

Accumulation and Recovery of Prolonged Low-Frequency Force Depression at Different Intensities of
Repetitive Isometric Contractions

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Prolonged Low Frequency Force Depression (PLFFD) may impact performance in the workplace by influencing musculoskeletal disorder (MSD) risk or reducing force stability. PLFFD is a reduction in low-frequency stimulated force with little change in high-frequency stimulated force for long period after contraction. The objective of this research was to measure changes in PLFFD over exposure and recovery from a half-shift of an isometric contraction task at two intensities on separate visits, and to determine whether there is a relationship between PLFFD and force stability.

Participants repetitively supported a weight with their elbow flexors for 4 consecutive 1-hour work-segments. Participants performed a low-force high-duty cycle and a high-force low-duty cycle workload-matched protocol on two different days. PLFFD and force stability were measured in the biceps brachii muscle throughout task exposure and recovery. PLFFD was measured as the ratio of elbow flexion force produced at low (10 Hz) and high (100 Hz) frequency transcutaneous stimulations on both the left (non-intervention) and right (intervention) arms. A repeated measures ANOVA detected a progression of PLFFD in the intervention arm through intervention and recovery, but no protocol-effects were detected. Force stability metrics of variability (normalized standard deviation) and unsteadiness (average rate of change) of force during an isometric elbow flexion force matching task were poorly predicted by PLFFD and better predicted by changes in Maximum Voluntary Force (MVF).

This research expanded on incidental findings of PLFFD from past research, and reinforced relationships between muscle fatigue and force stability. PLFFD did not recover at different rates depending on exertion intensity, nor impact force stability metrics, therefore likely not affecting worker performance. Muscle fatigue was shown to impact force unsteadiness to a greater extent than force variability, leading to the suggestion that force stability changes caused by muscle fatigue should be considered when designing a workplace.

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List of Abbreviations

ADP	Adenosine diphosphate
ANOVA	Analysis of Variance
ATP	Adenosine triphosphate
EMG	Electromyography
MSD	Musculoskeletal Disorder
MVF	Maximum Voluntary Force
RPM	Repetitions Per Minute
PAP	Post-Activation Potentiation
PLFFD	Prolonged Low Frequency Force Depression
VAS	Visual Analog Scale

Chapter 1 Introduction

Musculoskeletal Disorders (MSDs) impacted 1.9 billion people in 2019 (Cieza et al., 2020) even though we have the capacity to measure and control peak loads that workers encounter. This might suggest that in today's workplaces, MSDs may be a problem of accumulating lower, yet more frequent and/or sustained loads. Muscle fatigue has been closely linked to MSDs because they share risk factors (Nussbaum et al., 2001) such as repetitive work and insufficient recovery time. Factors influencing the rate and duration of recovery from muscle fatigue are unknown, where the ability to recovery may be critical to understanding potential relationships between fatigue and MSD development.

Long-duration muscle fatigue, referred to as Prolonged Low Frequency Force Depression (PLFFD), may last over multiple days and its recovery (or lack thereof) may play a role in the day-to-day accumulation of muscle fatigue. PLFFD can be measured and tracked over the course of hours and days through measuring the Lo/Hi ratio of the force response to electrical stimulation at low and high frequencies. The causes and acute effects of PLFFD have been investigated for many years (Edwards et al., 1977), however its response to submaximal work has been less extensively studied. It is expected that as work is performed, PLFFD will accumulate relative to the total workload performed (Iguchi et al., 2008). The workload of a task is defined as the impulse of the task (the area under the force-time curve). Research has incidentally shown that PLFFD may recover differently post-exposure depending on the exertion force magnitude, even when workloads are controlled.

Muscle fibres accumulate and recover from fatigue at different rates (Allen et al., 2008), and since they are selectively recruited depending on force level, PLFFD may recover at different rates depending on the level of force. Notably, it is expected that individuals can recover from fatigue faster after higher force exertions, however non-significant evidence suggests that workload-matched, higher force work results in a greater duration of PLFFD (Dennerlein et al., 2003; Hruschka, 2003). Therefore, the primary aim of this research is to evaluate whether workload-matched protocols performed at different force levels recover at the same or different rates.

Force stability impacts the quality of work in tasks which require precision and consistent force. PLFFD may impact force stability because rate of force production is reduced (Rashedi & Nussbaum, 2016), and thus PLFFD may impact work tasks by reducing force stability. Therefore, the second aim of this research is to determine whether a greater amount of accumulated PLFFD is related to lower force stability.

Research Objectives: This study aimed to examine the changes in PLFFD throughout a repetitive isometric exertion task and measure recovery after two workload-matched protocols of different intensities. Additionally, this study aimed to investigate whether accumulated PLFFD influenced force stability, where force stability is a useful surrogate measure for task performance and work quality in the workplace.

Research Question 1: Among a convenience sample of university students performing two-half shifts of an isometric elbow flexion task at either a high-force and low duty cycle, or a low-force and high duty cycle protocol, does the Lo/Hi ratio differ at any time points throughout recovery?

Hypothesis 1: It is hypothesized that the Lo/Hi ratio will be different between work protocols during recovery on the same day and at the start of the next day.

Research Question 2: Among a convenience sample of university students performing two-half shifts of an isometric elbow flexion task, is Lo/Hi ratio related to force stability?

Hypothesis 2: It is hypothesized that decreased Lo/Hi ratio will be associated with decreased force stability, independent of protocol.

Chapter 2 Literature Review

This literature review is broken down into 3 sections. The first section describes the mechanisms and effects of muscle fatigue as foundational background information. The second section describes PLFFD and how to quantify it, where PLFFD is the primary focus of this research. The difference in mechanisms between muscle fatigue and PLFFD is essential to understanding how to elicit and measure it adequately. The third section synthesizes the state-of-the-art-literature on the topic of PLFFD accumulation, recovery, and its possible relationship with force stability. Previous research is used generate new questions, as well as to inform study design.

2.1 Muscle Fatigue

Muscle fatigue is a reduction in power (force x velocity) producing capacity of the muscle (Allen et al., 2008), also measured as a reduction in force producing capacity during isometric contractions. However, it is important to note that muscle fatigue is not a state (i.e., fatigued or not), but rather a dynamic process. As a result, the presence of muscle fatigue does not necessarily prevent an individual from completing a task. Figure 1 illustrates how an individual can maintain task performance (the target force, shown as white bars) over time, even though their force producing capacity (dashed line) is decreasing (Bigland-Ritchie & Woods, 1984). Reductions in force producing capacity due to changes in central drive can be significant (Bigland-Ritchie et al., 1978), but those changes can be circumvented by using muscle stimulation. Force producing capacity can also vary through changes in peripheral function (Allen et al., 2008). Understanding the mechanisms that contribute to peripheral muscle fatigue can help differentiate it from other effects which modify force production.

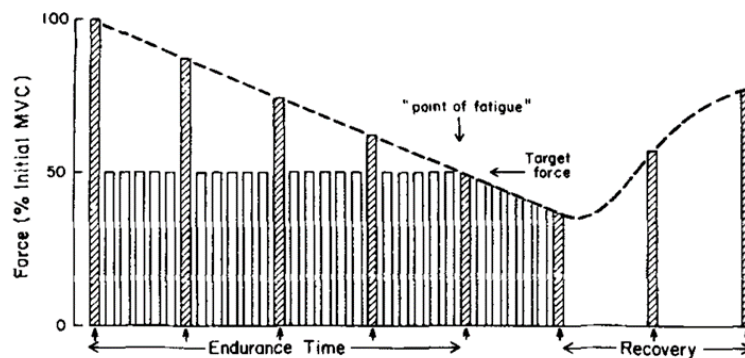


Figure 1. Repeated MVF tests (dark bars) with a repetitive 50% MVF task (light bars) over time, where the dashed line is the estimated maximum force. (Bigland-Ritchie & Woods, 1984).

