, p = 0.008), BB (105 ± 4 Hz to 84 ± 3 Hz, p < 0.001), MD (98 ± 3 Hz to 86 ± 3 Hz, p = 0.005), FCR (105 ± 5 Hz to 91 ± 7 Hz, p = 0.011), BR (115 ± 3 Hz to 101 ± 4 Hz, p < 0.001), and PEC (109 ± 3 Hz to 90 ± 4 Hz, p < 0.001). No significant effect of time was found for UT (p = 0.22) and AD (p = 0.083).

A significant effect of condition was found for PD MdPF, which was higher in the control session (101.19 ± 2.26 Hz) than in the intervention (94 ± 2 Hz, p = 0.015). No significant effect of

condition was observed for BB (p = 0.14), UT (p = 0.47), AD (p = 0.20), MD (p = 0.70), FCR (p = 0.18), BR (p = 0.64), or PEC (p = 0.09).

Sex did not have a significant effect on MdPF during the handgrip task for any muscles: PD (p=0.16), BB (p=1.00), UT (p=0.08), AD (p=0.06), MD (p=0.57), FCR (p=0.72), BR (p=0.07), and PEC (p=0.19).

Table 10. EMG MdPF During the First and Last 30 Seconds of the Fatiguing Handgrip Task.

Muscle	Sex	First 30s	Last 30s	Difference
PD	Male	99.13 (3.76)	91.15 (3.45)	7.98 (5.09) p = 0.14
	Female	107.09 (3.45)	93.56 (3.26)	13.53 (4.80)*** p = 0.01**
BB	Male	102.19 (5.18)	86.60 (4.88)	15.59 (7.32) p = 0.050
	Female	107.66 (4.89)	81.13 (4.60)	26.53 (6.90)*** p = 0.002**
UT	Male	104.20 (6.47)	101.42 (4.98)	2.78 (0.63) p = 0.63
	Female	93.31 (6.10)	86.25 (4.69)	7.06 (0.20) p = 0.20
AD	Male	119.86 (4.51)	119.78 (7.00)	0.07 (7.21) p = 0.99
	Female	115.79 (4.26)	97.45 (6.60)	18.35 (6.80)*** p = 0.02**
MD	Male	94.86 (3.83)	86.38 (4.95)	8.48 (5.41) p = 0.14
	Female	101.42 (3.61)	85.41 (4.67)	16.01 (5.10)*** p = 0.01**
FCR	Male	106.16 (7.61)	94.07 (10.47)	12.09 (0.10) p = 0.10
	Female	103.59 (7.18)	88.09 (9.87)	15.51 (6.57)*** p = 0.03**
BR	Male	120.36 (4.65)	107.17 (5.73)	13.20 (4.85)*** p = 0.02**
	Female	110.36 (3.80)	93.87 (4.68)	16.49 (3.96)*** p = 0.001**
PEC	Male	110.09 (4.34)	97.36 (6.02)	12.73 (4.78)*** p = 0.02**
	Female	107.29 (3.76)	82.80 (5.21)	24.49 (4.14)**** p<0.001**

Note: Values are means with standard errors in brackets. Bonferroni correction applied; p = 0.005 (*) and p < 0.001 (**).

4. Discussion

The main findings of this study were: 1) There was no significant effect of sex or condition on time to fatigue during the handgrip task but there were condition and sex-specific changes to EMG characteristics; 2) There was a significant effect of fatigue on both the activation amplitude and frequency characteristics of the EMG signal in the forearm and upper arm muscles during the RPTs; 3) There were significant sex differences in muscle activation patterns during the RPTs; 4) Blood flow restriction had significant sex-specific effects on muscles distal and proximal to the point of application; 5) There were significant main effects of sex and fatigue on muscle thickness from pre- to post-fatigue for some muscles, as well as sex-specific changes in biceps brachii thickness influenced by the condition.

4.1 Time to fatigue

The results showed no significant effect of sex or condition (control vs. intervention) on time to fatigue during the handgrip task. This finding was surprising given that prior literature indicates that females are less fatigable during sustained and intermittent isometric contractions in several muscle groups (Hunter, 2014; Russ & Kent-Braun. 2003). However, our findings align with Gonzales and Scheuermann (2007) who also reported that males and females did not show a difference in fatigue during isometric intermittent handgrip tasks. The authors suggested that this may be due to a similar neuromuscular activation pattern during this task. However, we found that females during the task showed a greater increase in EMG amplitude in not only the forearm muscles but also upper arm/shoulder muscles, while males showed a more stable EMG amplitude in all muscles. Females also showed greater signs of fatigue in the forearm muscles as well as in multiple upper arm and shoulder muscles, as reflected by broader decreases in the frequency

content of the EMG signal. In contrast, males only showed these indicators of fatigue in the forearm muscles and pectoralis major. This suggests that the similarity in endurance was not due to a similar neuromuscular recruitment pattern, rather a similarity in the effectiveness of the strategy employed. Females showed more compensatory activation of the upper arm and shoulder during the handgrip as seen in the reductions of EMG median power frequency at task termination, while males maintained a more consistent recruitment, with less pronounced fatigue or more reliance on upper arm and shoulder muscles.

