THE EFFECTS OF SELF CONTROL FATIGUE ON DYNAMIC TASK PERFORMANCE

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By Brian Zheng

Supervisor: Peter J. Keir

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Author: Brian Zheng, B. Sc. (McMaster University)

Supervisor: Peter Keir, PhD

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Thesis Abstract

Mental fatigue can lead to decreases in subsequent physical performance (e.g. Pageaux et al., 2018; Van Cutsem et al., 2017). The aim of this study was to assess the effects of self-control fatigue on displacement and upper extremity muscle activity during three different cyclic push-pull tasks. A randomized crossover design over 2 sessions was used. In each session, 22 participants completed either 12 minutes of the Stroop task or watched a documentary before performing the cyclic bimanual push-pull tasks (with the other condition in the next session). The physical tasks include (1) bimanual push-pull, (2) bimanual reciprocal push-pull, and (3) bimanual push-pull with 30% grip force on the right side. Each task was performed for 60 s and repeated 3 times. A metronome was set at 60 beats per minute to ensure that each cycle was 2 s (1 s push, 1 s pull). A target distance of 80% of standing reach was used. Two potentiometers and a dynamometer on the right side was used to measure displacement and grip force respectively. Surface electromyography was sampled bilaterally from the anterior deltoid, posterior deltoid, biceps brachii, triceps brachii, wrist flexors, and wrist extensors. Ratings of perceived exertion and self-control fatigue levels were collected at baseline and following each trial. The results revealed significantly higher levels of self-control fatigue following the Stroop condition compared to the control condition. Participants only reported higher levels of perceived exertion in the third task following the Stroop condition. Peak displacement was consistent across tasks and conditions. A significant increase in the right posterior deltoid (1.8%) and a decrease in the left triceps brachii (-0.8%) muscle activity was observed in task 1. Increases in the right posterior deltoid (4.9%), left anterior deltoid (0.6%), and right wrist extensors (3.1%) muscle activity was observed in task 2. Increased muscle activity in the right wrist extensors (16.7%), left anterior deltoid (1.4%) and right posterior deltoid (5.7%) muscle activity was observed in task 3. Despite no apparent differences

in task performance detected by the potentiometers, there were significant changes in muscle activity across the upper extremity, especially in the wrist extensors. Monitoring performance may not be the most efficient way to detect mental fatigue in ergonomic analyses, as masked changes in muscle activity could be a risk factor for occupational injuries.

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List of Abbreviations

VAS – Visual analogue scale

MVG – Maximal voluntary grip force

EMG – Electromyography

MVE – Maximal voluntary exertion

RPE – Ratings of perceived exertion

RAD – Right anterior deltoid

RPD – Right posterior deltoid

RBIC – Right biceps brachii

RTRI – Right triceps brachii

RWF – Right wrist flexors

RWE – Right wrist extensors

LAD – Left anterior deltoid

LPD – Left posterior deltoid

LBIC – Left biceps brachii

LTRI – Left triceps brachii

LWF – Left wrist flexors

LWE – Left wrist extensors

Chapter 1: Introduction

Self-control refers to the deliberate process of aligning our thoughts, emotions, and behaviours with standards and long-term goals (Miyake et al., 2000; Vohs & Baumeister, 2004). However, adhering to the principles of self-control can be inherently challenging and it is not always successful. For example, many can likely recall a time when they have fallen victim to the alluring temptations of immediate gratification. Moreover, maintaining self-control over time can be tiring and lead to a state of mental fatigue. Mental fatigue is characterized by overall tiredness, an unwillingness to exert any effort, and impaired cognitive abilities (Borghini et al., 2014; Ishii et al., 2014).

Mental fatigue was first described in the literature in 1891 by Angelo Mosso, who observed decreased muscle endurance in two professors following lectures and oral exams. While it took over a century since then for the effects of mental fatigue on physical performance to be examined in an experimentally controlled way, Mosso’s early ideas were foundational in linking mental and physical fatigue, which remains a hot topic in mental fatigue research today. In laboratory settings, mental fatigue is commonly induced through demanding cognitive tasks, like the Stroop task, which requires continuous response inhibition, a critical component of self-control (Fujita, 2011). Mental fatigue can lead to decreases in many performance outcome measures, including speed, accuracy, force, and productivity (e.g., Ding et al., 2024; de Jong et al., 2020). In laboratory cognitive tasks, mental fatigue results in slower responses and reduced task accuracy (Boksem & Tops, 2008; Hockey, 2011; Warm et al., 2008), along with subjective feelings of tiredness that are often quantified using a visual analogue scale (Kanfer, 2011; Wewers & Lowe, 1990).

Given that approximately half of the adult workforce complain of fatigue symptoms daily, mental fatigue is certainly a serious concern in the workplace not only because of its implications for productivity, but also for the safety of employees and their environments (Ricci et al., 2007). This is especially relevant in hazardous industries like construction, where operating heavy machinery requires extended periods of high vigilance (Li et al., 2019, 2020; Wang et al., 2023). Given the prominence of mental fatigue in the workplace, there is increased research efforts in finding ways to detect its onset (e.g. Kunasegaran et al., 2023; Li et al., 2017; Sampei et al., 2016). However, this is a difficult feat without a thorough understanding of its effects.

In the last decade, while the effects of mental fatigue have been heavily investigated, current understanding of its effects on movement are still limited for several reasons. Much of the research has used highly controlled single joint tasks, limiting its application to dynamic tasks (Brown et al., 2021; Le Mansec et al., 2018; Smith et al., 2016; Filipas et al., 2021). For example, research on the relationship between mental fatigue and muscle activity have often relied on isometric endurance tasks, such as handgrip squeezes (Bray et al., 2008; Graham et al., 2014) and localized lower extremity muscle contractions (Ferris et al., 2021). Additionally, many studies focused only on the primary agonist muscle, making it difficult to understand the broader impact on neighbouring synergist and antagonist muscles. Similarly, while mental fatigue reportedly decreases accuracy in sports like soccer, table tennis, and basketball, the skills involved are sport specific. Although these studies do offer a lot of valuable insight, the purpose of this thesis was to build on these findings and broaden our understanding of the effects of mental fatigue. With this in mind, the present study examined the effects of self-control fatigue on displacement and the activity of 12 upper extremity muscles during three different bimanual cyclic push-pull tasks.

Chapter 2: Literature Review

2.1 Mental Fatigue in the Workplace

Temptations are a regular part of daily life, presenting frequent challenges to one's self control. Whether it is the impulse to indulge in a chocolate bar from the checkout line or the urge to skip a planned workout, self-control helps us navigate these luring waters and resist immediate gratification for long term gains. These small, but additive tests of self-control persist in the workplace (Milyavskaya et al., 2020; Johnson et al., 2018). Workplace conditions like poor lighting (Smolders & de Kort, 2014), high temperatures (Qian et al., 2015; Otani et al., 2016), and loud noise (Jafari et al., 2019), along with job specific demands such as high corporate expectations (Zheng et al., 2022), prolonged periods of vigilance (Hopstaken et al., 2016), and monotonous tasks (Pattyn et al., 2008; Manly, 1999) are all factors that can increase mental fatigue among workers (CCOHS, 2023). While navigating these extrinsic elements, one needs to also demonstrate self-control regularly over their thoughts, feelings, and behaviours to succeed at work. For example, self-control is extremely relevant in helping employees maintain focus on their current goals, ignore distractions, and follow company policies. This idea of intentionally realigning easier inclinations to standards actively demonstrates the act of self-control. As one practices self-control throughout the day, their capacity to continue doing so may falter due to the strains of mental fatigue. This experience is demonstrated by Baumeister's strength model (2018) which posits that an initial act of self-control consumes a finite resource and makes subsequent self-control tasks more difficult. A major development to this model was that different types of mental exertions tap into the same, shared cognitive resource (Kahneman, 1973). In a study that compared three different cognitive tasks that each required a different set of executive function skills, all three tasks increased the participants' subjective ratings of mental fatigue to similar levels (Smith et al., 2019). These findings suggest that mental fatigue can manifest in similar ways despite different causes.

Theories on mental fatigue mechanisms typically follow either resource-based or motivational perspectives. The resource-based strength model proposed by Baumeister, Tice, and Heatherton (1996) outlines that self-control depend on a limited, shared pool of mental energy that depletes with each cognitive exertion, diminishing one's capacity for subsequent exertions. On the other hand, motivational theorists believe that self-control is limited by changes in cost benefit analyses. Inzlicht and Schmeichel (2012) and Kurzban et al. (2013) argue that self-control fails, or a state of mental fatigue is reached when motivation dips below the rising mental costs. Baumeister and Vohs (2016) later integrated these ideas, suggesting that with enough motivation, individuals may gain access to additional resources that may be otherwise reserved. However, these theories lack supporting empirical evidence (Forestier et al., 2021; Hockey, 2014; Galliot et al., 2007; Inzlicht & Schmeidel, 2012; Kurzban et al., 2013; Marcora et al., 2009). It is likely that the mechanisms of mental fatigue are multifaceted and cannot be readily explained by any single theory. Regardless of the cause, once a state of mental fatigue is reached, there is ample evidence in the literature indicating that it negatively affects subsequent physical performance. A comprehensive meta-analysis including 73 studies conducted by Brown et al. (2019) revealed that prior cognitive exertion had the most pronounced negative influence on dynamic resistance performance. This result aligns with earlier findings presented by Pageaux and Lepers (2016), further demonstrating that dynamic resistance tasks at submaximal intensities are sensitive to the negative effects of mental fatigue.

2.2 Ego Depletion, Mental Fatigue, and Self Control Fatigue

The term *ego depletion* was first introduced by Baumeister and colleagues to describe a state where the capacity for self-control is reduced due to depletion of a shared resource from previous acts of self-control (1998). However, over the years, *ego depletion* has taken on several different meanings and is frequently used interchangeably with *mental fatigue*, adding a layer of confusion when navigating the literature. Ego depletion and mental fatigue are two different phenomena (Forestier et al., 2021) as mental fatigue refers to the general feeling of tiredness that follows a period of cognitive activity (e.g. Van Cutsem et al., 2017). Since ego depletion studies often focus on the act of self-control, Forestier et al. (2021) suggested that it may be misleading to use the term *ego depletion* when experimental protocols often induce a mere reduction of self-control resources rather than complete exhaustion. In this way, Forestier et al. proposed that *self-control fatigue* is a more accurate term that describes this field of research, and it should be conceptualized as a specific type of *mental fatigue*. This is because any form of cognitive activity can lead to mental fatigue, but self-control fatigue refers to the feelings of tiredness that follow specifically, the exertion of self-control. To better foster clarity, this thesis will adopt the term *self-control fatigue* where possible in an effort to be more precise. The term *self-control fatigue* will be used in this review when describing studies that implemented a self-control task.