Peripheral fatigue results in a reduction in force producing capacity of the muscle even at supramaximal rates of stimulation. Metabolic byproducts (inorganic phosphate and ADP) created during contractions interfere with crossbridge function when at high concentrations, which directly reduces force generating capacity of the muscle (Allen et al., 2008). Decreased ATP results in reduced calcium release and reuptake, indirectly reducing force producing capacity and relaxation rate respectively (Allen et al., 2008). Figure 2 illustrates the multitude of effects that reduced ATP and increased metabolite concentration has on the muscle, both on effecting calcium release and reuptake and effecting crossbridge function. Together, these cellular mechanisms reduce force production at the level of the whole muscle and individual muscle fibre.

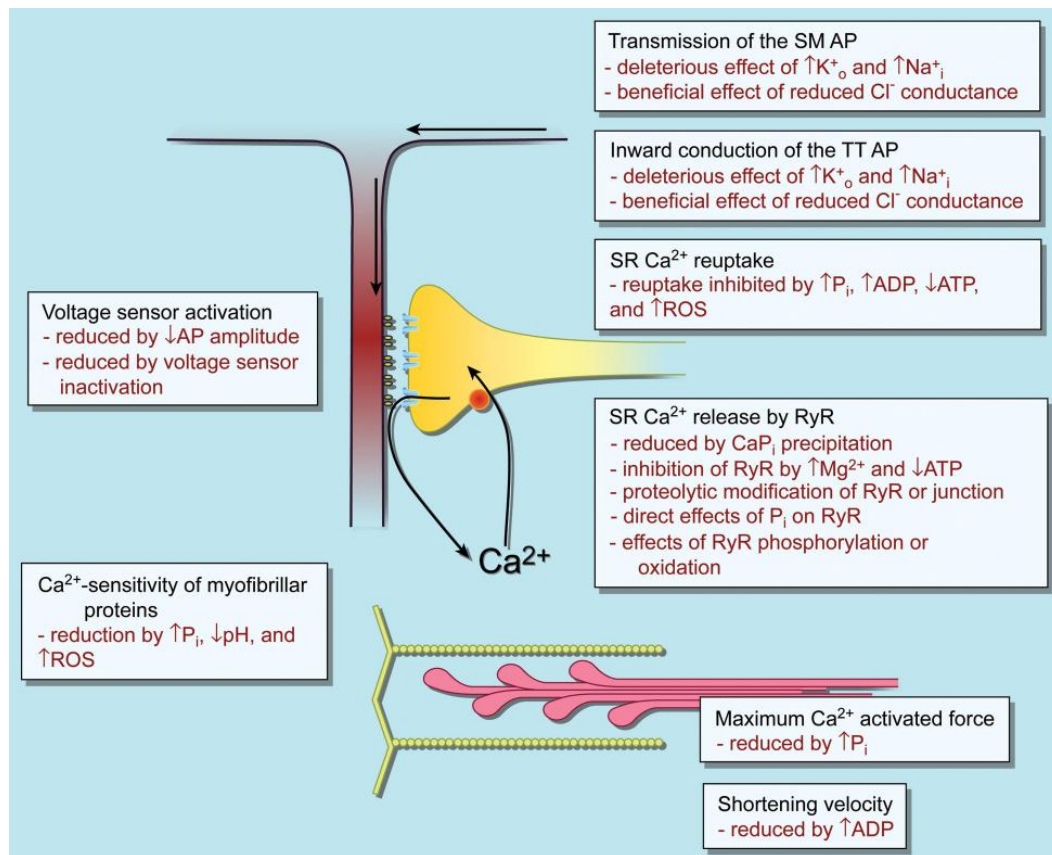


Figure 2. A diagram illustrating the major mechanisms contributing to muscle fatigue with the cellular function in black and the effects of fatigue in red (Allen et al., 2008).

Reductions in force producing capacity result in fibre-type-specific changes over time. High threshold fibres have a high force producing capacity but low resistance to fatigue and low threshold fibres have a low force producing capacity but high resistance to fatigue (Allen et al., 2008). When fatigued, individual muscle fibres have reduced force, a lower rate of force production, and a greater period of relaxation during both maximal and submaximal contractions (Allen et al., 2008). Depending on contraction intensity, recovery time will vary due to different workloads and muscle fibre types recovering at different rates.

2.2 Prolonged Low Frequency Force Depression

Prolonged Low Frequency Force Depression (PLFFD) is a form of muscle fatigue where individual muscle twitches have reduced force for a long duration post-contraction. PLFFD is observed when the force generated from low-frequency stimulated contractions is lower than when

stimulated in an unfatigued state, and where the force generated from high-frequency stimulated contractions is unchanged. PLFFD is a point of interest because it can take up to days for low-frequency stimulated force to return to pre-fatigue levels, whereas maximal force and high-frequency (fused tetanus) stimulated force can return to pre-fatigue levels relatively quickly (Edwards et al., 1977). Noting that MSD tend to accumulate over time, and that MSD share many links with factors related to muscle fatigue, PLFFD may be an important phenomenon to understand in order to better prevent MSDs that accumulate over time.

The cause of PLFFD remains unclear, but research continues to explore what factors do and do not influence PLFFD. The relative reduction in force produced by low frequency stimulated contractions seems to be related to the total amount of external work done relative to the strength of the muscle (Iguchi et al., 2008). It has been shown that if workload is controlled, the force level of contraction (high/low) or the type of contraction (concentric/eccentric) do not play a significant role in how much PLFFD the muscle accumulates (Baptista et al., 2009) (Dundon et al., 2008) (Iguchi & Shields, 2010).

The cellular mechanisms driving PLFFD differ from those causing reductions in force producing capacity. The primary mechanism causing PLFFD is believed to be reduced Ca^{2+} release upon each muscle fibre activation (Allen et al., 2008) and the reduced time Ca^{2+} spends outside the sarcoplasmic reticulum after each action potential (Keeton & Binder-Macleod, 2006) even with resting levels of ATP and metabolites present. Reduced Ca^{2+} release and time spent outside the sarcoplasmic reticulum are likely due to altered function of the sarcoplasmic reticulum and changes in cytosolic Ca^{2+} (Tupling, 2004). Changes in Ca^{2+} release and reuptake cause observable force changes in single muscle twitches or low-frequency stimulations, whereas in high-frequency stimulations the effect is overwhelmed by Ca^{2+} saturation. Figure 3 shows that a small negative shift in the sensitivity (portrayed by the dotted line) of the system results in a large change in force (black arrows) on the steep portion of the curve (low frequencies of stimulation, low $[\text{Ca}^{2+}]_i$) and a small change in force at the top part of the curve (high frequencies of stimulation $[\text{Ca}^{2+}]_i$) (Allen et al., 2008). In physiological contractions, muscle fibres do not all fire at the same rate, which means some muscle fibres were firing submaximally (influenced by PLFFD) whereas others are firing maximally, and thus, not influenced by PLFFD (De Luca & Hostage, 2010). Stimulated contractions make muscle fibres fire at the same rate which reveals the reduction in force caused by the decreased Ca^{2+} response seen in PLFFD.