The lack of performance difference between conditions (control vs. BFR) was also unexpected, given that BFR has been shown to accelerate fatigue by increasing metabolic stress (Loenneke et al., 2012; Broxterman et al., 2015). One possible explanation for this is that the 50% systolic occlusion in pressure may not have been high enough to meaningfully impact this specific task, as cuff pressure and size can significantly influence performance outcomes (Wong et al., 2019). Although BFR did not significantly impact time to fatigue, it had significant effects on muscle activation and fatigue responses. The application of BFR elicited some physiological responses, such as increased muscle activation and fatigue (as evidenced by both amplitude and frequency EMG characteristics), particularly in the upper arm. This was likely due to the proximity of these muscles to the occlusion site, which may have created a localized hypoxic environment and upregulated muscle activation, as can be inferred from previous results from Bowman et al. (2020). However, this did not affect performance in terms of time to fatigue, suggesting that mechanisms other than hypoxic ones are likely interpreted in the sensation of fatigue at least under our experimental conditions.

4.2. Muscle activation changes between pre- and post-fatigue RPTs

Significant changes in muscle activation were observed between the pre- and post-fatigue RPTs in the forearm and upper arm. Both forearm muscles were fatigued during the handgrip task, which appeared to influence how they were recruited during the subsequent RPTs. The Flexor carpi radialis, responsible for wrist stabilization during the RPT, showed a reduction in the frequency content of the EMG signal, suggesting localized fatigue. In contrast, the Brachioradialis exhibited a non-significant trend towards a decrease in EMG frequency content, likely due to its lesser role in the RPT and therefore experiencing less fatigue. Conversely, multiple muscles in the upper arm (Biceps Brachii, Upper trapezius and Middle deltoid) showed increases in frequency content during the post-fatigue RPT. This could indicate partial recovery of these muscles from their prior fatigue during the handgrip task. Additionally, the shift toward higher frequencies may reflect compensatory recruitment of these muscles to assist the fatigued forearm muscles, aligning with the idea that as distal muscles fatigue, the central nervous system recruits proximal muscles to maintain performance. This is consistent with previous studies that showed increased trunk muscle recruitment and trunk range of motion during other standing repetitive tasks of hammering and sawing performed to fatigue (Côté et al. 2002, 2008). There was no significant difference in post-fatigue to recovered RPT, suggesting the impact of the fatiguing task has effects which may exceed the allotted 10-minute static recovery.

4.3. Sex differences in muscle activation patterns

Several significant sex differences were observed in the muscle activation changes between the pre- and post-fatigue RPTs. Males exhibited shift toward higher EMG frequencies in the upper arm muscles (Biceps brachii, Middle deltoid and pectoralis major) and a shift to lower frequencies in the forearm (flexor carpi radialis) in the post-fatigue RPT. This may reflect a strategy to voluntarily recruit muscles of the upper arm to compensate for the fatigue accumulated in the

forearm during the handgrip. This compensatory recruitment, particularly in the upper arm muscles, is consistent with observations that males tend to exhibit greater recruitment of proximal muscles to maintain performance during dynamic, multi-joint tasks after forearm fatigue, as seen in sex differences in motor variability and muscle activity during repetitive tasks (Luger et al., 2020). Interestingly, females showed no significant shifts in EMG frequency characteristics in the upper arm during the RPT, despite signs of fatigue in these muscles during the handgrip. Due to a higher proportion of type 1 fibers, which generate less force, females may have recruited larger upper arm muscles during the handgrip to meet task demands. By the time of the RPT, these muscles were already fatigued, limiting further recruitment and resulting in minimal changes to the EMG signal's frequency profile. In contrast, males, who may have relied more on forearm muscles during the handgrip, compensated with increased upper arm recruitment during the RPT, as evidenced by the shifts to higher frequencies in the EMG signal. However, the strategies employed by females may place them at a greater risk for overuse injuries in dynamic tasks like the RPT after forearm fatigue. Because of their earlier reliance on upper arm muscles to compensate for the forearm fatigue during the handgrip, there could be an earlier onset of fatigue of these muscles by the time of the RPT. With these muscles already fatigued, females would exhibit less variability in muscle activation during the RPT, which would limit their ability to continue compensating, thereby increasing mechanical load and the risk of overuse injuries. In contrast, males would then tend to reserve more upper arm muscle recruitment capability until after forearm fatigue, which would allow for compensatory recruitment during the RPT and could reduce the likelihood of overuse injuries in repetitive tasks.

4.4 Blood flow restriction effects on muscle activation

BFR significantly affected muscle activation, particularly in males. Males exhibited a significant reduction in the frequency content of the EMG signal in flexor carpi radialis during the RPT following the fatiguing handgrip under BFR, reflecting greater fatigue likely due to the metabolic stress caused by restricted blood flow (Loenneke et al., 2012; Broxerterman et al., 2015). This shift to lower EMG frequency under BFR aligns with previous research showing that BFR increases reliance on anaerobic pathways, resulting in the accumulation of metabolites such as lactate and protons (Russ & Kent-Bruan, 2003). Contrary to our hypotheses, BFR did not alter the EMG frequency characteristics of female's flexor carpi radialis during the RPT. This observed stability in frequency may be attributed to their greater reliance on slow-twitch fibers and higher capillarization, which enhances oxygen delivery (Hunter, 2014; Hicks et al., 2001). This may have blunted the effects of BFR by reducing metabolite accumulation that occurs when relying on glycolytic pathways.