2.3 Mental Fatigue and Accuracy

Mental fatigue weakens executive functions like inhibition, attention, and decision making, functions that are essential in maintaining accurate responses, especially under pressure (Diamond, 2013; Gonzaga et al., 2014; Vestberg et al., 2012). The effects of mental fatigue on accuracy have been primarily studied in sport specific skills as precise passing and the ability to reliably hit a target is key in sports (Michailidis et al., 2013; Sun et al., 2021). Smith et al. (2016) investigated the effect of self-control fatigue on passing accuracy in fourteen soccer players using a cross over design. Over the course of two visits, participants were randomly assigned to spend 30 minutes either reading or performing the Stroop task before completing a passing test. In this test, participants were tasked with making sixteen consecutive short passes in random order, aiming at aluminum targets. The results revealed that while the time spent completing the passing test were similar across both conditions, passing accuracy significantly declined following the Stroop task. Similarly, a recent study in Australia also reported that mentally fatigued amateur soccer players displayed less accurate goal scoring patterns (Weerakkody et al., 2021). Similar declines in accuracy have also been reported in other sports such as table tennis (Le Mansec et al., 2017), hand ball (Izadi et al., 2020), and basketball (Fortes et al., 2022). In another study, McEwan et al. (2013) examined the effects of self-control fatigue on a dart throwing task. Sixty-two participants first performed a baseline dart throwing task where they aimed for the bullseye on a green signal and paused on a yellow signal. Following this, participants were separated into either a mentally fatiguing experimental condition (Stroop) or control condition before a second round of darts. The experimental group displayed lower mean accuracy, increasing by 0.93 cm from the bullseye in the second round while the control group actually improved by 0.79 cm. Additionally, the experimental group also tossed an increased number of darts on a yellow light. Furthermore, by using the *Brief Trait Self Control Scale,* the authors also found that individuals with inherently weaker trait self-control were more likely to underperform in the experimental group. While the results for sport specific skills may not be entirely generalizable to workplace tasks, these findings still provide important insight on the relationship between mental fatigue and accuracy. This is because the many executive functions required in various sports overlap with those necessary to succeed in the workplace.

While much of the research has focused on sports, there is a growing effort to better understand the role of mental fatigue in the workplace. de-Jong et al.’s (2020) longitudinal study examined the effects of mental fatigue in an office setting. They found increased typing errors in university administration workers as time on task increased. However, given the experimental design, it is challenging to determine the extent to which mental fatigue contributed to the observed performance declines, especially given that an administration office is a less controlled environment. Guo et al. (2018) investigated the effects of mental fatigue on response inhibition using a simulated driving task. Sixty-six participants initially completed a *Go/NoGo* task, where they had to react to a green stimulus but not to a red one. Then, participants completed either a 90-minute simulated driving task designed to induce mental fatigue or spent the time watching a documentary. The driving task required participants to keep a safe following distance behind a lead car that changed speeds and braked at random intervals. In the second round of the same *Go/NoGo* task, participants in the fatigue condition had slower reaction times and more frequently failed to react upon a green stimulus.

Negative effects on task accuracy are especially worth investigating in the workplace because they can have severe safety concerns. In a study of self-control fatigue in marksmanship accuracy, after 49 minutes of video watching (control) or a response inhibition task, 20 infantry soldiers completed a shooting task. During the shooting task, participants were given a series of targets that arise in a predictable cadence, however, whether the target required the participant to shoot or withhold was random. Participants in the fatigue condition responded more quickly to targets and this translated to significantly more errors with a higher incidence of shots being mistakenly fired (Head et al., 2017).

Similarly, mental fatigue is also one of the primary causes of construction equipment related accidents (Li et al., 2019). Collisions between workers and heavy machinery like excavators and cranes account for a significant number of construction accidents (Li et al., 2019). Extended working hours can cause mental fatigue in construction equipment operators, leading to attentional deficits and an increased risk of accidents due to a decline in their ability to detect potential hazards. Li et al. (2019) had twelve participants complete a two-part simulated excavation task. The primary task was a simulated conventional excavation task, where participants operated an excavator to dig and transfer soil to a truck. Simultaneously, the secondary task required participants to quickly react to visual cues, by spotting potential hazards through the excavator's rear-view mirrors. These hazards could be other workers or machinery and participants were required to respond accordingly. Mental fatigue was manifested among participants by manipulating the duration of the task, where a longer duration was intended to induce greater mental fatigue. A wearable eye tracker and subjective scale were used to ensure that mental fatigue was successfully induced. Eye movement metrics like increased blink rate (Stern et al., 1994), increased blink duration (Yamada & Kobayashi, 2018), and pupil constriction (Hopstaken et al., 2016) have been identified as reliable indicators of mental fatigue. Li and colleagues (2019) reported that mental fatigue was successfully induced by the *Time-On-Operating* procedure. Coupled with increases in reaction time, the authors found that participants were 40% more likely to overlook a peripheral hazard after a continuous 60-minute session. These findings offer important insight into the role mental fatigue plays in operators' hazard detection abilities and collision accidents.

Surgeons are also particularly susceptible to the negative effects of mental fatigue. Despite working extended hours and often deprived of sleep, surgeons must maintain a high level of executive functioning (Janhofer et al., 2019). Gerdes et al. (2008) looked at mental fatigue in trauma surgeons by comparing their performance in a virtual simulation task before and after a regular shift. Participants completed eight variations of a basic task that required them to place a ring on a series of ten randomly highlighted pegs. An error was recorded when the participant tried to place a ring on an unhighlighted peg. After finishing a shift, trauma surgeons made more errors and displayed decreased precision in movement and instrument handling during the simulation task. Mental fatigue negatively affects various accuracy metrics across a range of occupations, and this can potentially cause irreversible harm.

Whether there is a tendency to overshoot or undershoot targets have not been reported in mentally fatigued participants. In the motor control literature, Jaric et al. (1999) found that extensor muscle fatigue caused participants to undershoot during elbow extension but not flexion. Others showed that fatigue had no significant effects on the accuracy of endpoint trajectories in multi-joint tasks (Selen et al., 2007). While the effects of mental fatigue on performance have been said to be mediated by an increase in perceived effort (Van Cutsem et al., 2017), Goh et al. (2021) identified a positive correlation between self reported fatigue, perceived effort, and decreased accuracy in a reaching task. However, they did not specify any error patterns when reporting these inaccuracies. From depth perception studies, Proffitt et al. (2003) suggested that fatigue may influence our perception of size and distance. Specifically, objects may appear farther if participants rate the task as requiring more effort (Proffitt et al., 2003) but, support for these notions are limited (Woods et al., 2009).

2.5 Mental Fatigue and Muscle Activity

Several studies have recorded increased muscle activity following a cognitively demanding task (Bray et al., 2008; Brown & Bray, 2017; Pageaux et al., 2015). Mental fatigue related changes in muscle activity have been linked to declines in subsequent physical performance. For example, Bray et al. (2008) investigated the effects of self-control fatigue on hand grip endurance and forearm muscle activity. 49 participants completed two hand grip endurance tasks separated by either 3 minutes and 40 seconds of a modified Stroop test or a congruent control task. They found that participants in the fatiguing condition (Stroop test) exhibited significant declines in submaximal endurance and greater muscle activity during the first quarter of the task. Interestingly, Graham et al. (2014) reported that participants who engaged in a mental imagery exercise, in which they envisioned themselves resisting the urge to give up during an isometric handgrip task, reported significantly higher ratings of perceived mental exertion, demonstrating signs of mental fatigue. Similar to the findings presented by Bray et al. (2008), this visualization exercise led to decreased handgrip endurance and increased muscle activity in the flexor carpi ulnaris during the first quarter of an actual subsequent handgrip task.

In the lower extremities, Ferris et al. (2021) tested whether mental fatigue influenced rectus femoris electromyographic fatigue thresholds during a knee extension task. Using a cross over design, eight college students either watched a 60 minute video or completed the *AX continuous performance test* followed by a knee extension task. During the test, various letter sequences are displayed, participants must only react when the letter combination *AX* is observed. If any other letter comes before *X*, response must be inhibited. After completing the cognitive task (AX), the electromyographic fatigue threshold for the knee extensor muscles decreased during the subsequent physical task. Increased muscle activity has also been recorded during dynamic endurance tasks like cycling. In their study, Pageaux and colleagues (2015) observed elevated vastus lateralis EMG amplitude in self control fatigued participants during a cycling task. These findings suggest that when individuals are mentally fatigued, increased muscle activity is needed to achieve the same level of work (Bray et al., 2008; Brown et al., 2021).

Muscular responses have often been explored in the context of muscular fatigue. Mental fatigue and muscular fatigue differ in the way they affect physical performance, so it is likely that there are also different adaptations and strategies. Brown and Bray (2017) hypothesized that these initial increases in muscle activity during a physical task may be because any given task is perceived as more effortful when mentally fatigued. This may result in a more aggressive motor unit recruitment strategy in anticipation of a more difficult task, elevating muscle activity from the primary agonist muscle. This sounds like a compelling theory as research supports the idea of perception of effort being the main driver of submaximal physical performance (Brown et al., 2021; Van Cutsem et al., 2017). However, not all studies have found an increase in ratings of perceived exertion (RPE) following the physical task in mentally fatigued participants (Bray et al., 2008; Dallaway et al., 2020; Ferris et al., 2021).

Another theory is that synergists may be sharing the load to alleviate fatigued muscles. Monetary incentives have been found to mediate the effects of mental fatigue on physical endurance and muscle activity. In Brown and Bray (2017), 82 participants were randomized into four conditions. Participants completed either a 12 minute mentally fatiguing Stroop task or a control task where they watched a documentary before performing a submaximal handgrip endurance task. For the endurance task, participants were asked to maintain a handgrip of 50% of their maximal voluntary contraction for as long as possible, and only half of the participants were offered a $10 incentive for their efforts. Impaired physical endurance performance was only reported in self-control fatigued participants who were not incentivized. The same performance decrements were not observed in participants from the other three conditions. Similarly, the greatest increase in flexor carpi radialis muscle activity was also reported in non-incentivized, self-control fatigued participants, particularly towards the last quarter of the task. This increase in muscle activity seemed to be mitigated when participants were given an incentive. The authors hypothesized that participants may have been more motivated by a monetary incentive and adopted strategies to enhance their endurance performance even when fatigued. The absence of increased muscle activity among the incentivized, self-control fatigue group suggests that the primary agonist muscle was less active and potentially protected by other synergistic muscles like the flexor carpi ulnaris. Similar redistribution strategies are commonly reported in the muscle fatigue literature (Bonnard et al., 1994; McDonald et al., 2019; Tse et al., 2016), but they have not been observed in terms of mental fatigue. These notions are merely theories because a major limitation to these studies is that surface electromyography (EMG) is only recorded at the primary agonist muscle.

Regardless of how this increase in muscle activity occurs, sustained elevations in muscle activity increases musculoskeletal injury risks. Constant muscle loading from low resistance, repetitive work tasks has been linked to myalgia in workers (e.g. Larsson et al. 1988; Thorn et al., 2002). Drawing from the *Cinderella* hypothesis, the small motor units are the first to work and the last to rest (Hägg, 1991). This makes low threshold motor unit muscle fibres more prone to selective fibre injuries (Keir & Brown, 2012; Larsson et al. 1988; Thorn et al., 2002).

It is important to note that not all studies have found significant differences in muscle activity even when performance decrements were observed (Budini et al., 2022; Dallaway et al., 2022; McEwan et al., 2013) and recent efforts to gather more comprehensive surface EMG data did not capture any significant effects of mental fatigue on muscle activity (Brown et al., 2017; Staiano et al., 2023). Kowalski & Christie (2020) actually reported decreases in motor unit firing rate and EMG amplitude. In their study, intramuscular and surface EMG from the tibialis anterior was also recorded while participants performance 10 second isometric dorsiflexion holds. They found a significant decrease in mean motor unit firing rate and EMG root mean squared amplitude when the isometric hold was completed after the vigilance task, compared to EMG data that was collected before and during the mentally fatiguing task. Nonetheless, physical tasks in the workplace are rarely isometric and there is very limited research on the effect of mental fatigue on muscle activity during dynamic submaximal tasks (Pageaux et al., 2016, Brown et al., 2021). These results suggest that there may be different muscular responses to mentally fatiguing tasks, but more research is needed to better understand these adaptations.