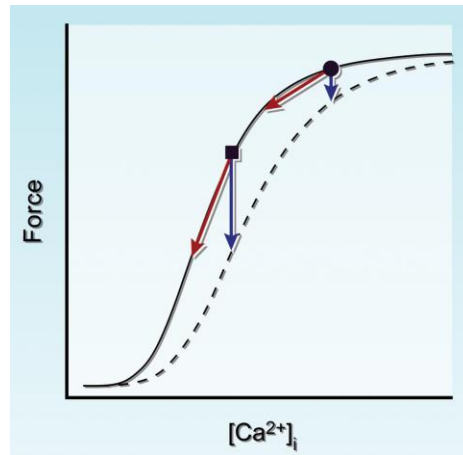


Figure 3. A conceptual activation (x axis) versus force (y axis) curve where the dotted line represents a negative shift in the sensitivity of the system to calcium (Allen et al., 2008).

Important considerations should underscore the measurement of PLFFD. First, PLFFD can be measured by stimulating the muscle at a low frequency of stimulation and then normalizing the low frequency stimulated force to a high frequency stimulated force (which is unaffected by PLFFD). By normalizing, changes in posture, blood flow, and temperature which influence force production can be controlled for when considering PLFFD measurement. Second, it's important to consider how the muscle is stimulated. Studies have used paired pulses a set time apart to simulate a low and high frequency stimulation (Ehrström et al., 2018), however recent literature suggests this will underestimate the magnitude of PLFFD (Ruggiero et al., 2021). Instead of paired pulses, it is generally recommended to continue to use a 1 second train of 10 Hz stimulations followed by at least a 0.5 second train of 100 Hz stimulations to quantify PLFFD (Ruggiero et al., 2021). Third, it is important to consider the method of stimulation. Percutaneous stimulation involves placing electrodes over the muscle belly to stimulate axons of motor nerves. Percutaneous stimulation can be used to effectively measure PLFFD (Martin et al., 2004) when the stimulation voltage effectively recruits as many muscle fibres as possible. Firstly, larger diameter axons have a lower resistance to electrical flow and were stimulated first as stimulation intensity increases (Feiereisen et al., 1997). Second, deeper axons are more difficult to stimulate because of impedance caused by muscle and skin between the axon and the electrode (Feiereisen et al., 1997). If the intensity of stimulation is not sufficient to recruit all muscle fibres due to size or positional impedance, smaller muscle fibres may remain inactive. In order to compensate for potential partial recruitment from percutaneous

stimulation, it is recommended to scale up the stimulating voltage at a high frequency which elicits a contraction equal to 50% of the participant's MVF (Martin et al., 2004).

Once PLFFD measures are taken, important considerations like Post-Activation Potentiation (PAP) may influence interpretation. PAP is an increase in muscle twitch force observed following low frequency stimulations immediately post-contraction and can confound PLFFD measurements. PAP is caused by phosphorylation of regulatory light chains of myosin (RLC) (Rassier & MacIntosh, 2000). High Ca^{2+} concentration (during contraction) results in phosphorylation of RLC, increasing the sensitivity of the contractile proteins to Ca^{2+} and enhancing submaximal contractile response (Rassier & MacIntosh, 2000). Figure 4 demonstrates the large, immediate effect of PAP post-contraction and the exponential decrease of PAP over approximately 5 minutes (MacIntosh & Willis, 2000). When interpreting PLFFD in the 5-10-minute period post contraction, PAP can act as a compensatory mechanism to offset PLFFD, where the force output may seem similar to the force produced at a similar firing rate in an unfatigued, unpotentiated state (Green & Jones, 1989) (Zero et al., 2023). Care must be taken when attempting to interpret PLFFD because changes in force producing capacity and PAP can influence twitch force measurements. However, understanding the duration and rate of recovery transient muscle behaviour changes can provide insight on how to interpret PLFFD.

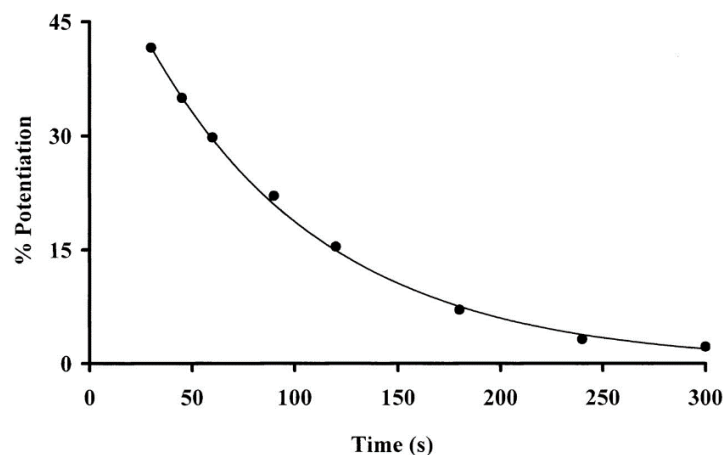


Figure 4. Measures of twitch forces over time, where % Potentiation represents the increase in force seen during a twitch after a potentiating contraction compared to before contraction (MacIntosh & Willis, 2000).

Recovery of force generating capacity of the muscle is quicker than the dissipation of PAP (Carroll et al., 2017) and can influence the measurement of PLFFD as well. The trend of recovery

from PAP varies depending on the amount of work done (Houston & Grange, 1990) due to the competing effects muscle fatigue and PAP. PAP can last up to (or beyond) 10 minutes (Houston & Grange, 1990) (Requena et al., 2008) but submaximal activation results in PAP with a shorter period until dissipation (MacIntosh & Willis, 2000). In cases where a contraction is performed until failure (as seen in Figure 5), a reduction in force producing capacity overwhelms the effect of PAP for a short duration, however once force producing capacity reaches its resting level, PAP is shown to have a greater potentiating effect than when less work is done (Houston & Grange, 1990). This means that the competing effects of muscle fatigue and PAP can cause a delayed increase in twitch force post-contraction, and as such, care must be taken to ensure PAP is consistent during measurement.

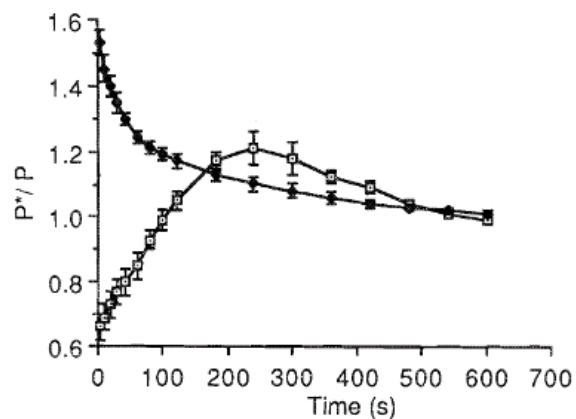


Figure 5. Electrically stimulated isometric twitch tensions over time after a 10-s (solid symbols) and 60-s (open symbols) MVF contraction (Houston & Grange, 1990).