Estrogen may also play a role in mitigating the effects of BFR on muscle fatigue and damage, providing protective benefits that allow females to maintain stable muscle activation under conditions of restricted blood flow (Enns & Tiidus, 2010). However, the present study did not directly measure hormonal influences so the role of hormonal differences in this case remains speculative.

4.5. Muscle thickness changes after fatigue

Significant increases in forearm thickness were recorded for both males and females after fatigue; however, females had a more pronounced difference in the flexor digitorum superficialis and flexor digitorum profundus whereas males had a more significant difference in the flexor carpi radialis. Increases in muscle thickness indicates swelling or tissue perfusion commonly associated

with muscle fatigue (Wan et al., 2017). There were also significant fatigue effects in biceps thickness for females in the control condition, and for males in the occlusion condition. This suggests that the fatiguing task by itself may have required the triggering of increased perfusion to meet the task demand only to females, whereas occlusion was necessary for this to occur in males. This is consistent with previous studies showing the need for females to engage more upper limb muscles than the main agonists during upper limb tasks (Anders et al., 2004; Fedorowich et al., 2009; Srinivasan et al., 2016). Together with those previous studies, these findings specific to females are likely a result of their lesser strength and resort to more complex coordinative strategies in order to accomplish the many upper limb tasks of everyday life.

4.6 Practical applications

Understanding sex-specific fatigue effects under different conditions (e.g., BFR) across different tasks is critical to identify how local fatigue responses may influence broader movement performance and injury risk. This is particularly relevant in workplace settings where individuals often switch between tasks where fatigue from one location could affect otherwise non-fatigued muscle function.

Our findings suggest that although BFR did not affect time to fatigue during the handgrip task, it did produce sex-specific effects on EMG characteristics, particularly in how males and females adapted during the subsequent RPTs. Males demonstrated a clear shift in activation of more proximal muscles during the post-fatigue RPTs in both conditions. In contrast females showed limited compensatory recruitment of proximal muscles, particularly following the BFR condition. Thus, females continued to rely on already-fatigued forearm muscles during the RPT. This persistent reliance on the fatigued muscles especially under increased metabolic stress due to BFR may increase mechanical strain and elevate the risk of overuse injuries in females.

These findings support the use of BFR as an experimental tool to reveal sex-specific fatigue mechanisms and emphasize the need for ergonomic strategies that address not just the site of fatigue, but the compensatory capacity of other muscle groups. Further studies are warranted to understand how sex differences in local fatigue responses impact subsequent muscle recruitment and activation particularly in higher risk populations and body regions, such as females' neck and shoulder region. Identifying the physiological mechanisms driving these compensatory limitations may clarify the specific risk factors contributing to females' heightened vulnerability to neck and shoulder WMSDs.

4.7 Limitations

The findings of this study should be interpreted within the context of a small sample size (n=21), which limits statistical power, particularly regarding sex-specific differences. Additionally, variations in blood flow restriction protocols across studies, (i.e., cuff pressures and widths) may have influenced the observed outcomes. Prior research has shown that these factors significantly impact BFR-induced fatigue and muscle activation responses (Wong et al., 2019), complicating comparisons with existing literature. The lack of direct measures of blood flow or metabolic activity, such as Doppler ultrasound or lactate assessments, further limits the interpretation of the physiological mechanisms underlying the observed fatigue and activation patterns. Finally, hormonal variations in females, such as menstrual cycle phases, were not controlled for. Fluctuations in estrogen and progesterone may influence fatigue and recovery responses, potentially confounding sex-specific findings. Future studies with larger samples, standardized BFR protocols, and comprehensive physiological assessments are needed to address these limitations and provide deeper insights into the mechanisms underlying sex-specific fatigue responses.

5. Conclusion

The present study is the first to investigate sex-specific effects of forearm fatigue and blood flow restriction on changes in muscle thickness (a proxy for muscle perfusion) and in muscle activity during a repetitive upper limb task. While sex and blood flow restriction did not significantly impact time to fatigue during the forearm fatigue protocol, they influenced neuromuscular strategies and muscle responses during and in subsequent repetitive tasks. During the post-fatigue repetitive task, females exhibited localized fatigue in the flexor carpi radialis, as evidenced by reductions in median power frequency, while males demonstrated increased proximal muscle recruitment, such as in the biceps brachii and middle deltoid. Both sexes showed post-fatigue increases in muscle thickness, with males exhibiting more pronounced changes following the blood flow restriction condition. These findings highlight the interplay between localized fatigue, blood flow, and sex-specific neuromuscular adaptations, highlighting the potential for local fatigue response to influence non-fatigued muscles. Future research should include hormonal cycle considerations and direct measures of blood flow to further elucidate these mechanisms and their implications for task performance and injury risk, particularly in occupational and athletic settings.