2.6 Summary

Mental fatigue may negatively affect subsequent physical performance in different ways. This investigation into the effects of self-control fatigue on accuracy, and muscle activity holds significant repercussions for the efficacy, safety, and overall, wellbeing of workers. There are limited investigations on the effects of mental fatigue on dynamic tasks and muscle activity is typically only recorded from the primary agonist muscle, limiting the understanding of compensatory mechanisms and translatable insights to the workplace. Thus, additional research is necessary to foster a better understanding of self-control fatigue's effects on dynamic, submaximal work tasks. This novel study aims to build on previous findings and expand the collective understanding in this field. The purpose of this study was to examine the effects of self-control fatigue on accuracy and bilateral upper extremity muscle activity during three bimanual push and pull tasks. We hypothesized that after completing the Stroop test, participants would demonstrate a reduction in accuracy and increased activity in synergistic and agonist muscles.

Chapter 3: Manuscript

The Effects of Self-Control Fatigue on Dynamic Task Performance

Brian Zheng (BSc) and Peter J. Keir (PhD)

Department of Kinesiology, McMaster University, Hamilton, Canada

*Corresponding Author:
Peter J. Keir, PhD
McMaster University
Department of Kinesiology
Ivor Wynne Centre, room 219B
1280 Main Street West
Hamilton, ON, Canada, L8S4K1
Telephone: 905-525-9140 ext. 23543
Email: pjkeir@mcmaster.ca

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Abstract

Self-control fatigue is the feelings of tiredness that follow strenuous response inhibition tasks. The aim of this study was to assess the effects of self-control fatigue on accuracy and upper extremity muscle activity during three different cyclic push-pull tasks. A randomized crossover design with 22 participants was used over two sessions. In each session, participants completed either a 12-minute Stroop task or watched a documentary before performing three dynamic tasks: (i) bimanual push, (ii) bimanual reciprocal push, and (iii) bimanual push with 30% grip force on the right side. Each task lasted 60 seconds and was repeated three times. Participants followed a metronome set at 60 beats per minute to ensure that each cycle was 2 s (1 s push, 1 s pull). Displacement was tracked and surface electromyography was sampled at 12 sites of the upper extremity. Ratings of perceived exertion and subjective levels of mental fatigue was collected at baseline and following each trial. Participants reported significantly higher levels of self-control fatigue across tasks and increased perceived exertion only in the third task following the Stroop condition compared to the control condition. Across tasks, no significant changes in displacement were observed between conditions. However, results revealed task dependent changes in muscle activity following the Stroop condition. In Task 1, muscle activity changes were minimal, with a significant increase observed in the right posterior deltoid (1.8%, $F = 6.13$, $p < 0.05$) and a decrease in the left triceps brachii (-0.8%, $F = 8.26$, $p < 0.01$). In Task 2, increases in muscle activity were more widespread, with the right posterior deltoid (4.9%, $F = 4.78$, $p < 0.05$), left anterior deltoid (0.6%, $F = 7.80$, $p < 0.01$), and right wrist extensors (3.1%, $F = 4.35$, $p < 0.05$) demonstrating significant increases. Task 3 showed the most pronounced changes, particularly in the right wrist extensors, which exhibited the highest increase across all tasks (16.7%, $F = 16.92$, $p < 0.001$), alongside significant increases in the left anterior deltoid (1.4%, $F = 6.00$, $p < 0.05$) and right

posterior deltoid (5.7%, $F = 5.32$, $p < 0.05$). This means that when mentally fatigued, increased muscle activity across the upper extremity was required to maintain physical task performance. These findings suggest that relying on performance decrements alone may not be an effective method for mental fatigue detection.

3.1 Introduction

Execution of sustained work requires not only adequate physical capability but also a sufficient level of cognitive functioning to initiate and maintain appropriate responses. The strength model of self-control suggests that the expression of such willpower depends on a finite energy resource (Baumeister et al., 2007). As this resource depletes following prolonged cognitive activity, the ensuing feeling of tiredness known as mental fatigue, can increase reluctance to exert effort, and impair subsequent cognitive and physical performance (Boksem & Tops, 2008; Borghini et al., 2014). Specifically, meta-analyses have revealed small to medium negative effects of performing prior cognitive tasks on subsequent endurance performance (Brown et. al., 2019; Giboin & Wolff, 2019). This decline in performance is not completely harmless. The effects of mental fatigue may have serious consequences, especially in hazardous work environments. For example, mental fatigue is a common risk factor for accidents in both car drivers and aircraft pilots (Borghini et al., 2014). Even in situations with no immediate safety risks, Lew and Qu (2014) reported that mental fatigue increased the likelihood for slips and falls. These findings demonstrate that the effects of mental fatigue extend beyond mere feelings of discomfort or sluggishness, but it can pose concerns for occupational health, and safety.

Mental fatigue has been reported to affect key outcome variables like accuracy, and muscle activity (Brown et al., 2019). These variables are important as inaccuracies or prolonged muscle activity can lead to injuries (e.g. Head et al., 2017). Studies have reported decreases in accuracy in sports like soccer, handball, and basketball (Fillipas et al., 2020; Izadi et al., 2020; Fortes et al., 2022). This decline in precision is thought to be attributed to weakened executive fucntion skills like inhibition, attention, and decision making under mental fatigue (Sun et al., 2021). Conversely, the literature around the effects of mental fatigue on muscle activity is quite divided. Pageaux et al. (2015) reported increases in vastus lateralis muscle activity during cycling after the Stroop task, and Ferris et al. (2021) found similar increases in the rectus femoris during knee extension. In studies with an isometric gripping physical task, Bray et al. (2008) and Graham et al. (2014) observed increased muscle activity in wrist flexors following the Stroop task. In more recent studies done by Dallaway (2020) and Jacquet et al. (2024), they did not find such increases in the forearm muscles. Their result may be because they did not use the Stroop task, suggesting that observations depend on the inclusion of a self-control component.

The central fatigue hypothesis suggests that muscular fatigue is controlled by processes within the central nervous system, rather than by peripheral mechanisms within the muscles themselves (Meeusen et al., 2021). Consistent with this perspective, the literature generally agrees that the primary determinant of physical performance at submaximal intensities is the perception of effort, which helps explain the relationship between mental fatigue and physical performance (Van Cutsem et al., 2017). In a meta-analysis of eleven studies, Van Cutsem and colleagues (2017) found that while other physiological variables like heart rate, oxygen uptake, and cardiac output were unaffected by mental fatigue, a decline in endurance performance was associated with an increased perceived exertion. A popular theory is that mental fatigue may increase the accumulation of adenosine, an inhibitory neurotransmitter in the anterior cingulate cortex, the area related to perceived exertion (Hakim et al., 2022; Lovatt et al., 2012).

A meta-analysis of 29 studies revealed that physical performance at submaximal, but not maximal intensities is particularly sensitive to the effects of mental fatigue (Pageaux & Lepers, 2018). Despite the ubiquity of repetitive submaximal tasks in laborious occupations, the effects of mental fatigue are rarely explored with ergonomics in mind. Instead, the effects of mental fatigue are often investigated in sport specific skills or highly controlled tasks that lack generalizability to the workplace (Brown et al., 2021; Le Mansec et al., 2018; Smith et al., 2016; Filipas et al., 2021).

As such, this novel study implemented a cyclic push-pull task that was inspired by common workplace tasks that require gripping and repetitive back and forth hand motion. Such movements are often observed in tasks like hand sawing in carpentry, package handling in warehouses, and grinding in construction (Song et al., 2021). Unfortunately, these repetitive exertions are known to contribute to musculoskeletal disorders and overuse injuries in the upper extremity. Especially in the wrist and finger extensors due to high extensor muscle activity associated with gripping tasks (Hägg and Milerad, 1997; Hoozemans et al., 2014). Constant muscle loading, even at low levels, has also been linked to muscle fatigue, pain, and myalgia (Larsson et al., 1998). Nonetheless, pushing and pulling require coordination of several muscles but, most mental fatigue investigations up to this point have mainly focused on one or two muscles (Keir and Brown, 2012). This narrow focus makes it challenging to understand the full picture and assess whether there are any changes in muscle activity among synergists or antagonist muscles during dynamic tasks.

With increased awareness of psychosocial contributors to workplace productivity and safety, a better understanding of mental fatigue in the workplace is becoming increasingly important for the modern ergonomist. This novel study utilized a cyclic push-pull task that emulates common workplace tasks while capturing electromyography data from a broader range of muscle groups. The purpose of this study was to assess the effects of self-control fatigue on accuracy and upper extremity muscle activity during a dynamic push-pull task. This study aims to build upon the literature and provide more insight into the effects of mental fatigue in the workplace.

3.3 Methods

3.3.1 Participants

Twenty-two right-hand dominant male and female participants completed the study. Eleven males (age: 21.3 ± 1.5 years; height: 176.2 ± 6.4 cm; mass: 77.1 ± 6.0 kg; arm length: 70.1 ± 5.8 cm; MVG: 281.1 ± 50.0 N) and eleven females (age: 21.6 ± 2.2 years; height: 166.6 ± 7.3 cm; mass: 67.4 ± 9.9 kg; arm length: 67.3 ± 6.0 cm; MVG: 214.6 ± 49.3 N) were recruited from the McMaster University community. Exclusion criteria included upper extremity neuromuscular disease in the last year, and colour blindness. This study received clearance from the McMaster Research and Ethics Board (MREB #6947).

3.3.2 Testing Apparatus

The physical task was inspired by manual push and pull tasks in the workplace. A custom twin-track apparatus was built, featuring vertically mounted hand grip dynamometers (MIE Medical Research Ltd., Leeds, UK) that served as the handles on the left and right sides. Each handle was mounted on a moveable platform that slides independently on their respective tracks with minimal friction. Resistance was created by attaching two kg weights to each handle with cables that were suspended using a pulley system (Figure 3.1) (Keir & Brown, 2012). Linear potentiometers, affixed to the handle platforms, were used to record the position of the handles. A target was set and marked at 80% of each participant's maximal reach to account for both under reaching and overreaching. Set up was anchored on a height adjustable structure to accommodate participant heights, ensuring that in the starting position, their forearms were parallel to the ground with elbows flexed at 90°.