To ensure a consistent level of PAP during PLFFD measurement, muscles may be potentiated using conditioning stimulations (Rashedi & Nussbaum, 2016) or rested before PLFFD measurement to allow PAP to dissipate post-contraction. Resting between work and PLFFD measurement is more viable after lower force contractions because PAP dissipates more quickly when compared to higher force contractions. Even if the muscle is unpotentiated by resting post-contraction, the stimulated contractions used to measure PLFFD may cause PAP, which is why the order of stimulated contractions matter. The muscle should be stimulated at a low frequency before a high frequency because PAP will influence the high frequency measurement much less than the low frequency measurement. Resting a consistent period of time post-contraction and stimulating at a low frequency first when measuring PLFFD can help maintain a low magnitude of PAP in the muscle.

In summary, PLFFD is a form of muscle fatigue that influences twitch forces during low frequency stimulated contractions. Previous research has provided recommendations for order and type of stimulation to effectively measure PLFFD. Force producing capacity and PAP must be taken into consideration when measuring PLFFD or else it will be difficult to tease out individual effects of force producing capacity, PAP, and PLFFD.

2.3 Accumulation and Recovery of PLFFD

Although PLFFD may be important to understand in the context of muscle fatigue and perhaps MSD, few studies have investigated how PLFFD may accumulate and recover in the context of a workplace. Therefore, the following section addresses the current state of the literature as background used to inform the study design for this research. This is followed by two potential gaps in research (PLFFD recovery & force stability) that should be investigated due to their relevance to the workplace.

Dennerlein et. al (2003) examined the effects of PLFFD on successive days of isolated ulnar deviation work. This novel research measured PLFFD before and after a task which was sustainable for an 8-hour workday, whereas previous studies with submaximal interventions intentionally fatigue the participant to a threshold of force production capacity reduction (Kamandulis et al., 2022) (Ruggiero et al., 2021) (Ruggiero et al., 2019) (Bruce et al., 2021). The primary research question of the Dennerlein et al. (2003) paper was whether PLFFD would accumulate on consecutive workdays, which resulted in null findings. Participants worked at two different work rates on separate exposure days (20 RPM and 25 RPM), and at self-selected intensities for each work rate. Even though participants worked for approximately similar workloads in each work rate and accumulated similar amounts of PLFFD, the two exposure intensities had non-significant differences in PLFFD from the first to second workdays. Figure 6 illustrates that participants seemed to accumulate the same amount of PLFFD between work rates (H0 to H8 on day 1 for 20 RPM versus 25 RPM) but recover at different speeds (H8 & H11 of day 1 to H0 of day 2 for 20 RPM versus 25 RPM). Interestingly, the condition with lower force (25 RPM) had a lower amount of recovery than the condition with the higher force (20 RPM) which conflicts with muscle fatigue trends where recovery is expected to be faster after a higher force contraction. The choice to measure PLFFD through stimulating first at 50 Hz and then at 20 Hz may have impacted the effect size of PLFFD changes by potentiating low frequency stimulated contractions. By controlling for workload between participants and intensities,

and measuring PLFFD through accumulation and recovery, one might be able to better understand potential relationships between force and PLFFD recovery.

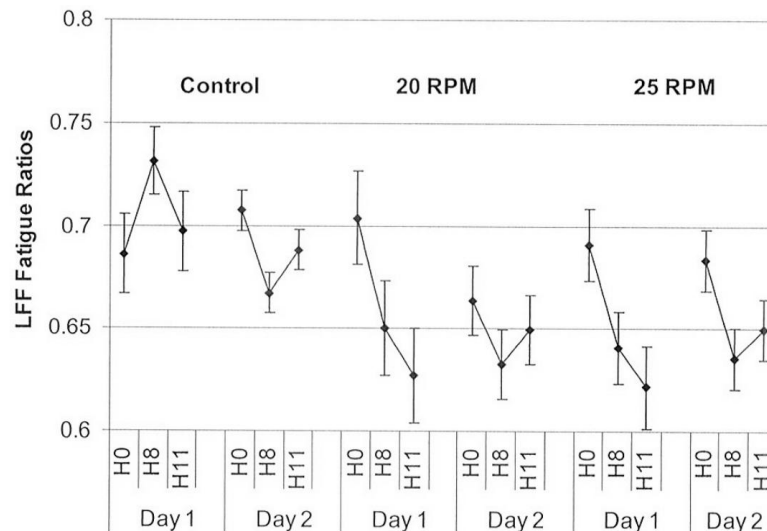


Figure 6. Unnormalized Lo/Hi frequency force ratios across two simulated workdays at two different work rates and a control day (Dennerlein et al., 2003).

An unpublished thesis by Hruschka also observed participants performing repetitive work over multiple days with the intention of assessing whether PLFFD accumulates across days. (Hruschka, 2003). This research was different from the Dennerlein et. al (2003) study because PLFFD was measured intermittently throughout the workload and during recovery. Participants worked at either 25% or 30.9% MVF for an 8-hour workday performing dynamic wrist flexion contractions 15 times per minute. The researchers concluded there was no accumulation effect at the end of the second day but noted that PLFFD accumulated non-significantly faster during the higher force condition and levelled off at around 4-6 hours of exposure for both conditions. The choice to use the last 3 (in a set of 4) measurements of PLFFD for each time point may have reduced the effect size of PLFFD changes by potentiating low frequency stimulated contractions. This research showed a novel plateauing effect where the Lo/Hi ratio remains relatively stable for participants through the latter half of the workday after 4-6 hours (Figure 7). 24 hours after initiating the higher force condition, participants had a lower 20:50 Hz ratio relative to the lower force condition (0.79 ± 0.14 vs 0.88 ± 0.10). Incidental differences between protocols may either be the effect of lack of workload control or a

difference in recovery rate. Further research should investigate how exertion force may impact PLFFD recovery in controlled workloads.