Disclosure Statement

The authors report no potential conflicts of interest.

CONCLUSION

The aim of this thesis was to investigate sex-specific neuromuscular strategies during a repetitive upper-extremity task, focusing on how these strategies are influenced by prior forearm fatigue and by blood flow restriction. Surface electromyography, ultrasonography, and limb circumference were used to measure muscle activation and muscle thickness, respectively, in healthy male and female participants. Despite similar time to fatigue during the fatiguing task in both conditions, males and females exhibited distinct responses during the fatigue protocol and repetitive tasks. Females maintained stable forearm recruitment during the repetitive task, while males showed greater proximal compensation. Muscle thickness and circumference increased post-fatigue in both sexes, with males exhibiting more pronounced changes following the blood flow restriction condition. These results suggest that sex-specific recruitment strategies and physiological responses to fatigue influence subsequent task performance. Future research should expand on these findings by including larger sample sizes and incorporating direct measures of blood flow to better understand the physiological basis of these sex-specific strategies. Additionally, controlling for menstrual cycle phases could provide deeper insight into sex-specific neuromuscular fatigue responses. Exploring how localized fatigue influences subsequent multi-joint tasks could inform the development of sex-specific injury prevention strategies, particularly in occupational settings where task-switching under fatigued conditions may elevate injury risk.

REFERENCES

Alrowayeh, H. N., Alshatti, T. A., & Aljadi, S. H. (2010). Prevalence, characteristics, and impacts of work-related musculoskeletal disorders: A survey among physical therapists in the State of Kuwait. *BMC Musculoskeletal Disorders, 11*, 116. https://doi.org/10.1186/1471-2474-11-116

Amann, M., & Dempsey, J. A. (2008). Locomotor muscle fatigue modifies central motor drive in healthy humans and imposes a limitation to exercise performance. *The Journal of physiology*, *586*(1), 161–173. https://doi.org/10.1113/jphysiol.2007.141838

Amann, M., Venturelli, M., Ives, S. J., McDaniel, J., Layec, G., Rossman, M. J., Richardson, R. S., & Bachetti, T. (2013). Peripheral fatigue limits endurance exercise via a sensory feedback-mediated reduction in spinal motoneuronal output. *Journal of Applied Physiology, 115*(3), 355–364. https://doi.org/10.1152/japplphysiol.00049.2013

Anders, C., Bretschneider, S., Bernsdorf, A., Erler, K., & Schneider, W. (2004). Activation of shoulder muscles in healthy men and women under isometric conditions. *Journal of Electromyography and Kinesiology, 14*(6), 699–707. https://doi.org/10.1016/j.jelekin.2004.04.003

Barbero, M., Merletti, R., Rainoldi, A. (2012). Atlas of Muscle Innervation Zones: Understanding Surface Electromyography and Its Applications. Italy: Springer Milan.

Bhattacharya, A. (2014). Costs of occupational musculoskeletal disorders (MSDs) in the United States. *International Journal of Industrial Ergonomics, 44*(3), 448–454. https://doi.org/10.1016/j.ergon.2014.01.001

Broxterman, R. M., Craig, J. C., Smith, J. R., Wilcox, S. L., Jia, C., Warren, S., Barstow, T.J. (2015). Influence of blood flow occlusion on the development of peripheral and central fatigue during small muscle mass handgrip exercise. *The Journal of Physiology, 593*(17), 4043–4054. https://doi.org/10.1113/JP270424

Canadian Centre for Occupational Health and Safety. (2024). *Work-related musculoskeletal disorders (WMSDs). Diseases, disorders, and injuries.* https://www.ccohs.ca/oshanswers/diseases/wmsd.html

Canadian Institutes of Health Research. (2019). *IMHA strategic plan 2014–2018: Enhancing musculoskeletal, skin, and oral health.* https://cihr-irsc.gc.ca/e/46455.html

Centers for Disease Control and Prevention [CDC]. (2020). Work-Related Musculoskeletal Disorders & Ergonomics.

Colombini, D., & Occhipinti, E. (2006). Preventing upper limb work-related musculoskeletal disorders (UL-WMSDS): New approaches in job (re)design and current trends in standardization. *Applied Ergonomics, 37*(4), 441–450. https://doi.org/10.1016/j.apergo.2006.04.008

Côté, J. N. (2012). A critical review on physical factors and functional characteristics that may explain a sex/gender difference in work-related neck/shoulder disorders. *Ergonomics, 55*(2), 173–182. https://doi.org/10.1080/00140139.2011.586061

Counts, B. R., Rossow, L. M., Mattocks, K. T., Mouser, J. G., Jessee, M. B., Buckner, S. L., & Dankel, S. J. (2018). Let's talk about sex: Where are the young females in blood flow restriction research? *Clinical Physiology and Functional Imaging, 38*(1), 1–3. https://doi.org/10.1111/cpf.12394

Cowley, J. C., & Gates, D. H. (2017). Proximal and distal muscle fatigue differentially affect movement coordination. *PLoS One, 12*(2), e0172835. https://doi.org/10.1371/journal.pone.0172835

Enoka, R. M., & Duchateau, J. (2016). Translating fatigue to human performance. Medicine and Science in Sports and Exercise, 48(11), 2228–2238. https://doi.org/10.1249/MSS.0000000000000929.