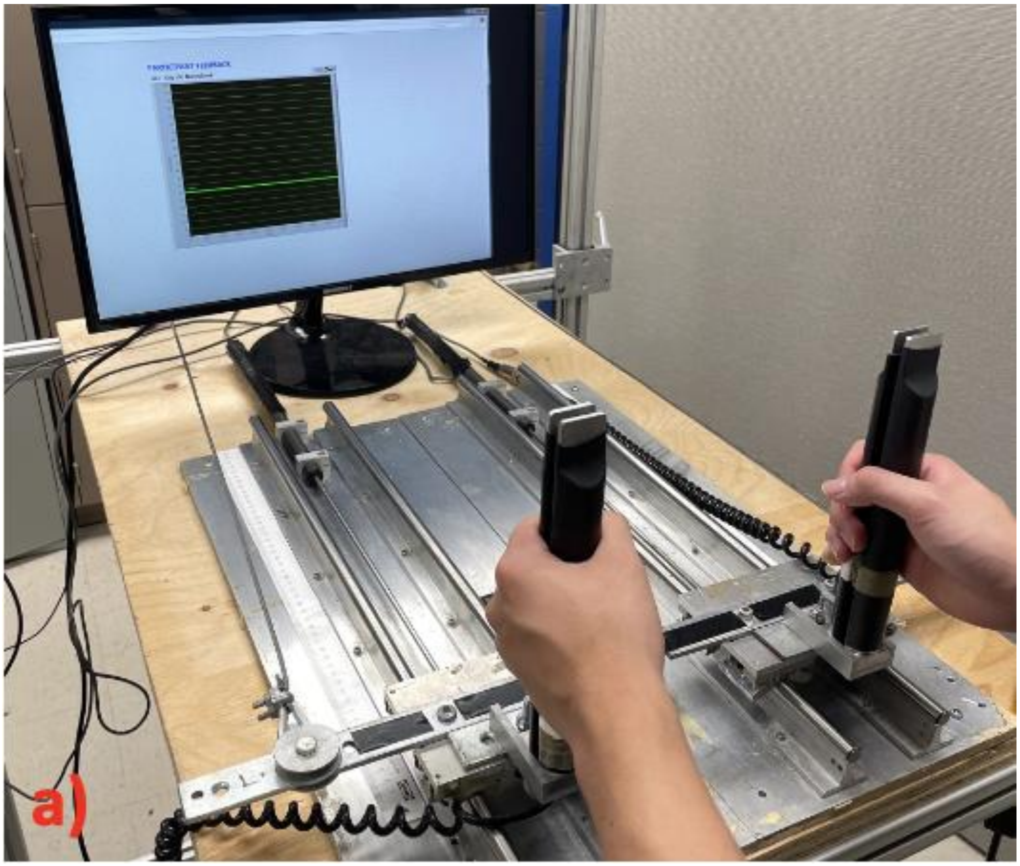

Figure 3.1: The apparatus featuring two hand grip dynamometers attached to two independent platforms that slide on two tracks with built in linear potentiometers. Participants are provided with visual feedback with the green line representing their 30% MVG.

3.3.3 Experimental Conditions

During the Stroop condition, participants performed 12 minutes of a computerized version of a modified incongruent Stroop task (e.g. Wallace and Baumeister, 2002; Bray et al., 2008). The word stimulus (BLACK, BLUE, GRAY, GREEN, PINK, and RED) was presented on a white background in 48 point Times New Roman font. Each stimulus was shown for 800 milliseconds. Participants had 100 milliseconds after each stimulus to quickly and accurately say the colour of the word out loud while ignoring the actual word itself. For example, if *BLUE* was printed in green, participants would say "green", not "blue". For added difficulty, when a word was written in red specifically, participants were told to ignore the original set of instructions and read the word instead of naming its colour. For example, if the word *GREEN* was printed in red, participants would have to say "green", not "red". All participants were informed that their errors would be recorded. This task challenges participants' response inhibition.

For the control condition, participants watched the documentary "Our Planet: Coastal Seas" for the same duration. To ensure attention, participants were instructed to count how many times they heard the keyword *water*, which was mentioned three times during the 12 minutes of the film. This control task is commonly used in mental fatigue research because it does not affect affective state or arousal (e.g. Zering et al., 2017).

3.3.4 Protocol

A randomized crossover design requiring two sessions was used. At the start of both visits, participants completed the Physical Activity Readiness Questionnaire, provided informed consent, and filled out a demographic survey (age, sex, height, weight). A visual analogue scale (VAS) was used to assess baseline levels of mental fatigue from 0 (none) to 100 (maximal). Each participant's maximum voluntary grip force (MVG) was measured using a hand grip dynamometer. During a 10 second trial, participants gradually ramped up their grip force to maximum and MVG was calculated as the peak from the trial. Activity of six upper extremity muscles was recorded bilaterally using a wireless surface electromyography (EMG) system (Trigno™, Wireless Systems, Delsys Inc, Ma, USA). The muscles recorded included the (i) anterior deltoid, (ii) posterior deltoid, (iii) biceps brachii, (iv) triceps brachii, (v) wrist flexors, and (vi) wrist extensors. Before placing the electrodes, the skin around the muscle belly was shaved and cleaned with isopropyl alcohol. The electrodes were then positioned parallel to the muscle fibres and secured with Hypafix adhesive bandage (BSN Medical Inc, NC, USA). EMG signals were sampled at 2000 Hz while displacement from the potentiometers were sampled at 1000 Hz using a custom designed program (LabView 2016, National Instruments, TX, USA).

In each session, participants completed two maximal voluntary exertions (MVE) per muscle, followed by either 12 minutes of the high cognitive demand or low cognitive demand condition before performing three cyclic push-pull tasks, with the remaining condition completed in the next session. For the high cognitive demand condition, participants completed five two min blocks of the modified Stroop task, each consisting of 135 trials, with four 30 second break in between. For the low cognitive demand condition, participants watched a 10 min documentary divided into two minute segments with similar 30 second breaks in between. Participants reported their levels of self-control fatigue using a VAS during each break and at the end of each condition.

The three cyclic push-pull tasks consisted of: (1) a bimanual push, (2) a bimanual reciprocal push, and (3) a bimanual push with 30% grip force on the right side. Each task lasted 60 seconds and was repeated three times, resulting in a total of nine trials. A one minute rest was given after every three trials. The order of tasks was block randomized for each participant. A metronome was set at 60 beats per minute to ensure each cycle was two seconds (one second push, one second pull). A familiarization trial was completed prior to each experimental condition. After each trial, participants verbally reported their levels of self-control fatigue and rating of perceived exertion (RPE) using a VAS and the Borg CR10 RPE Scale (Borg, 1998) respectively. The Borg CR 10 RPE scale ranged from 0, indicating no effort, to 10, indicating the hardest possible effort. Participants completed the same dynamic push and pull task under the opposite experimental condition for the second visit. Instructions were standardized for all participants, who were informed to prioritize accuracy during all trials when pushing to the set target distance.

3.3.5 Data Analysis

MVE was calculated for each muscle by identifying the peak value across the two MVE trials during each visit. Raw EMG was debiased by subtracting the electrical zero, then full wave rectified, and dual pass Butterworth filtered using a 3 Hz low pass filter (Winter 2005). All EMG signals were normalized to the MVE of each muscle. The linear potentiometers output voltage was converted to millimeters, Butterworth filtered, and normalized to the target distance for each participant. To standardize the timing across participants and trials, individual cycles were identified based on its peak displacement, which corresponds to the maximum reach during the push phase. The peak displacements were aligned to the one second mark within each two second cycle, ensuring that the push phase for all participants peaked at exactly one second. The first and last cycles of each trial were removed for consistency. This alignment allowed for temporal standardization of the cycles. The same time intervals were also applied to the EMG data. This ensured that the EMG cycles were synchronized with the displacement cycles. All processing was performed using a combination of RStudio (Version 5.12.10) and Python (Version 3.9).

A mixed effects model was used to assess self-control fatigue reported by participants during both experimental conditions. The model included the main effect of condition, the main effect of time across the task, and an interaction term between condition and time. Participant was modeled as a random effect to account for individual variation. The dependent variable was self-reported fatigue. Similarly, six separate mixed effects models were used to assess mental fatigue (three models) and RPE (three models) during each subsequent physical task. All six models included condition as the main effect with participant included as a random effect.

To assess accuracy, three more mixed effects models were used to examine the main effects of condition (control vs. Stroop), side (left vs. right), and their interaction on peak displacements for each task. Participant was included as a random effect in each model. The dependent variable was peak displacement during each 2 second cycle. These models analyzed the effects of condition on peak displacement for each task.

Additionally, separate mixed effects models were fitted for each muscle (12) and task (3) combination to look at the effect of condition on muscle activity. For each muscle, the model included condition as a main effect and participant as a random effect. Assumptions of mixed effects models were verified visually using the *performance* package. Likelihood ratio tests were also conducted to compare nested models. All mixed effects models were computed in RStudio (Version 5.12.10).

3.4 Results

3.4.1 Self-Control Fatigue and Ratings of Perceived Exertion

The interaction between condition and time was significant on self-control fatigue, with the Stroop condition resulting in a greater increase in fatigue over time compared to the control condition ($F = 22.73$, $p < 0.001$). Specifically, participants in the Stroop condition reported an increase of 20.2 points out of 100 in self-control fatigue compared to the control condition (Figure 3.2). The main effect of condition was significant, self-control fatigue was higher in the Stroop condition, with an overall increase of 10.9 points compared to the control condition **(**$F = 18.04$, $p < 0.001$**)**. The main effect of time was also significant, fatigue increased over time in both conditions, with an increase of 0.7 points per minute **(**$F = 5.57$, $p = 0.019$). Together, these findings demonstrate that participants reported feeling more self-control fatigued in the Stroop condition, and at an increased rate compared to the control condition. This means that the Stroop condition successfully induced self-control fatigue in participants. This study administered the Stroop test the same way as previously done by Brown et al. (2021), and the observed increases in self-control fatigue are consistent with their findings.

In task 1, the main effect of condition on RPE was not significant ($F = 1.28$, $p = 0.261$). Similarly, in task 2, no significant difference of RPE was observed ($F = 0.19$, $p = 0.666$). In contrast, the main effect of condition on RPE for task 3 was significant ($F = 18.41$, $p < 0.001$), with participants reporting an increase of 0.6 points out of 10 in the Stroop condition compared to the control condition (Figure 3.3).

The main effect of condition on self-reported fatigue scores during the physical tasks was significant for all three tasks. During task 1, participants self-reported fatigue scores that were 5.0 points higher in the Stroop condition compared to controls ($F = 18.34$, $p < 0.001$). Similarly, self-reported fatigue scores were 4.3 points higher during task 2 after the Stroop test compared to the control condition ($F = 13.88$, $p < 0.001$). Finally, for task 3, the effect of condition remained significant ($F = 8.39$, $p = 0.0046$), with participants reporting fatigue scores that were 3.6 points higher in the Stroop condition. These results show that the Stroop condition consistently induced higher levels of MF across all three tasks, with the largest effect observed in task 1 (Figure 3.4).