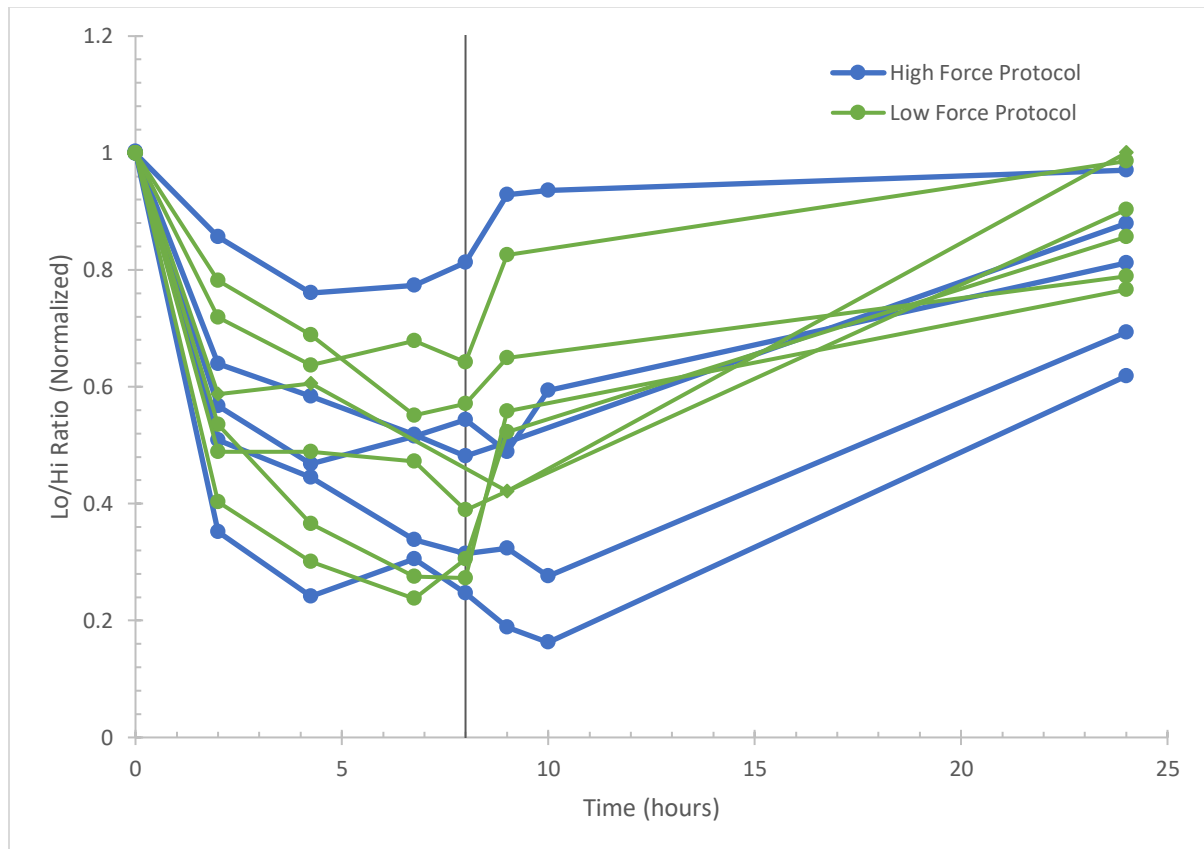


Figure 7. Lo/Hi ratio over the first day of work and recovery for individual participants in either the high or low force protocol where the vertical line represents the end of the work task at 8 hours (Hruschka, 2003).

While it has been shown that the accumulation of PLFFD is workload specific and not force-specific (Iguchi et al., 2008), research has yet to investigate whether the magnitude of force impacts the rate of recovery from PLFFD independent from workload. Because muscle fibre types may recover from muscle fatigue at different rates and are selectively recruited depending on contraction force (De Luca & Hostage, 2010), the muscle may recover from PLFFD at different rates after protocols of identical workloads but different intensities. Therefore, this research aims to elucidate the possible relationship between contraction force and rate of PLFFD recovery.

The presence of PLFFD in the workplace may result in a compromised ability to maintain a constant force, and thus, reduce quality of work. Because PLFFD reduces rate of force development (Rashedi & Nussbaum, 2016), adjustments made to compensate for unexpected changes in force may take longer to produce, resulting in a reduced force stability. Force stability can be defined in two metrics: force variability describes the variation from the mean that a force deviates. Force unsteadiness is defined by the average rate of change of force (Yacoubi & Christou, 2024). High amounts of muscle fatigue result in decreased force stability (Missenard et al., 2008), likely due to decreased thresholds of recruitment of muscle fibres which result in greater changes in force with the same change in central drive (Garland et al., 1994) and higher threshold muscle fibres having a faster rate of contraction. Conversely, with the same increase in central drive, lower rates of force production due to PLFFD could result in lower changes in force, such that there may be more force variability and unsteadiness because there needs to be more central drive to adjust for noise. There is limited research on the potential relationship between PLFFD and force stability, and thus, it should be investigated due to its potential relevance in the workplace.

In summary, studies examining the day-to-day effect of PLFFD accumulation may have revealed an effect of force level on rate of recovery from PLFFD. No studies have examined the recovery from PLFFD when comparing different intensities of the same total workload after a simulated work task. Lastly, no studies have investigated force stability as it relates to PLFFD. Therefore, the current study focuses on identical workloads between protocols while being able to measure PLFFD throughout accumulation, recovery, and 20 hours post-work.

Chapter 3 Methodology

3.1 Research Design

This study used a repeated measures intervention design where participants experienced low force and high force protocols on different days one week apart. Two participants were in the lab at one time on each exposure day to encourage engagement. Participants start times were offset by half an hour to allow measurements to be made while the other works. Protocol work rates were balanced to produce the same total external work each condition. Muscle function was assessed on their intervention (right) and non-intervention (left, control) limb at 8 time points on the intervention day and 1 time point on the follow-up day for each protocol. This study received ethics clearance from the University of Waterloo Research Ethics Board (ORE #46737).

3.2 Population and Sample

A total of 20 participants (9 male, 11 female) were recruited from a convenience sample of university students for this study, demographics information is presented in Table 1. Sex specific changes were not expected (Bruce et al., 2021) but a sex-based analysis is presented in Appendix E for completeness. Participants were not allowed to participate in a collection if they qualified for any of the following: Pain or injury in the shoulders or upper limbs in the past 6 months that has prevented work or activities of daily living; the presence of a medical condition which would prohibit electrical shocking; allergies to silver or adhesives; or an inability to withstand the possible discomfort caused from electrical stimulation. Participants were not permitted to exercise their upper body for the full week preceding an intervention day nor until they completed their follow-up visit. Participants were not permitted to consume caffeine on intervention days nor until they completed their follow-up visit. Participants were not excluded based on hand dominance; however, all participants were required to perform the work task with their right arm. Each recruited participant who completed the setup visit successfully completed the entire study. Extrapolating from data found in previous published literature (Dennerlein et al., 2003), a sample size estimation was performed in G*Power with an estimated effect size of $\eta^2 = 0.083$, 80% power, and an alpha of 0.05. The sample size estimation for research question 1 resulted in a sample size of 24. Data corruption occurred during a collection that resulted in a participant's post-low force protocol follow-up MVF being lost. When MVF data is used, it is a sample of 19 participants, rather than 20.

Table 1 Participant demographics and Maximum Voluntary Force (MVF) of both arms at time point 1 on intervention days

Sex	Stature (m)	Body Mass (kg)	Average MVF (N)
Female	1.66 (± 0.064)	54.3 (± 8.60)	205.952 (± 36.565)
Male	1.79 (± 0.033)	78.8 (± 9.31)	360.850 (± 40.183)

3.3 Data Collection Methods

3.3.1 Dynamometry

A Bertec PY6 load cell measured elbow flexion force at 1000 Hz. The load cell was situated in a forearm jig to prevent arm movement and facilitate consistent placement of the wrist and elbow between collections. The head of the ulna was placed distal to the far side of the load cell, so the shafts of the radius and ulna were resting in a supinated position on the top of the lead cell (Figure 8). A strap bound the forearm to the top of the load cell. An adjustable elbow rest was situated such that the olecranon is resting on a foam pad.