Farina, D., Merletti, R., & Enoka, R. M. (2014). The extraction of neural strategies from the surface EMG: An update. *Journal of Applied Physiology, 117*(11), 1215–1230. https://doi.org/10.1152/japplphysiol.00162.2014

Fedorowich, L., Emery, K., Gervasi, B., & Cote, J. N. (2013). Gender differences in neck/shoulder muscular patterns in response to repetitive motion-induced fatigue. *Journal of Electromyography and Kinesiology*, 23(5), 1183–1189. https://doi.org/10.1016/j.jelekin.2013.06.005

Fulco, C. S., Rock, P. B., Muza, S. R., Lammi, E., Cymerman, A., Butterfield, G., Moore, L. G., Braun, B., & Lewis, S. F. (1999). Slower fatigue and faster recovery of the adductor pollicis muscle in women matched for strength with men. *Acta Physiologica Scandinavica, 167*(3), 233–239. https://doi.org/10.1046/j.1365-201x.1999.00613.x

Fuller, J. R., Lomond, K. V., Fung, J., & Côté, J. N. (2009). Posture-movement changes following repetitive motion-induced shoulder muscle fatigue. *Journal of Electromyography and Kinesiology, 19*(6), 1043–1052. https://doi.org/10.1016/j.jelekin.2008.10.009

Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiological Reviews, 81*(4), 1725–1789. https://doi.org/10.1152/physrev.2001.81.4.1725

Gepfert, M., Jarosz, J., Wojdala, G., Krzysztofik, M., Campos, Y., Filip-Stachnik, A., Kostrzewa, M., Gawel, D., Szkudlarek, A., Godlewski, P., Stastny, P., & Wilk, M. (2021). Acute impact of blood flow restriction on strength-endurance performance during the bench press exercise. *Biology of Sport, 38*(4), 653–658. https://doi.org/10.5114/biolsport.2021.103726

Hagg, G.M. (1991). Static work and myalgia – a new explanation model. *Electromyographical kinesiology*, Elsevier Science: Amsterdam, 159-165.

Halperin, I., Chapman, D. W., & Behm, D. G. (2015). Non-local muscle fatigue: effects and possible mechanisms. *European journal of applied physiology*, *115*(10), 2031–2048. https://doi.org/10.1007/s00421-015-3249-y

Hammer, S. M., Alexander, A. M., Didier, K. D., & Barstow, T. J. (2020). Influence of blood flow occlusion on muscular recruitment and fatigue during maximal-effort small muscle-mass exercise. *The Journal of Physiology, 598*(19), 4293–4306. https://doi.org/10.1113/JP279925

Hicks, A. L., Kent-Braun, J., & Ditor, D. S. (2001). Sex differences in human skeletal muscle fatigue. *Exercise and Sport Sciences Reviews, 29*(3), 109–112. https://doi.org/10.1097/00003677-200107000-00005

Hughes, L., Paton, B., Rosenblatt, B., Gissane, C., & Patterson, S. D. (2017). Blood flow restriction training in clinical musculoskeletal rehabilitation: A systematic review and meta-analysis. *British Journal of Sports Medicine, 51*(13), 1003–1011. https://doi.org/10.1136/bjsports-2016-097071

Hunter, S. K. (2014). Sex differences in human fatigability: Mechanisms and insight to physiological responses. *Acta Physiologica, 210*(4), 768–789. https://doi.org/10.1111/apha.12234

Hunter, S. K., & Enoka, R. M. (2001). Sex differences in the fatigability of arm muscles depend on absolute force during isometric contractions. *Journal of Applied Physiology, 91*(6), 2686–2694. https://doi.org/10.1152/jappl.2001.91.6.2686

Hunter, S. K., Critchlow, A., Shin, I.-S., & Enoka, R. M. (2004). Men are more fatigable than strength-matched women when performing intermittent submaximal contractions. *Journal of Applied Physiology, 96*(6), 2125–2132. https://doi.org/10.1152/japplphysiol.01342.2003

Hunter, S. K., Griffith, E. E., Schlachter, K. M., & Kufahl, T. D. (2009). Sex differences in time to task failure and blood flow for an intermittent isometric fatiguing contraction. *Muscle & Nerve, 39*(1), 42–53. https://doi.org/10.1002/mus.21203

Hunter, S. K., Schletty, J. M., Schlachter, K. M., Griffith, E. E., Polichnowski, A. J., & Ng, A. V. (2006). Active hyperemia and vascular conductance differ between men and women for an isometric fatiguing contraction. *Journal of Applied Physiology, 101*(1), 140–150. https://doi.org/10.1152/japplphysiol.01567.2005

Kennedy, A., Hug, F., Sveistrup, H., & Guevel, A. (2013). Fatiguing handgrip exercise alters maximal force-generating capacity of plantar-flexors. *European Journal of Applied Physiology, 113*(3), 559–566. https://doi.org/10.1007/s00421-012-2462-1.