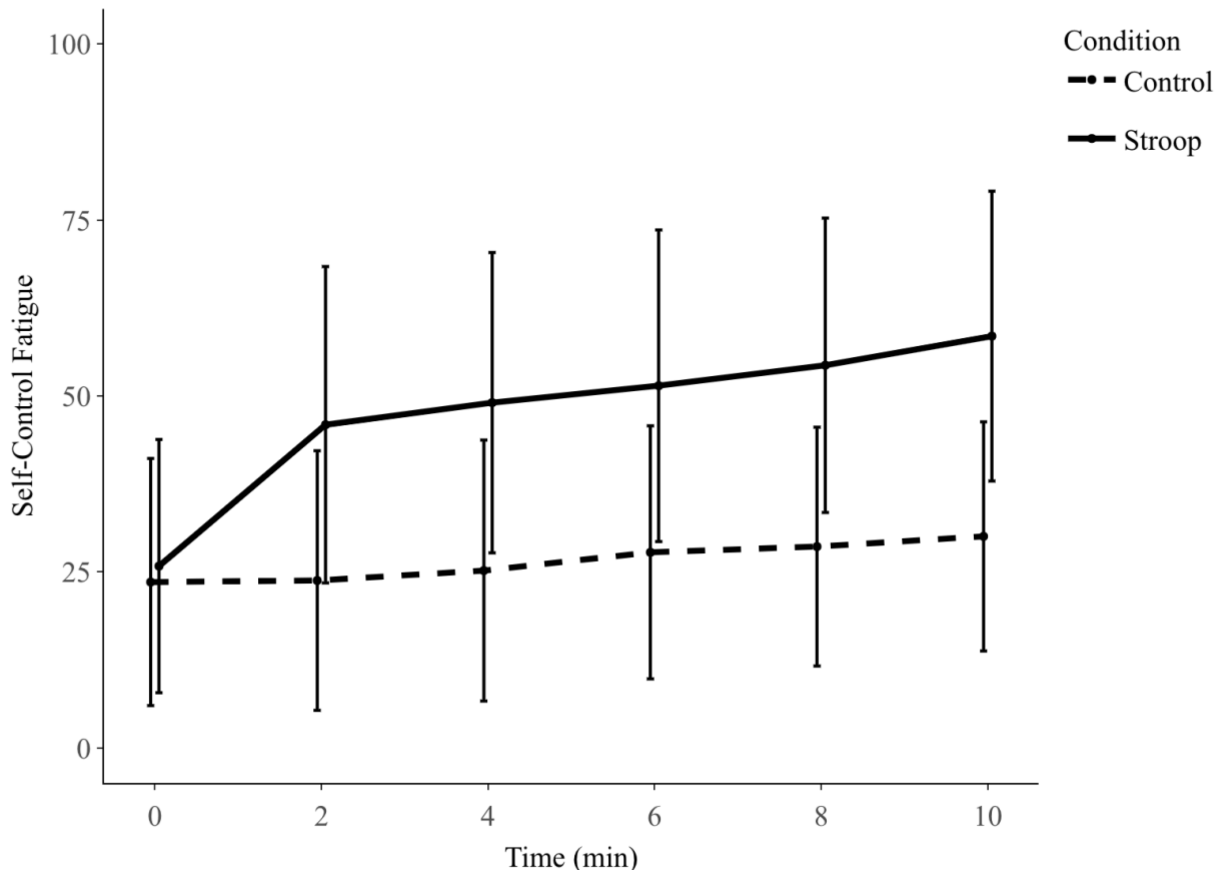

Figure 3.2: Self-control fatigue ratings reported overtime during the Stroop (solid) and control (dashed) conditions obtained using a visual analogue scale (0 – 100). Each data points represents the mean, with bars representing standard deviation.

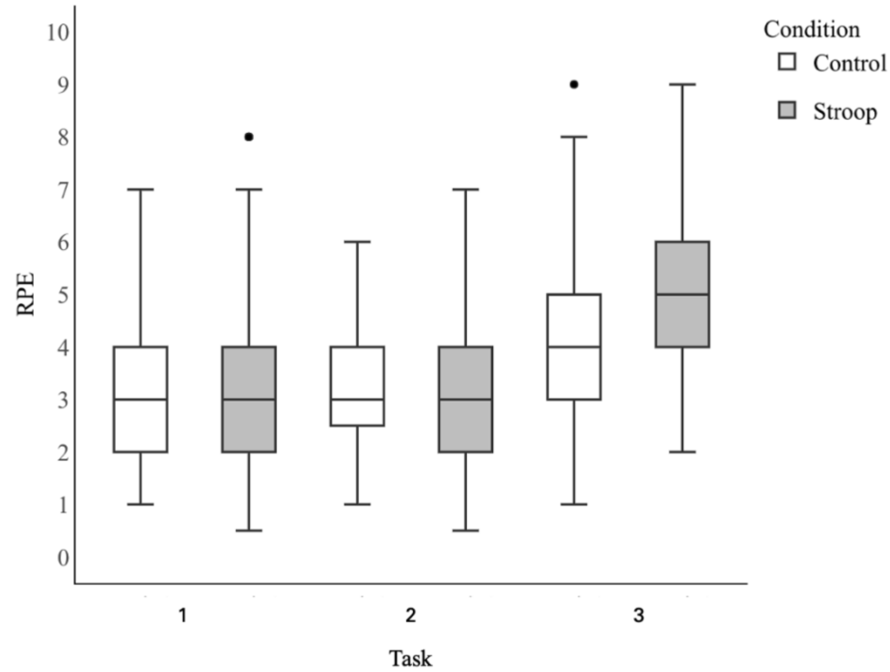

Figure 3.3: Self-reported RPE scores across the control (white) and Stroop (gray) conditions for Tasks 1, 2, and 3. Boxplots show the median, interquartile range, and outliers, with RPE measured on a 0 – 10 scale.

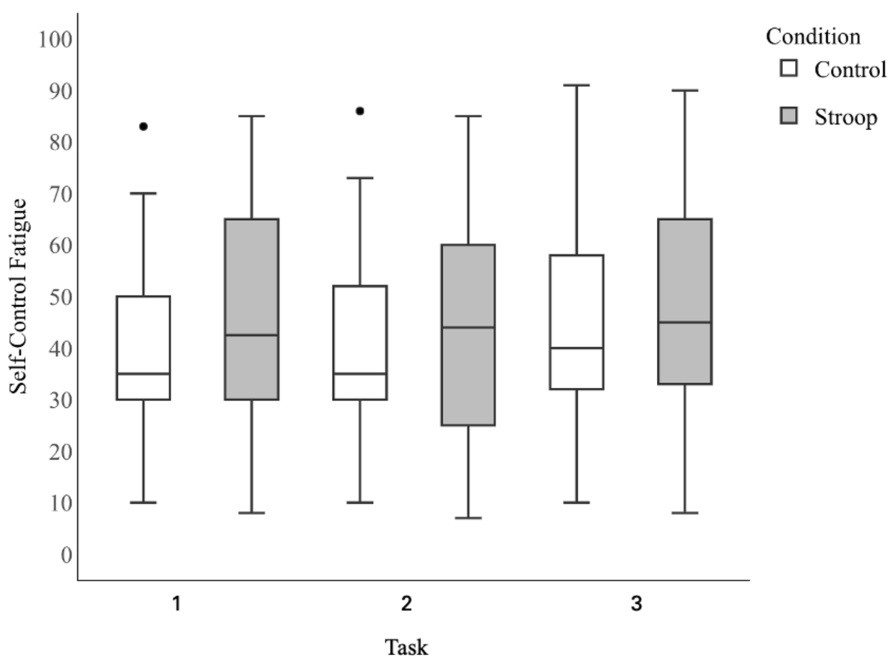

Figure 3.4: Self-reported self-control fatigue scores across the control (white) and Stroop (gray) conditions for tasks 1, 2, and 3. Boxplots show the median, interquartile range, and outliers, with fatigue measured on a 0 – 100 scale.

3.4.2 Displacement

Mean peak displacement in the control condition on the left side reached 117.0% ($p < 0.001$), 114.2% ($p < 0.001$), and 118.5% ($p < 0.001$) of the target distance in task 1, task 2, and task 3 respectively. In task 1, there were no significant effects of condition ($F = 0.32$, $p = 0.573$), side ($F = 0.18$, $p = 0.668$), or their interaction ($F = 0.01$, $p = 0.908$). Similarly, in task 2, no significant effects of condition ($F = 0.19$, $p = 0.665$), side ($F = 0.13$, $p = 0.722$), or their interaction ($F = 0.11$, $p = 0.735$) were observed. Finally, in task 3, there were also no significant effects of condition ($F = 1.34$, $p = 0.248$), side ($F = 1.73$, $p = 0.189$), or their interaction ($F = 0.96$, $p = 0.328$). Together, these findings indicate that peak displacement was consistent across both conditions and sides for all three tasks (Figure 3.5).

3.4.3 Muscle Activity

In task 1, the bimanual push task, the overall changes in muscle activity were small but the main effect of condition was still significant in two muscles (Figure 3.6). Proximally, the right posterior deltoid showed an increase of 1.8% in muscle activity ($F = 6.1282$, $p < 0.05$). The results from the anterior deltoids and left posterior deltoid revealed nonsignificant changes following the Stroop condition. In contrast, the left triceps brachii showed a small but significant decrease of 0.8% in muscle activity ($F = 8.2645$, $p < 0.01$) in the Stroop condition. The biceps and right triceps showed no significant changes. Distally, the main effect of condition was also not significant for the wrist flexors and extensors from both sides.

In task 2, the bimanual reciprocal push task, several muscles demonstrated increased in muscle activity for participants in the Stroop condition (Figure 3.7). The left and right anterior deltoids showed a small but significant increase of 0.6% ($F = 7.7982$, $p < 0.01$; $F = 4.53$, $p < 0.05$). The right posterior deltoid showed a significant increase of 4.9% ($F = 4.78$, $p < 0.05$), but the main effect of condition was not significant for the left posterior deltoid. In the distal muscles, muscle activity in the left and right wrist extensors showed a significant increase of 1.6% ($F = 4.37$, $p < 0.05$) and 3.1% ($F = 4.3533$, $p < 0.05$) respectively. Additionally, the right wrist flexors showed a significant increase in muscle activity of 1.8% ($F = 5.26$, $p < 0.05$). In contrast, the main effect of condition was not significant for the biceps, triceps, and left wrist flexors.

The changes in muscle activity in task 3, the bimanual push task with 30% right hand grip, were more pronounced than the other two tasks (Figure 3.8). Proximally, the left anterior deltoid showed a significant increase of 1.4% ($F = 6.00$, $p < 0.05$) in muscle activity while the posterior deltoid on the right side showed a significant increase of 5.7% ($F = 5.32$, $p < 0.05$) in muscle activity. The left wrist extensors showed a significant increase of 3.7% ($F = 6.6954$, $p < 0.05$) in muscle activity. Interestingly, the right wrist extensors had a significant increase of 16.7% ($F = 16.92$, $p < 0.001$) in muscle activity, representing the highest increase across all muscles and tasks. In contrast, the main effects of condition were not significant for the wrist flexors. Additionally, similar to task 2, the biceps and triceps showed negligible changes. Overall, while no significant changes were observed in accuracy through the potentiometer data, the results revealed increases in activity across several muscles.