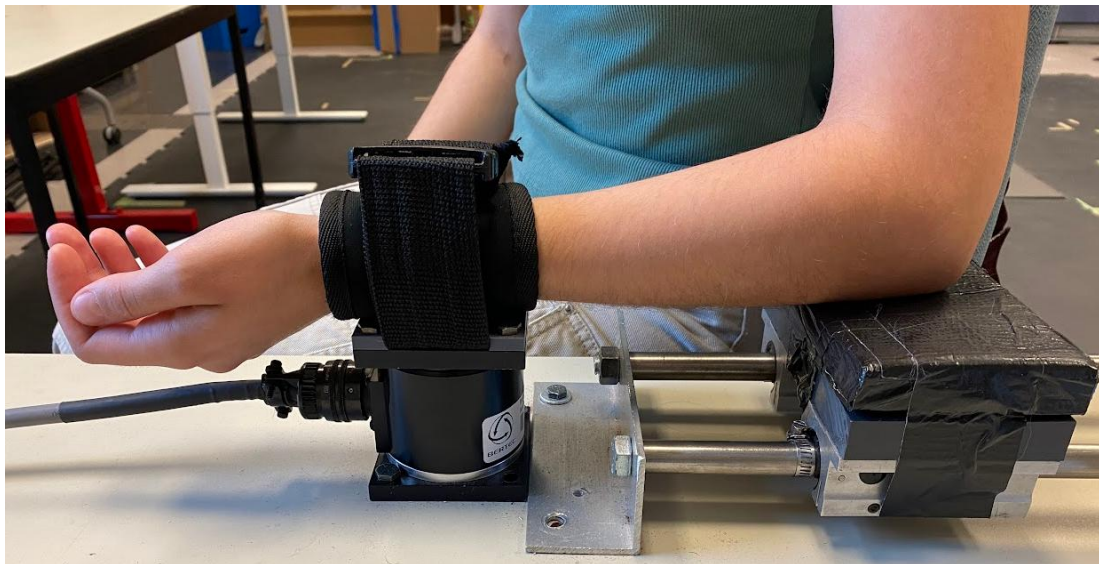


Figure 8 Participant forearm resting in measurement setup. The supinated forearm rests on an adjustable elbow pad and is strapped to a force transducer.

3.3.2 Electromyography

Surface electromyography (sEMG) was collected during voluntary contractions on the force cube to monitor for muscle fatigue accumulation and changes in muscle behaviour in the biceps brachii during intervention days (time points 1-8). EMG data were collected at a sampling rate of 2000 Hz. The skin of the arm over the muscle of interest was cleaned with abrasive gel and alcohol wipes. Recording electrodes had a 2.5 cm interelectrode distance. Electrodes were placed in line with the long axis of the arm while the forearm was supinated and placed laterally to the superior stimulation electrode (Figure 9). EMG electrodes remained on the participant for the full duration of the intervention days and new electrodes were used each visit.

3.3.3 Muscle Stimulator

The biceps brachii was stimulated using a Grass S48 electrical stimulator and SIU5 isolation unit (Grass Instruments, Quincy, MA) preprogrammed to elicit low (10 Hz) and high (100 Hz) trains of stimulation for 1 second (Table 2). One stimulation electrode was placed over the motor point of the biceps brachii, with the other stimulation electrode placed distally on the musculotendinous junction of the biceps brachii (Figure 9).

Table 2. Grass S48 Muscle Stimulator Settings

Train Rate	1 train per second
Train Duration	1000 milliseconds
Stimulation Rate	10 Pulses per second (low frequency) 100 Pulses per second (high frequency)
Delay	0.01 millisecond
Pulse Duration	0.05 milliseconds
Voltage	Increased to maximum amount within participant's bounds of acceptability

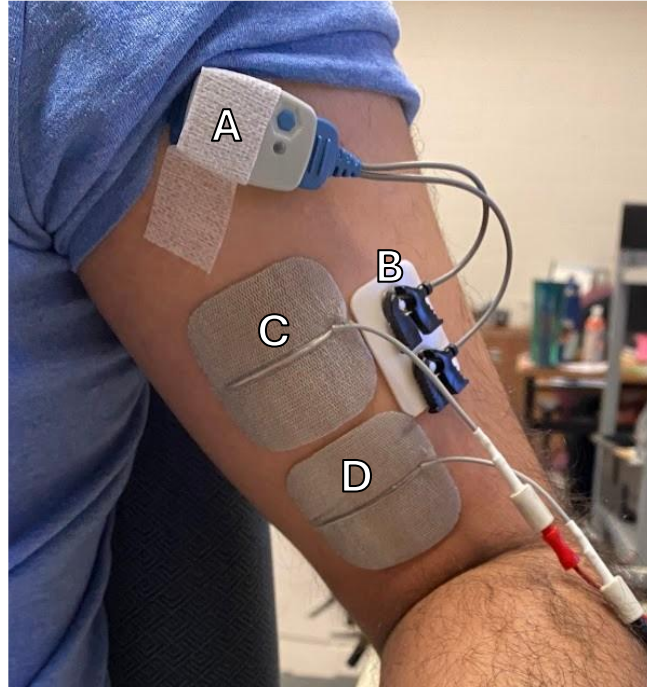


Figure 9 Bilateral upper arm setup, where A is the EMG recording unit, B is the recording electrodes, C is the superior stimulation electrode, and D is the inferior stimulation electrode

3.3.4 Ratings of Perceived Fatigue

A 0-10 Visual Analog Scale (VAS) was used to quantify a participant's perceived level of subjective fatigue. Participants were familiarized with the introduction from the Rating-of-Fatigue Scale (Micklewright et al., 2017) to connect extreme values to past experiences during orientation (Appendix A). The participant was presented a sheet of paper and asked to silently mark on a 10-cm line how they felt, where 0 cm was feeling refreshed and 10 cm was feeling completely exhausted. Each time the VAS was presented to the participant, previous answers were obscured, and the participant was asked to evaluate how they feel with respect to the extremes of the line, rather than relative to their previous answers.

3.3.5 Maximum Force Measurement

A participant's maximum voluntary force (MVF) was measured three times for each arm on the setup day to set the intervention weights and force matching targets. MVFs were measured three times on intervention days, and once on each follow up day to track the progression of muscle fatigue.

The MVFs on the setup day were separated by 2 minutes to facilitate recovery and only initiated once the participant expressed that they were ready to perform another MVF. On intervention days, the participant performed an MVF after the force stability measurement on each arm at time points 1, 5, and 8. The participant also performed an MVF on each follow up day after each force stability measurements. MVF of the participant was determined as the maximum force exerted during a 5-second ramp up, hold, ramp-down protocol. The maximum force from the three contractions for an arm on the setup day was used to normalize the force stability target for that arm and the intervention force for the low and high force protocols.

3.3.6 Stimulation Voltage Setup

The stimulation voltage was determined for each participant on the setup day. Voltage began at 10 volts and then progressively increased by 10 volts after stimulating at 100 Hz for 1 second with 30 seconds of rest until the participant indicated that they wish to have no further voltage increases due to discomfort. The stimulation device used had a 150-volt limit, which some participants were willing to endure. The stimulation voltage determined on the setup day was used for all stimulations that participant experienced in following visits.

3.3.7 Prolonged Low Frequency Force Depression Measurement

PLFFD was measured by recording the force of contraction when the muscle was stimulated at 10 Hz for 1 second, rested for 2 seconds, and stimulated at 100 Hz for 1 second.

3.3.8 Force Stability Measurement

Participants were instructed to apply and hold a static elbow flexion force equal to 30% of their MVF for 10 seconds. Participants had visual feedback of their exerted force and the target force during the task, both of which were extracted from the Z (vertical) axis of the force cube.