Kennedy, D. S., McNeil, C. J., Gandevia, S. C., & Taylor, J. L. (2014). Fatigue-related firing of distal muscle nociceptors reduces voluntary activation of proximal muscles of the same limb. *Journal of Applied Physiology, 116*(4), 385–394. https://doi.org/10.1152/japplphysiol.01166.2013

Loenneke, J. P., Wilson, G. J., & Wilson, J. M. (2010). A mechanistic approach to blood flow occlusion. *International Journal of Sports Medicine, 31*(1), 1–4. https://doi.org/10.1055/s-0029-1239499

Loenneke, J. P., Wilson, J. M., Marin, P. J., Zourdos, M. C., & Bemben, M. G. (2012). Low intensity blood flow restriction training: A meta-analysis. *European Journal of Applied Physiology, 112*(5), 1849–1859. https://doi.org/10.1007/s00421-011-2167-x

Mantooth, W. P., Mehta, R. K., Rhee, J., & Cavuoto, L. A. (2018). Task and sex differences in muscle oxygenation during handgrip fatigue development. *Ergonomics, 61*(12), 1646–1656. https://doi.org/10.1080/00140139.2018.1504991.

Marco, G., Alberto, B., & Taian, V. (2017). Surface EMG and muscle fatigue: multi-channel approaches to the study of myoelectric manifestations of muscle fatigue. *Physiological measurement*, *38*(5), R27–R60. https://doi.org/10.1088/1361-6579/aa60b9

Martin, P. G., & Rattey, J. (2007). Central fatigue explains sex differences in muscle fatigue and contralateral cross-over effects of maximal contractions. *Pflügers Archiv - European Journal of Physiology, 454*(6), 957–969. https://doi.org/10.1007/s00424-007-0243-1

McManus, L., De Vito, G., & Lowery, M. M. (2020). Analysis and biophysics of surface EMG for physiotherapists and kinesiologists: Toward a common language with rehabilitation engineers. *Frontiers in Neurology, 11*, 576729. https://doi.org/10.3389/fneur.2020.576729

Renda, E., Yang, C., & Cote, J. N. (2022). Sex-specific myoelectric manifestations of localized fatigue during a multi-joint repetitive task. *Journal of Electromyography and Kinesiology, 67*, 102717. https://doi.org/10.1016/j.jelekin.2022.102717

Russ, D. W., & Kent-Braun, J. A. (2003). Sex differences in human skeletal muscle fatigue are eliminated under ischemic conditions. *Journal of Applied Physiology, 94*(6), 2414–2422. https://doi.org/10.1152/japplphysiol.01145.2002

Sadler, C. M., & Cressman, E. K. (2019). Central fatigue mechanisms are responsible for decreases in hand proprioceptive acuity following shoulder muscle fatigue. *Human Movement Science, 66*, 220–230. https://doi.org/10.1016/j.humov.2019.04.016.

Simoneau, J.-A. & Bouchard, C. (1989). Human variation in skeletal muscle fiber-type proportion and enzyme activity. *American Journal of Physiology*, 257(4.1)E567-72.

Srinivasan, D., Sinden, K. E., Mathiassen, S. E., & Cote, J. N. (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. https://doi.org/10.1007/s00421-016-3487-7

Taylor, J. L., Amann, M., Duchateau, J., Meeusen, R., & Rice, C. L. (2016). Neural contributions to muscle fatigue: From the brain to the muscle and back again. *Medicine & Science in Sports & Exercise, 48*(11), 2294–2306. https://doi.org/10.1249/MSS.0000000000000923

Tornero-Aguilera, J. F., Jimenez-Morcillo, J., Rubio-Zarapuz, A., & Clemente-Suarez, V. J. (2022). Central and peripheral fatigue in physical exercise explained: A narrative review. *International Journal of Environmental Research and Public Health, 19*(7), 3909. https://doi.org/10.3390/ijerph19073909

Van der Windt, D. A., Thomas, E., & Bouter, L. M. (2000). Occupational risk factors for shoulder pain: A systematic review. *Occupational and Environmental Medicine, 57*(7), 433–442. https://doi.org/10.1136/oem.57.7.433

West, W., Hicks, A., Clements, L., & Dowling, J. (1995). The relationship between voluntary electromyogram, endurance time and intensity of effort in isometric handgrip exercise. *European Journal of Applied Physiology, 71*, 301–305. https://doi.org/10.1007/BF00240408

Wong, V., Abe, T., Chatakondi, R. N., Bell, Z. W., Spitz, R. W., Dankel, S. J., et al. (2019). The influence of biological sex and cuff width on muscle swelling, echo intensity, and the fatigue response to blood flow restricted exercise. *Journal of Sports Sciences, 37*(16), 1865–1873. https://doi.org/10.1080/02640414.2019.1599316

Wüst, R. C., Morse, C. I., de Haan, A., Jones, D. A., & Degens, H. (2008). Sex differences in contractile properties and fatigue resistance of human skeletal muscle. *Experimental Physiology, 93*(7), 843–850. https://doi.org/10.1113/expphysiol.2007.041764