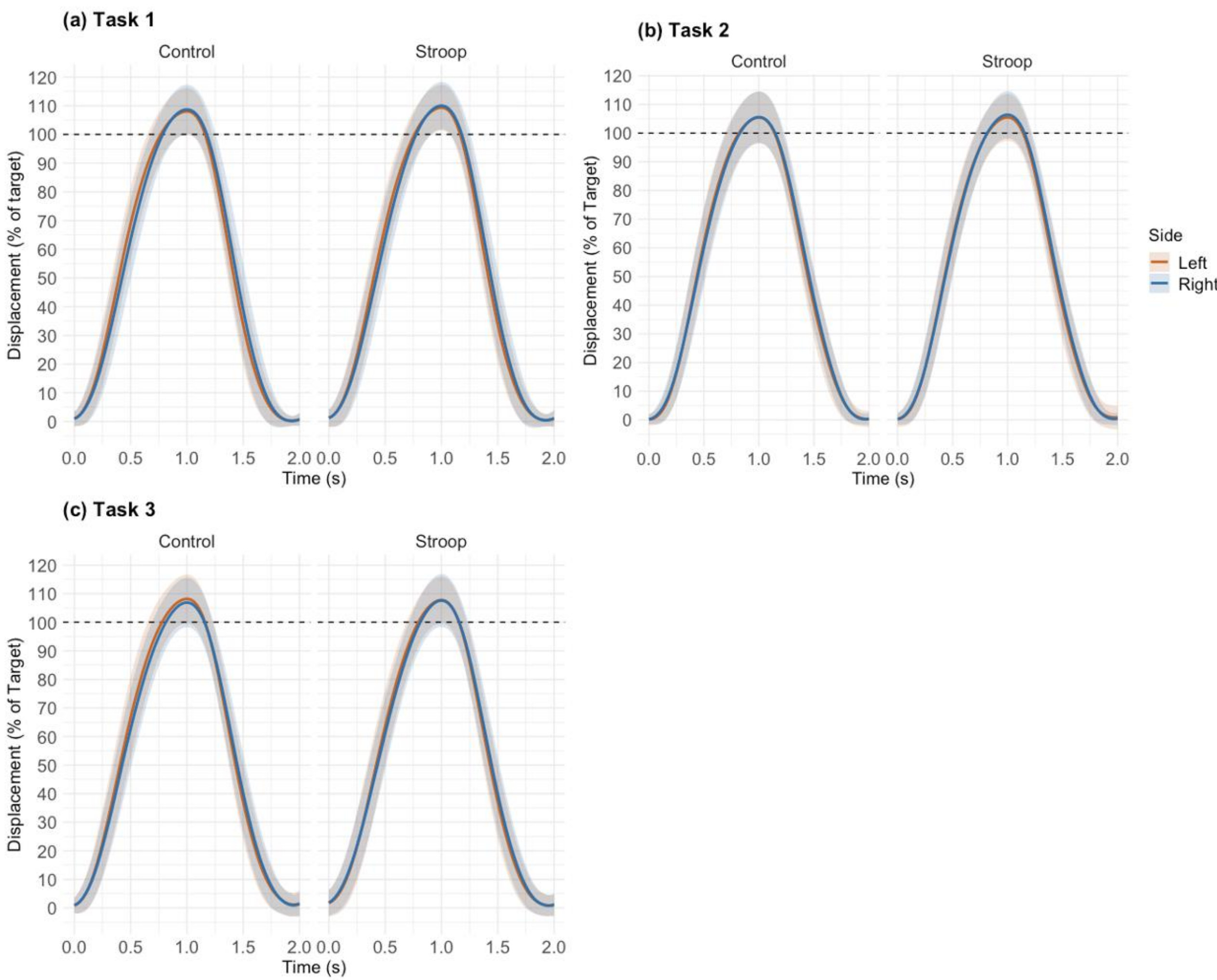

Figure 3.5: Normalized displacement during an average 2 second cycle across control and Stroop conditions for (a) task 1, (b) task 2, and (c) task 3. The left and right side displacements are represented by red and blue lines, respectively. The dashed black line at 100% indicates the target. The shaded regions represent standard deviation. The horizontal dashed line at 100% indicates the target distance. Time (in seconds) is plotted on the x-axis, and displacement (as a percentage of the target) is shown on the y-axis.

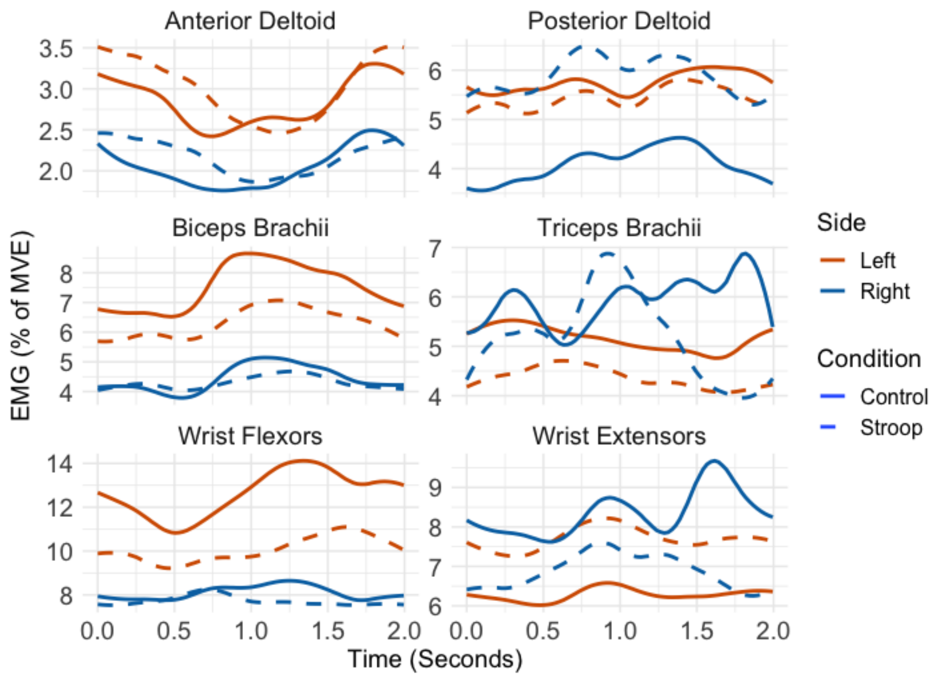

Figure 3.6: Normalized muscle activity (anterior deltoid, posterior deltoid, biceps brachii, triceps brachii, wrist flexors, and wrist extensors) over an average 2 second cycle for the left (red) and right (blue) sides under the control (solid) and Stroop (dashed) conditions for task 1.

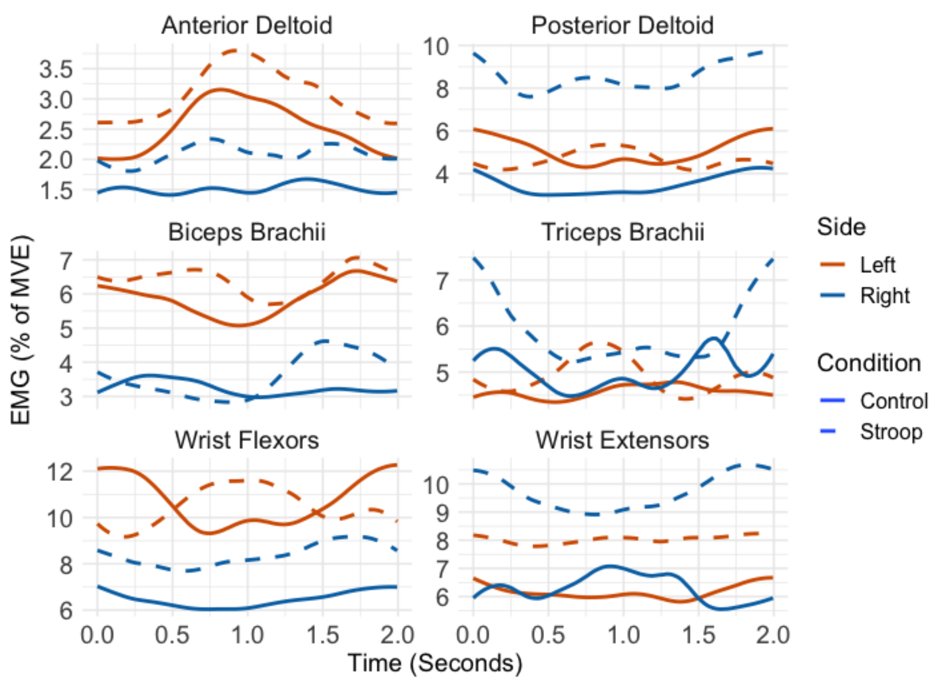

Figure 3.7: Normalized muscle activity (anterior deltoid, posterior deltoid, biceps brachii, triceps brachii, wrist flexors, and wrist extensors) over an average 2 second cycle for the left (red) and right (blue) sides under the control (solid) and Stroop (dashed) conditions for task 2.

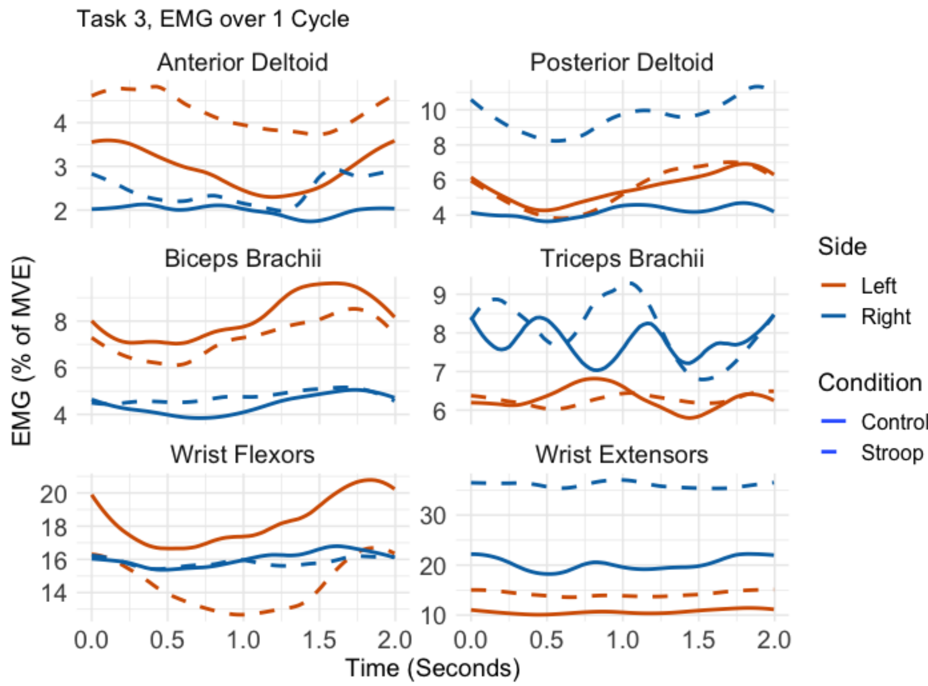

Figure 3.8: Normalized muscle activity (anterior deltoid, posterior deltoid, biceps brachii, triceps brachii, wrist flexors, and wrist extensors) over an average 2 second cycle for the left (red) and right (blue) sides under the control (solid) and Stroop (dashed) conditions for task 3.

3.5 Discussion

This is the first study to look at the effects of self-control fatigue on bimanual submaximal tasks and it is the first study to observe increases in activity across several upper extremity muscles. This study aimed to expand our understanding of how mental fatigue affects our movement. The significant increases in proximal and distal upper limb muscle activity support the notion that mental fatigue may drive changes in motor unit recruitment during subsequent physical tasks (Pageaux et al., 2015; Ferris et al., 2021; Bray et al., 2008; Graham et al., 2014). The purpose of this study was to examine the effects of self-control fatigue on displacement and muscle activity across twelve different sites during a cyclic push-pull task. We expected to see a decrease in distance traveled following the Stroop condition, in addition to elevated muscle activity in various muscles across the upper extremity. Contrary to our initial hypothesis, peak displacement was consistent across conditions in all 3 tasks. Additionally, changes in muscle activity appeared to be task dependent. The results from this study provide novel insights into how the body adapts to maintain performance under the effects of mental fatigue.