3.3.9 Workday Protocol

The workday protocol consisted of four 1-hour segments of isometric work, with 15-minute breaks after each segment. Three hours of rest followed the work protocol. The task was comprised of a weight hanging from the participant's wrist which they isometrically supported during periods of exertion. In order to reduce the risk of muscle fatigue-induced task failure, the balance between duty cycle and intervention weight was determined by the maximum acceptable effort equation (Potvin,

2012), which has been validated to prevent large amounts of muscle fatigue from accumulating (Friedel et al., 2025). The low force condition's weight was equal to 15% MVF, where the participant held the weight for 30 seconds of every minute (50% duty cycle). The high force condition's weight was equal to 25% MVF, where the participant held the weight for 18 seconds of every minute (30% duty cycle). The total cycle time for the task was 1 minute, such the time spent suspending the load within each minute was continuous. A pair of LEDs in the participant's field of view provided an indication on when the weight should be held or rested. When the green LED was lit, the participant was instructed to suspend the weight, and when the red LED was lit, the participant rested the weight and placed their forearm on the armrest of their chair to allow for rest (Figure 10). Adjacent to the LEDs was an LCD screen which displayed a progress bar that filled up for the duration of time that the green LED was lit such that the participant was aware of how much time they had left to hold the weight.



Figure 10 Participant posture during on (left) and off (right) phases of work

Each participant underwent an assessment protocol the start of the day, during each 15-minute break, and at the end of each hour for 3 hours post-work. The assessment protocol included a rating of perceived fatigue on the VAS, and measurements of PLFFD and force stability on the non-intervention (left) arm and then the intervention (right) arm. The measurement of PLFFD and force

stability in the left arm occurred 5 minutes after the cessation of work and the measurement of PLFFD and force stability in the right arm occurred 10 minutes after the cessation of work to ensure there was minimal PAP present in the muscles. At time points 1, 5, 8, and 9 the participant performed an MVF following the force stability measurements on each arm (Figure 11).

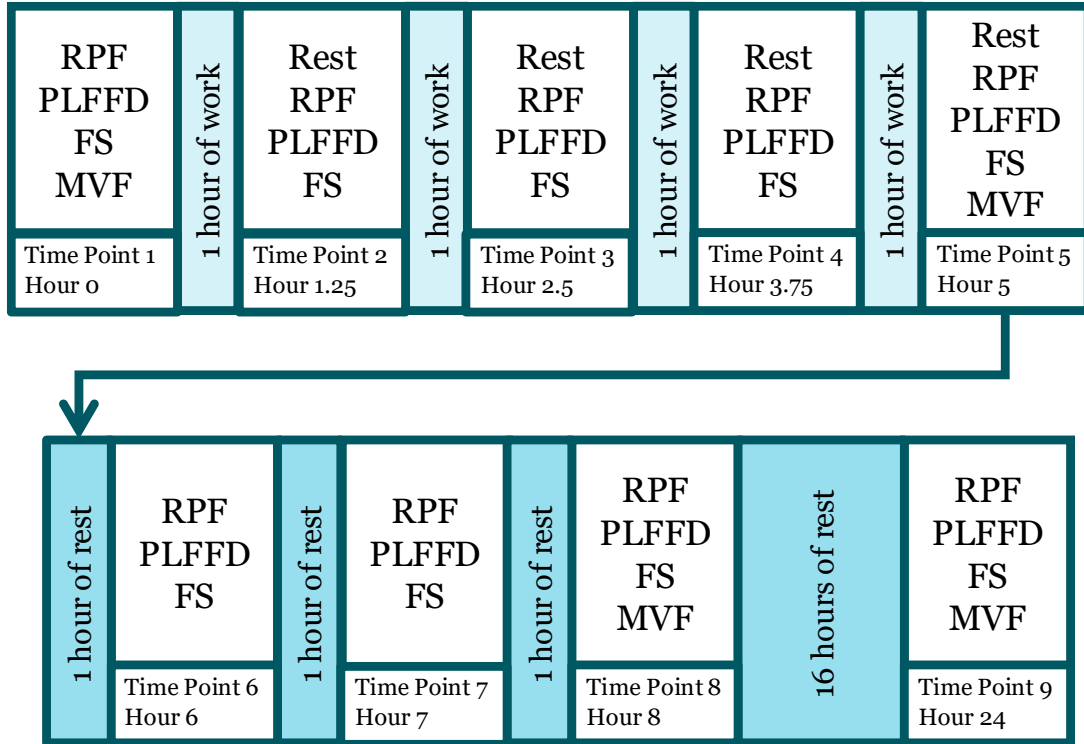


Figure 11. Intervention and follow-up day procedure illustrating when RPF (Rating of Perceived Fatigue), PLFFD (Prolonged Low Frequency Force Depression), FS (Force Stability), and MVF (Maximum Voluntary Force) were measured.

3.4 Data Analysis Methods

Data analysis was performed in MATLAB 2023 and statistical analysis was performed in R Studio. All data was visually screened for errors before filtering, after filtering, and after algorithmic windowing to ensure the data was analyzed properly.

Force data were filtered using a low-pass dual-pass 2nd order 17.5 Hz-cutoff Butterworth filter to remove high frequency noise and create a smooth force profile. The 17.5 Hz cutoff frequency was determined through residual analysis from pilot data. All force data had the resting bias of the arm

removed before calculating the triaxial vector of force application. Force stability, Lo/Hi ratio, and MVF calculations were calculated using the triaxial force vector of the arm. The last 5 second epoch of the 10-second static force hold was used to calculate force stability values (Force coefficient of variation, Equation 1, and force unsteadiness, Equation 2) (Yacoubi & Christou, 2024). The 5 second epoch was algorithmically windowed through the following steps. 1) Calculate the rate of change of force data. 2) Find the peak negative rate of change, which is when the participant is releasing the static hold. 3) Identify the first frame prior to the peak negative rate of change in which the rate of change of force is greater than or equal to 0. 4) Select the epoch of data between that point and 5 seconds prior. Force stability values were normalized to that arm's measurement during first time point for each protocol the participant experiences.

$$\text{Force Coefficient of Variation} = \frac{SD}{\mu}$$

Equation 1. The coefficient of variation is the standard deviation (SD) of the force during a static contraction which has an average force of μ .

$$\text{Force Unsteadiness} = \sqrt{\frac{1}{n} \sum_i \left(\frac{dF}{dt} \right)_i^2}$$

Equation 2. Force unsteadiness is the root mean square of the rate of change of force during a static contraction, where n is the number of samples and i is the frame number of the change in force.

The force recorded during PLFFD stimulations were windowed to separate the 10 Hz from the 100 Hz portion by finding the peak force (start of 100 Hz stimulation) and peak force prior to the 100 Hz stimulation (10 Hz stimulation). The resting force bias between stimulations was subtracted from the maximum force applied during the 10 and 100 Hz stimulations. The ratio between the peak low and high frequency stimulated forces (Lo/Hi) were normalized to the first value taken on each intervention day for each arm.

$$\text{Lo/Hi Ratio} = \frac{\text{Peak 10 Hz force}}{\text{Peak 100 Hz force}}$$

Equation 3. Lo/Hi ratio is the force generated from a 10 Hz stimulation normalized to the force generated from a 100 Hz stimulation.

A zero-lag 2nd order 20Hz-500Hz bandpass filter was applied to EMG data to remove high frequency environmental noise and low frequency cable sway and movement noise (Merletti & Cerone, 2020). No ECG contamination was detected, and thus no filtering was done to remove ECG contamination (Drake & Callaghan, 2006). Mean power frequency was calculated using the entire 5-second epoch in the middle of the force stability task. An activation profile was generated by calculating the RMS (Root Mean Square) of a 1-second sliding window across the whole trial (Cifrek et al., 2009). The activation for a time point was calculated as the average RMS value across the whole 5-second epoch. Activation values were normalized to the maximum RMS EMG during that arm's time point 1 MVF to calculate the normalized activation for that time point. EMG results are presented in Appendix B as a secondary measure.