Yoon, S., Bailey, C. A., Cohen, N. R., & Cote, J. N. (2021). Changes in muscle activation, oxygenation, and morphology following a fatiguing repetitive forward reaching task in young adult males and females. *Journal of Electromyography and Kinesiology, 59*, 102564. https://doi.org/10.1016/j.jelekin.2021.102564

Yoon, T., Schlinder Delap, B., Griffith, E. E., & Hunter, S. K. (2007). Mechanisms of fatigue differ after low- and high-force fatiguing contractions in men and women. *Muscle & Nerve, 36*(4), 515–524. https://doi.org/10.1002/mus.20844

Zahiri, A., Goudini, R., Alizadeh, S., Daneshjoo, A., Mahmoud, M. M., Konrad, A., et al. (2024). The duration of non-local muscle fatigue effects. *Journal of Sports Science and Medicine, 23*(2), 425–435. https://doi.org/10.52082/jssm.2024.425

APPENDICES

Appendix 1. Recruitment Flyer

McGill | Faculty of Education | Department of Kinesiology and Physical Education

Do you want to experience the world of biomechanics research? This is your chance to participate and contribute to the understanding our neuromuscular systems!

Criteria:

You must be between the age of 18 - 30 years old.

You must be willing to provide written informed consent to participate.

You must be available to attend two lab visits within 7 days.

You must be right-handed.

5) You must be Free from any musculoskeletal impairments and or symptoms that impair upper extremity endurance

Objective:

To determine how muscle fatigue effects muscle activity during a repetitive pointing task.

Duration:

The study includes two lab visits (within one week) each visit will be approximately 2 hours long.

Location:

Biomechanics of Occupation and Sport (BOS) Laboratory, Currie Gymnasium, McGill University, 475 Pine Avenue West, Montreal, Qc.

For more information, contact

Carson Graham : carson.graham@mail.mcgill.ca

Dr. Julie Côté : julie.cote2@mcgill.ca

McGill | Faculty of Education | Department of Kinesiology and Physical Education

Voulez-vous découvrir le monde de la recherche en biomécanique? C'est votre chance de participer et de contribuer à notre compréhension du système neuromusculaire.

Critere

Vous devez avoir entre 18 et 30 ans.

Vous devez être disposé à fournir un consentement éclairé écrit pour participer.

Vous devez être disponible pour assister à deux visites en laboratoire dans les 7 jours.

Vous devez être droitier.

Vous devez être exempt de toute altération musculo-squelettique ou symptôme affectant l'endurance des membres supérieurs

Objectif :

Déterminer comment la fatigue musculaire affecte l'activité musculaire pendant une tâche de pointage répétitive.

Durée :

Vous devrez participer à 2 sessions d'une durée approximative de 2 heures.

Lieu :

Biomechanics of Occupation and Sport (BOS) Laboratory, Gymnase Currie, Université McGill, 475 avenue des Pins Ouest, Montréal, Qc.

Pour plus informations, veuillez contacter:

Carson Graham (carson.graham@mail.mcgill.ca)

Dr. Julie Côté (julie.cote2@mcgill.ca)

Appendix 2. Consent Form

Consent form

Title

Sex-specific effects of intermittent submaximal fatiguing handgrip plus blood flow restriction on upper limb neuromuscular characteristics during a repetitive pointing task

Researcher in charge of project

Julie Côté, Ph.D. Full Professor, Department of Kinesiology and Physical Education, McGill University, julie.cote2@mcgill.ca, (514) 398-4184 ext. 0539.

Research trainee

Carson Graham, MSc. Candidate student in Department of Kinesiology and Physical Education, McGill University, caron.graham@mail.mcgill.ca

Source of funding

Julie Côté

NSERC Discovery operating grant (#RGPIN-2015-05111)

Canada Foundation for Innovation equipment and infrastructure grant (#36715)

Carson Graham

McGill University, Grad Excellence Award (#00144)

Conflicts of interest

There are no known conflicts of interest among the researchers, institutions, and sponsors involved in this project.

Introduction

You are invited to take part in a research study that aims to advance our knowledge on occupational ergonomics. Before agreeing to participate in this project, please take the time to read and carefully consider the following information.

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

This consent form may contain words that you do not understand. We invite you to ask any questions that you deem useful to the researcher and the other members of the staff assigned to the research project, and ask them to explain any words or information that are not clear to you.

Project description and objectives

We are kindly inviting you to participate in our study that investigates how blood flow and fatigue of the forearm may affect muscle activity of the shoulder during a repetitive movement, and how males and females differ in these responses.

The practical outcome of this project is to enhance injury prevention by making it more personalized and tailored to the individual's sex.

Thirty healthy subjects will be recruited for this project and will perform a laboratory assessment protocol. Results from this project will be disseminated in the form of a master's thesis, peer-reviewed conference presentations, and publications.

Study Procedures

Experimental protocol

If you agree to participate you will be asked to attend two testing visits (~ 1.5-2 hours) in the Biomechanics of Occupation and Sport Lab at McGill University (Room 326, Currie Gymnasium). On arrival for your first visit, you will be given an opportunity to read this information letter as you decide whether or not to participate in the study. Then, you will be seated on the massage table while the researcher marks the locations of the surface electrodes with a make-up pen. These areas will be shaved and cleaned with alcohol. Once the electrodes are placed, the baseline strength of each muscle will be measured.