Given that mental fatigue is linked to a reluctance to exert any effort, this study hypothesized a decrease in displacement during the cyclic push tasks following the Stroop test as we expected to see less energy expenditure (Wang et al., 2022). In two separate studies, Smith et al. (2015; 2016) observed a decrease in running distance when mentally fatigued. Contrary to the literature, displacement remained consistent across tasks and conditions. Declines in performance are often associated with an increase in RPE (Van Cutsem et al., 2017). After completing the Stroop test, participants reported a 0.59 point higher in RPE during task 3, leading us to expect performance decrements for that task, but no changes were observed. This means that despite feeling more mentally fatigued, participants were able to manage the increase in RPE without adversely affecting performance. The dual regulation system of mental fatigue proposed by Ishii et al. (2014), suggests that when mentally fatigued, the activation of the mental facilitation system which composes of the thalamic frontal loop helps us maintain our performance while the activation of the mental inhibition system impairs our performance. It is the balance of these two systems that determine our performance. Integrating ideas from motivational theorists, this result suggests that RPE may need to surpass a certain threshold where the perceived costs outweigh the benefits, before an impact on performance can be observed (Harris & Bray, 2021).

While no differences in accuracy were found across conditions for all tasks, there were significant changes in muscle activity across several muscles. This result means that when participants felt mentally fatigued, increased activity in several muscles was necessary to maintain the same level of performance. It could also be rooted in decreased muscle activation efficiency so rather than executing the physical task in a smooth and well coordinated manner, participants were stiff and over activated for what needed to be done. We consistently observed increased deltoid and wrist extensors activity across task 2 and 3. Reciprocal pushing and pulling in task 2 requires nonhomologous bilateral muscle activity, placing a greater demand on the central nervous system (Swinnen et al., 1998; Temprado et al., 2003; Tournament & Laurent, 2003). In a previous study, Gruevski et al. (2010) found that continuous reciprocal push-pull tasks require more anterior and posterior deltoid muscle activity compared to in-phase bimanual push-pull tasks, suggesting that task 2 is more physically demanding than task 1. This could explain why we saw greater increases in deltoid muscle activity in task 2 compared to task 1. The increase in wrist extensor activity in both task 2 and 3 is likely explained by the added pushing component, as a previous study by Dominizio & Keir (2010) found that pushing and simultaneous gripping tasks tend to increase forearm extensor activity while reducing flexor activity when compared to isolated gripping tasks. The 16.7% increase in right wrist extensor activity in task 3 following the Stroop test represents the most substantial change observed across all muscles and tasks. These novel findings highlight that the effects of mental fatigue are far deeper than surface level kinematics and affect the activity of a broad range of muscles, influencing not only the primary agonists but also the surrounding musculature.

In a recent study, Alix-Fages et al. (2023) found that mental fatigue did not change the threshold or firing rates of individual motor units, so it could be the recruitment of additional, larger motor units that is contributing to the increase in muscle activity observed. When mentally fatigued, increases in muscle activity during a subsequent physical task are thought to be driven by central processes rather than the muscles themselves. An increase in perceived exertion, thought to be caused by an accumulation of adenosine in the anterior cingulate cortex following a fatiguing cognitive task, is often associated with decreased endurance performance and increased muscle activity (Pageaux & Lepers, 2016). This heightened perception of effort may trigger the recruitment of additional motor units in preparation for a more challenging task, elevating muscle activity (Brown & Bray, 2017). However, an increase in self-reported RPE was only observed in task 3, despite increases in muscle activity also being observed in task 1 and 2. This raises the potential for other underlying mechanisms that may contribute to the observed changes, beyond perceived exertion alone. Studies have shown that mental fatigue can lead to increased sympathetic nervous system activity, which in turn may influence muscle activity (Mizuno et al., 2011). Additionally, decreased prefrontal cortex activity, which play an important role in motor planning, may also contribute to these results (Shortz et al., 2015). The neuromuscular changes following prolonged cognitive tasks are complex, and further research is needed to provide empirical evidence that can clarify the underlying mechanisms.

Regardless of how this increase in muscle activity occurs, this finding has important practical implications, as constant muscle loading, even at low levels, has also been linked to muscle fatigue, pain, and myalgia (Larsson et al., 1998). The elevated wrist extensor activity is especially concerning because it is linked to the development of lateral epicondylitis, a common overuse injury (Chen et al., 2024). Additionally, when it comes to detecting mental fatigue in the workplace, the results from this study suggest that purely relying on performance metrics may not be the most effective approach (Pimenta et al., 2014). The results from this study suggest that underlying muscular compensatory mechanisms, which are not visible through performance measures, can mask early signs of fatigue.

In an effort to capture the bigger picture, a distinct strength of this work is the collection of EMG data from twelve muscles as opposed to focusing just on the primary agonist muscle.

Additionally, another strength of this study is the inclusion of asymmetrical physical tasks, this design allowed for some interesting side dependent results. Conversely, there are some limitations to this study. Most participants in this study were students from the McMaster Kinesiology Department, who are younger than the general working population. Additionally, the nature of the Stroop task followed by moving handles on a track likely limit generalization to the workplace. However, the effect of Stroop task on wrist extensor muscle activity during our dual task of movement plus active gripping was substantial. In future studies, a more diverse recruitment strategy could be used to obtain a sample that better represents the general population.

3.6. Conclusion

In this novel study, we explored the effects of self-control fatigue on displacement and muscle activity across a broader range of muscles beyond the primary agonists during a cyclic push-pull task. This is the first study to observe significant increases in muscle activity across several upper extremity muscles during a subsequent physical task. After the Stroop test, participants were able to maintain physical task performance, but significant increases in muscle activity across several sites were needed to offset the effects of mental fatigue. These significant, underlying changes would go unnoticed if we monitored performance alone, especially the substantial increase we saw in the wrist extensors, which has been heavily linked to lateral epicondylitis. Furthermore, these findings build on the existing literature and provide more insight into the effects of mental fatigue on dynamic tasks and effective detection tools.

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3.8 Supplementary Tables

Table 3.1: Results of the mixed-effects model analysis for task 1 across all 12 muscles. The table presents the intercept and condition estimates, along with the F-values and p-values. Significant p-values ($p < 0.05$) are denoted by an asterisk (*).

Muscle	Intercept	Condition Estimate	F Value	p Value
RAD	2.0385	0.1319	0.3828	0.54
RPD	4.0783	1.8112	6.1282	< 0.05*
RBIC	4.4062	-0.1095	0.0918	0.76
RTRI	5.8742	-0.678	0.4928	0.48
RWF	8.0424	-0.3195	0.3377	0.56
RWE	8.38	-1.497	1.1235	0.29
LAD	2.827	0.1802	0.8464	0.36
LPD	5.7148	-0.2771	0.6196	0.43
LBIC	7.475	-1.1613	2.4738	0.12
LTRI	5.1158	-0.7544	8.2645	< 0.01*
LWF	12.548	-2.486	3.0573	0.08
LWE	6.3476	1.3544	3.8113	0.05

Table 3.2: Results of the mixed-effects model analysis for task 2 across all 12 muscles. The table presents the intercept and condition estimates, along with the F-values and p-values. Significant p-values ($p < 0.05$) are denoted by an asterisk (*).

Muscle	Intercept	Condition Estimate	F Value	p Value
RAD	2.4597	0.622	7.80	< 0.01*
RPD	5.0877	-0.4301	3.2451	0.07
RBIC	6.174	0.2367	0.081	0.78
RTRI	4.3638	0.5528	1.2401	0.27
RWF	11.0402	-0.5607	0.2129	0.65
RWE	6.439	1.59	4.3675	< 0.05*
LAD	1.524	0.5662	4.529	< 0.05*
LPD	3.697	4.845	4.779	< 0.05*
LBIC	3.3725	0.2135	0.6256	0.43
LTRI	4.9985	0.8505	1.1096	0.29

LWF	6.5669	1.81	5.2598	< 0.05*
LWE	6.587	3.095	4.3533	< 0.05*

Table 3.3: Results of the mixed-effects model analysis for task 3 across all 12 muscles. The table presents the intercept and condition estimates, along with the F-values and p-values. Significant p-values ($p < 0.05$) are denoted by an asterisk (*).

Muscle	Intercept	Condition Estimate	F Value	p Value
RAD	1.94	0.47	1.65	0.20
RPD	3.32	5.69	5.32	< 0.05*
RBIC	4.08	0.37	1.25	0.27
RTRI	7.54	0.36	0.12	0.73
RWF	15.83	-0.23	0.06	0.81
RWE	20.58	16.67	16.92	< 0.001*
LAD	2.57	1.38	6.0	< 0.05 *
LPD	5.14	-0.04	0.02	0.90
LBIC	7.84	-0.93	1.8	0.18
LTRI	5.87	-0.03	0.01	0.94
LWF	17.07	-4.10	2.43	0.12
LWE	10.31	3.74	6.7	< 0.05*

Chapter 4: Thesis Discussion

4.1 Contributions

Our study is the first to look at the effects of self-control fatigue on bimanual dynamic tasks and it is the first study to observe increases in activity across several upper extremity muscles. Before this, there were limited investigations that looked at the effects of mental fatigue on dynamic tasks and a focus on the primary agonist muscle. The bimanual and asymmetrical nature of the physical tasks gave rise to interesting side dependent results. While the underlying mechanisms are still uncertain, mental fatigue seems to have a clear effect on how we move. The observed increases in deltoid and forearm muscle activity supports the notion that the carryover effects of mental fatigue may drive changes in motor unit recruitment in subsequent physical tasks. Despite feeling more mentally fatigued and reporting higher RPE, participants were able to maintain their performance across conditions through increased muscle activity in several muscles. These findings can be applied to workplace interventions such as detection, as solely relying on performance indicators may not be the most effective method. At last, this study adds to the growing body of mental fatigue literature and enhanced our understanding of its effects on physical performance.

4.2 Rationale for Methods

The aim of this study was to investigate the effects of self-control fatigue on displacement and muscle activity during a cyclic push-pull task. Prior to this work, the effects of mental fatigue were often investigated in sport specific skills or highly controlled isolated endurance tasks that lack generalizability to dynamic tasks. Additionally, investigations on the effects of mental fatigue have primarily been focus on the primary agonist muscle. Therefore, this study aimed to examine the effects of mental fatigue on dynamic submaximal tasks and look at a broader range of muscles.

During the conceptualization stages of the study, I found a lack of standardization among fatiguing protocols while reviewing the mental fatigue literature. Understandably, mental fatigue can develop through different sources, so different studies used different procedures to induce this condition experimentally. While this is true, Smith et al. (2019) found that the effects of mental fatigue lasted longer following cognitive tasks with an inhibition component. Given this and the fortunate opportunity to have Dr. Bray as a resource, the Stroop protocol used in this study has historically been able to induce mental fatigue in participants. There are also advantages to keeping the methods consistent because it helps to address questions like what parameters effectively induce mental fatigue in a laboratory setting.

The physical task in this study was inspired by common pushing and pulling workplace tasks in mind. While it does not directly replicate any specific workplace task in particular, the inclusion of a dynamic submaximal physical task is a step toward better understanding the effects of mental fatigue in laborious workplace settings. The inclusion of three different physical tasks was to test the resource theory of mental fatigue. According to the theory, a more effortful task will require more cognitive resources and in turn, result in further decreases in performance. This was partially successful as the third task was the only task to result in a significant increase in self-reported RPE. Given that the effects of mental fatigue are sensitive to factors like feedback and motivation, a standardized script was used for all participants throughout each stage of the study visits. While participants were familiarized to the task, feedback was not provided during the actual trials themselves, which may have contributed to the tendency to overshoot observed in this study. A frequency of 30 pushes per minute was selected based on a study previously conducted within this lab, as this rate was found to feel most natural to participants (Gruevski et al., 2017).