Each experimental visit is comprised of three stages: a) Repetitive pointing task, b) a fatiguing handgrip, and c) Fatigued repetitive pointing task. The first visit will have an additional 15 minutes allocated to familiarization of the tasks prior to the experimental protocol.

Protocol tasks:
a) Repetitive Pointing task: A forward-backward arm movement at shoulder height.

b) Fatiguing task: You will perform a handgrip exercise to fatigue the forearm muscles.

c) Fatigued repetitive pointing task: This task is identical to task a), depending on the session, it will be done with or without a blood pressure cuff applied to the arm.

Benefits

You should not expect to benefit from your participation in this research. However, we hope to learn more about the fundamental science of biomechanics, and applied knowledge in occupational science.

Risks

None of the measurements present any medical risk as they are non-invasive.

A blood pressure cuff will be used for blood flow restriction– there are no known risks beyond discomfort during inflation. This is also resolved immediately upon cuff deflation.

The handgrip exercise task may produce forearm fatigue that will disappear quickly at the end of the protocol. Similarly, the application of cuff occlusion at the end of exercise may cause discomfort that rapidly dissipates upon cuff deflation.

You will experience fatigue towards the end of the handgrip protocol which may cause minor tenderness, stiffness, and/or pain in the forearm during and/or following the session. These symptoms should dissipate within 48 hours following the completion of the protocol.

In case of adverse events, emergency protocols are in place to contact emergency personnel (911, McGill security, Sports Medicine and Winsor Clinics).

Personal inconvenience

The duration of each experimental session will last a maximum of 2 hours, this may represent an inconvenience for you. The possibility that some small areas (about 3x3 cm each) of the skin over your upper arms and forearm muscles have to be shaved before placing the electrodes may also represent an inconvenience for you. Although it is hypo- allergenic, the adhesive tape used to fix the electrodes on your skin may occasionally produce some slight skin irritation. Should this happen, a hypo-allergic lotion will be available to relieve skin irritation.

Compensation

You will not be compensated for your time.

Confidentiality

All the personal information collected for this study will be coded with numbers and/or letters to ensure confidentiality. Physical data will be stored in a locked cabinet accessible only by the researcher's keys. Digital data will be encrypted and stored in a password- protected folder on a lab desktop computer.

Identifiable data will only be accessible by the researcher in charge and research trainee identified on this consent form on page 1, while other researchers involved in the project will only have access to the coded data. Other lab personnel may conduct further data analysis for future publications and conference presentations but will only have access to the de-identified data. If the

results of this research project are presented or published, nothing will allow your identification. A member of the McGill Institutional Review Board, or a person designated by this Board or by McGill University may access the study data and records to assess the ethical conduct of this study.

The data will be kept for a period of 7 years from the date of publication. After this period, the data will be destroyed. The hard copy information will be shredded, and digital information will be erased. Lastly, no access to your medical file is required for this study.

COVID-19 safety protocol

Please note that the following health and safety protocols have been implemented to minimize the risk of transmission of COVID-19 during your study participation. These measures have been devised from current federal and provincial public health, and McGill

University directives:
2-meter distancing will be respected whenever possible.
When 2-meter distancing is not possible (e.g., during placements of sensors), the researcher will wear a face mask (only one researcher will be within 2-meters for appropriate sensor placements and testing).
Every person in the center will wear a face mask, except for yourself when you perform the exercise protocol.
Hand washing and sanitization will be done before and after study participation.
All surfaces that have been in contact with or in close proximity to lab staff and study participants will be disinfected after each lab visit and between users.

Our laboratory members have training on prevention of infection spread.
By agreeing to participate in this study, you acknowledge that you have been informed of the health and safety procedures in place and agree to follow them. Please be reminded that participation is voluntary, and you may decline or postpone participation at any time.

Contact

If you need to ask questions about the project, signal an adverse effect and/or an incident, you can contact Julie Côté, Ph.D., at julie.cote2@mcgill.ca, (514) 398-4184 ext. 0539 or Carson Graham at carson.graham@mail.mcgill.ca. If you have any questions or concerns regarding your rights or welfare as a participant in this research study, you can contact the McGill Ethics Officer at 514-398-8302 or ilde.lepore@mcgill.ca.

DECLARATION OF CONSENT

STUDY: The effects of handedness on muscle activation during a repetitiveoverhead fatiguing task

I declare to have read and understood the project, the nature and the extent of theproject, 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 do not give up any of my legal rights by signing this consent form. I do not freethe researchers, or the institutions involved from their legal and professional obligations.

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 takemy decision.

A signed copy of this information and consent form will be given to me. NAME OFPARTICIPANT (print):_____SIGNATURE OF PARTICIPANT:__SIGNED IN
_____, on___, 20___.

COMMITMENT OF RESEARCHER

I, undersigned,, certify

having explained to the signatory the terms of the present form;

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

having clearly told him/her that he/she is at any moment free towithdraw from the research project described above; and

that I will give him/her a signed and dated copy of the presentdocument.

_____

Signature of person in charge of the project or representative

SIGNED IN__, on___20____.