A custom apparatus previously used within our lab was also employed for this study. Given constraints of the pulley system, we were not able to adjust the resistance as a heavier weight caused excessive swinging of the cords around the pulley, instead a standardized 2kg weight per handle was used for all participants. While two hand grip dynamometers were vertically mounted as handles, only one was plugged in. This is because based on the literature, we know that grip force varies with handle diameter (Kong & Lowe, 2004).

To answer our research questions, mixed effect models were used for displacement and EMG data. The advantages of using a linear mixed include its versatility and robustness, being able to account for individual variability and additional random effects while handling repeated measures. The condition x side interaction term was also able to provide further insight into potential asymmetries in performance. Mixed effects models offered the same advantages when analyzing the EMG data, being flexible and able to account for individual variability. Additionally, while analysing our potentiometer data, we also looked at velocity and acceleration and we were unable to find any significant changes in kinematics. However, several significant increases emerged in EMG following the Stroop test. This further demonstrates that the effects of mental fatigue go beyond feelings of tiredness and performance decrements that are reported in the literature but may also serve a risk factor for repetitive strain injuries.

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APPENDIX A – Study Materials
Appendix A.2: Consent Form

Letter of Information and Consent
The Effects of Self Control Fatigue on Performance During Three Dynamic Tasks

Faculty Supervisor: Peter Keir, PhD
Professor
Department of Kinesiology McMaster University
(905) 525-9140 ext. 23543
pjkeir@mcmaster.ca

Student Investigator: Brian Zheng, MSc Candidate
Department of Kinesiology
McMaster University
(647) 554-9688
Zhengb12@mcmaster.ca

Purpose of the Study
You are invited to take part in this study self control and performance, I am doing this research for a thesis under the supervision of Dr. Peter Keir. Self control refers to the act of resisting immediate gratifications for long term gains. As one exercises self control against everyday temptations throughout the day, their ability to continue doing so may decrease due to the strains of mental fatigue. Mental fatigue is the ensuing feelings of tiredness that follows prolonged cognitive activity, and it can negatively affect subsequent endurance performance. Specifically, mental fatigue has been reported to affect performance metrics like accuracy and muscle activity. While repetitive submaximal tasks are common in laborious occupations, the effects of mental fatigue are not often explored with ergonomics in mind. The goal of this project is to look at the effects of mental fatigue on (i) accuracy, and (ii) bilateral upper extremity muscle activity over three dynamic push and pull tasks. This study aims to provide better insight into the effects mental fatigue in the workplace.

Procedures involved in the Research
This study will involve a two laboratory session taking approximately 90 minutes each to complete. All procedures will be completed by the researchers in the study.

1. During visit 1, informed consent will be obtained after details of the experiment are explained and any questions are answered. During visit 1, Participant demographic (age, sex), anthropometric (height, weight, arm length) measurements will be recorded. The International

Physical Activity Questionnaire will also be completed to assess weekly minutes of moderate-to-vigorous physical activity during the past 6 months. During Visit 2, we will verbally reaffirm consent.

Methods common to both sessions:
2. At the start of each session, a visual analogue scale (VAS) will be used to assess baseline level of mental fatigue. This scale ranges from 0 (none) to 100 (maximal). Participants will mark a point on the scale that appropriately corresponds to their current level of fatigue.

3. Surface electromyography used to record the muscle activity of six upper extremity muscles bilaterally. These muscles will include: (i) anterior deltoid, (ii) posterior deltoid, (iii) biceps brachii, (iv) triceps brachii, (v) flexor digitorum superficialis, and (vi) extensor digitorum communis. Before the placement of electrodes, the skin over the muscle belly will be shaved (if necessary) and cleaned with isopropyl alcohol. Electrodes will be placed parallel to the direction of the muscle fibres over the muscle belly for each muscle. After the electrodes are attached, a quiet (resting) trial, and maximal voluntary exertion (MVE) for each muscle will be recorded for each muscle.

4. Each participant's maximum voluntary grip force (MVG) for the right hand will be determined using the grip dynamometer on the right side of the apparatus in the starting position. Participants will be asked to slowly ramp their grip force up to maximum and hold it for a minimum of 3 seconds.

5. Prior to the physical task in each session, participants will randomly be assigned to the experimental condition or the control condition for session 1 (with the other in session 2):
(i) Experimental session (high mental fatigue): In the experimental, the modified Stroop colour word test will be completed in 2 minute intervals with a 30 second rest period for five times, totalling 12 minutes and 30 seconds.
(ii) Control Session (low mental fatigue): The control condition will watch a 12 minute segment of the documentary Planet Earth.
A VAS will be completed after each 2 minute interval and at the end of each condition.

6. For the physical task, participants will push and pull the handles of the testing apparatus in three randomized conditions:(i) bilateral - simultaneously with both arms, (ii) bilateral - alternating between arms, and (iii) bilateral - with a dual task. The dual task will require participants to use both arms simultaneously while maintaining a grip force of 30% MVG. These trials will be completed three times each totalling 9 trials per participant. A familiarization trial will be completed prior to each condition prior to the test trials. Each trial will last 60 seconds with a 1 minute rest in between each set. The resistance (2 kg per handle) and frequency (30 cycles per minute using a metronome) will remain constant for all trials.

7. Participants will verbally report their perceived exertion after completion of each trial using the Borg CR10 Rating of Perceived Exertion (RPE) Scale (Borg, 1998). The scale ranges from 0 (no effort) to 10 (maximal effort).

8. Participants will complete the same dynamic push and pull task under the opposite experimental condition for the second visit with at least 3 days between visits.

9. Photos may be taken for use in publications and presentations only after obtaining consent.

Potential Harms, Risks or Discomforts
Minimal risks are anticipated from this study.

Muscle Fatigue
You may feel fatigued following the session due to the repetitive pushing and pulling motions. You will be given 2 minutes rest between 90 second long exertions to mitigate these effects but may still experience fatigue similar to that following a light workout
Skin Sensitivity
You may experience mild skin irritation/redness from the adhesive of the electrodes. This is similar to the irritation that may be caused by a bandage and typically fades within 2 to 3 days.

Psychological risks
Given that the purpose of the study is to investigate the effects of mental fatigue. Participants may experience sluggishness or feel unmotivated following the modified Stroop colour matching task (experimental protocol). the 12 minute Stroop task is broken up in five 2 minute sessions with a 30 seconds rest between each session. Breaks during the task are incorporated to prevent excessive buildup of mental fatigue.

Potential Benefits
The outcome of the study will allow us to inform occupational guidelines. The research will not benefit you directly.

Incentive:
Participants will be provided with financial incentive. For each visit completed (2 visits in total, 2 hours each), participants will receive $20 for a maximum of $40 as remuneration for your time. These will be in the form of etransfers, the total will be paid to you at the end of your participation in this study. Your contact information may be shared with the Kin Grad Admin to ensure your compensation. The amount received is taxable. It is your responsibility to report this amount for income tax purposes.

Confidentiality:
Your identity will be kept confidential, and data collected will be used for research purposes only. Only the identified researchers for this study Keir, Zheng, and the Kin Grad Admin will have access to this data. It will be stored securely on a password protected computer in encrypted format. Participant data will use an alpha-numeric code to identify the session and will not be linked to a name. Consent forms will be obtained and signed in person.

Participant contact information will only be recorded on a password protected computer and will not be transported anywhere. Similarly, signed participant consent forms will be held electronically and encrypted on a password protected tablet in the lab and will not be transported anywhere.

The information directly pertaining to you will be locked in a cabinet or stored electronically on a password protected computer for 10 years. During the collection there may be undergraduate research assistants present in the lab space.

Participants' will be asked if they would be willing to have photos of them taken for use in publications and presentations. Photo data will only be used with their consent and will only capture the participants' torso and arms. Any potentially identifying features will be pixelated.

Participation:
Your participation in this study is voluntary. If you decide to participate, you can decide to stop at any time, even after signing the consent form or part-way through the study. If you decide to stop participating, there will be no consequences to you. If you chose to withdraw at any time in the study, you will still be compensated for your time. Upon the completion of the data collection process (both visits), the linking file connecting participant ID to each participant number will be destroyed. So, participants will not be able to withdraw their data.

Information about the Study Results:
You may obtain information about the study results by contacting Dr. Peter Keir at (905) 525-9140 (x 23543) or indicating "Yes" at the bottom of this form.

Questions about the Study:
If you have questions or need more information about the study itself, please contact me at:
Brian Zheng (zhengb12@mcmaster.ca)

This study has been reviewed by the McMaster Research Ethics Board and received ethics clearance under project 6947. If you have concerns or questions about your rights as a participant or about the way the study is conducted, please contact: McMaster Research Ethics Office, Telephone: (905) 525-9140 ext. 23142, E-mail: mreb@mcmaster.ca

CONSENT

- I have read the information presented in the information letter about a study being conducted by, Mr. Brian Zheng and Dr. Peter Keir of McMaster University
- I have had the opportunity to ask questions about my involvement in this study and to receive additional details I requested
- I understand that if I agree to participate in this study, I may withdraw from the study at any time. Upon the completion of the data collection and at the start of the data analysis process, I will have until the anticipated start of the data analysis date (May 31, 2024) to withdraw my data.
- I understand I will receive a signed copy of this form via email
- I agree to participate in the study

Signature: ______________________________________ Date: ________________________
Name of Participant (Printed) ___________________________________

1. Would you like a copy of the study results?
   [ ] Yes, I would like to receive a summary of the study's results with the following email: _________________
   [ ] No, I do not want to receive a summary of the study's results.

Appendix A.2: International Physical Activity Questionnaire

How active are you usually? Please consider your usual activity level during a typical 7 day period in the past 6 months and answer the following about moderate and vigorous activity participation.

MODERATE Physical Activity Definition
Moderate physical activity or exercise includes activities such as brisk walking, light swimming, dancing, biking, gardening, and yardwork. You should be able to carry on a conversation when doing moderate activities. Please consider a TYPICAL week for you and answer the following questions about moderate activities.

1. How many days per week are you moderately physically active or do you exercise moderately?

_____ **days per week**

2. Approximately how many minutes are you moderately physically active or do you exercise moderately each day?

_____ **minutes per day**

VIGOROUS Physical Activity Definition:

Vigorous physical activity or exercise includes hard activities such as jogging, aerobics, swimming, and fast biking. You may have a hard time carrying on a conversation when doing vigorous activities. Please consider a TYPICAL week for you and answer the following questions about vigorous activities.

1. How many days per week are you vigorously active or do you exercise vigorously?

_____ **days per week**

2. Approximately how many minutes are you vigorously active or do you exercise vigorously each day?

_____ **minutes per day**

Appendix A.3: Ratings of Perceived Exertion Scale

0 Nothing at all

0.3

0.5 Extremely weak

1 Very weak

1.5

2 Weak

2.5

3 Moderate

4

5 Strong

6

7 Very Strong

8

9

10 Absolute Maximum

Appendix A.4: Mental Fatigue Visual Analogue Scale

Please mark (X) on the line the point that you feel represents your perception of your current state of **MENTAL FATIGUE**.

None at all 0
____ 100
Maximal