Ratings of perceived fatigue using the VAS were documented and reported using descriptive statistics. Values were digitized from the paper copy to an excel file through hand-measuring placement of marks on the 10-cm scale with a digital sliding caliper.

To address hypothesis one, a 9x2x2 (time x arm x protocol) repeated measures ANOVA was performed on Lo/Hi ratios. *Post hoc* pairwise testing was then performed with a Holm-Bonferroni correction. All data used in an ANOVA was assessed for normality through a Kolmogorov-Smirnov test and Mauchly's test for sphericity. Data was additionally inspected for skew and kurtosis.

To address hypothesis two, 2 standard multiple regressions were performed to determine how well protocol (low = 0, high = 1) and Lo/Hi ratio predict force variation and unsteadiness. All data used in a regression was assessed for regression assumptions, normality, and homoscedasticity. Time point 1 data was not used in the regressions because all normalized values would be exactly 1.000, biasing the regression toward significance.

Chapter 4 Results

Figure 12 illustrates the progression of perceived fatigue over time between protocols. RPF increased from baseline (baseline: 1.06 ± 1.10 cm) through the four work hours and decreased through the three rest hours (mean of all time points: 2.75 ± 2.04 cm), returning to approximately baseline at the follow-up visit (follow up: 1.29 ± 1.30 cm). Progression of perceived fatigue was similar between both protocols (Low Force: 2.62 ± 2.02 cm, High Force: 2.88 ± 2.06 cm) and both weeks (Week 1: 2.78 ± 2.08 cm, Week 2: 2.72 ± 2.00 cm).

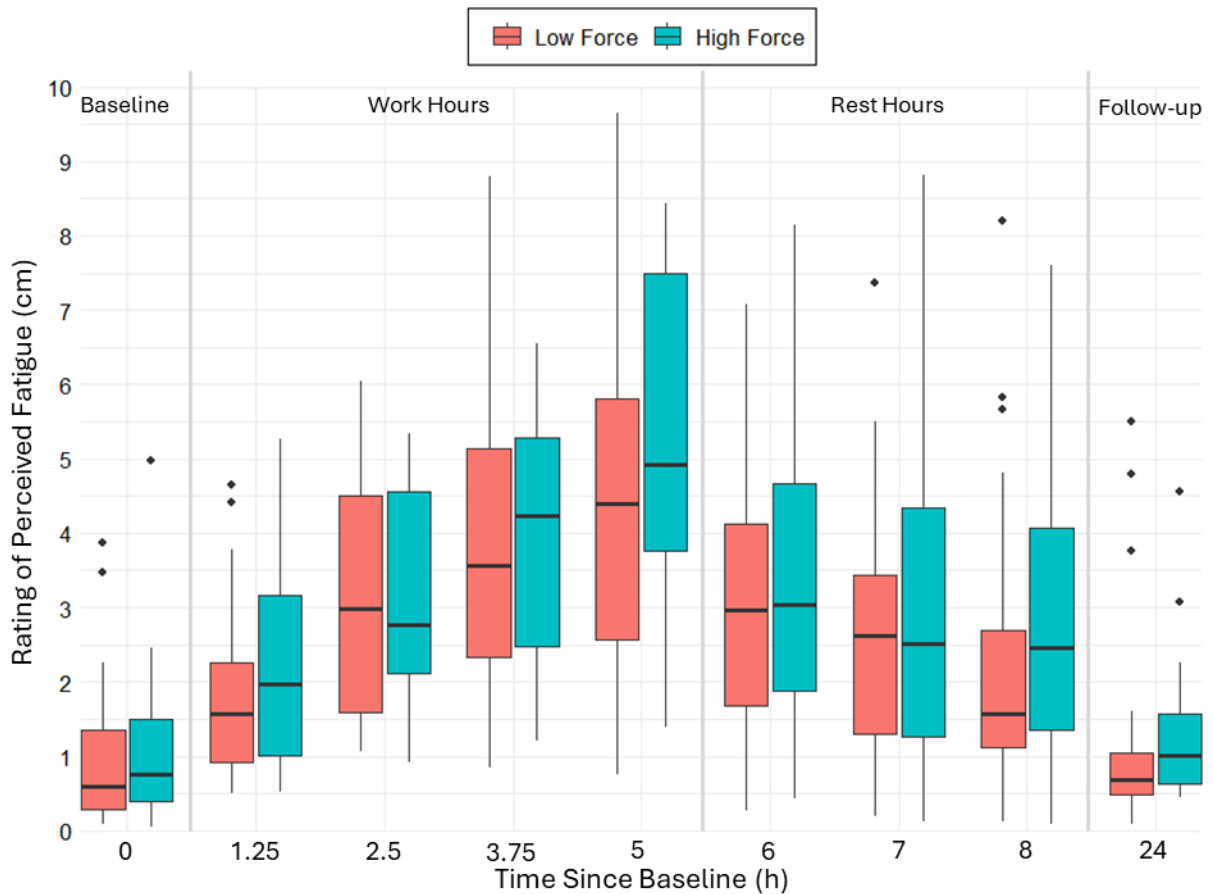


Figure 12 Rating of perceived fatigue over time between protocols across an intervention day and follow up visit broken down between work hours and rest hours.

Lo/Hi ratio met ANOVA assumptions of normality. The ANOVA revealed a significant main effect of time ($F_{(8, 152)} = 8.079$, $p < 0.001$, $\eta_p^2 = 0.298$) and interaction effect of time and arm ($F_{(8, 152)} =$

4.845, $p = 0.001$, $\eta_p^2 = 0.203$) on Lo/Hi ratio. Mauchly's test for sphericity was significant for both the main effect and interaction effect, so the Greenhouse-Geisser correction was applied. Post-hoc testing of the main effect of time revealed that Lo/Hi ratio was significantly different from baseline at all time points post-baseline (See **Error! Reference source not found.** in Appendix C). However, post-hoc testing of the interaction effect of time on the control arm revealed that Lo/Hi ratio of the control arm was significantly different from baseline at time points 7 and 8 (Table 3). Post-hoc testing of the interaction effect of time on the intervention arm revealed that Lo/Hi ratio was significantly different from baseline at all time points (Table 4). The intervention arm was significantly different from the control arm at time points 2 ($p = 0.026$), 3 ($p = 0.021$), 4 ($p = 0.011$), and 5 ($p = 0.002$). The intervention arm was not significantly different from the control arm at time points 1 ($p = 0.33$), 6 ($p = 0.49$), 7 ($p = 0.98$), 8 ($p = 0.25$), and 9 ($p = 0.94$). No significant effects of protocol were detected.

Table 3 Grouped means and SD of Lo/Hi ratio from an electrically evoked contraction for an interaction effect of time on Control arm.

Time Since Baseline (h)	Mean Lo/Hi ratio ($\pm$ SD)	Mean change from baseline ($\pm$ SD)	Change from baseline p-value
0	0.26 ($\pm$ 0.08)	--	--
1.25	0.26 ($\pm$ 0.08)	+0.00 ($\pm$ 0.04)	1.000
2.5	0.25 ($\pm$ 0.08)	-0.01 ($\pm$ 0.05)	1.000
3.75	0.24 ($\pm$ 0.07)	-0.02 ($\pm$ 0.05)	0.462
5	0.25 ($\pm$ 0.07)	-0.01 ($\pm$ 0.05)	1.000
6	0.24 ($\pm$ 0.07)	-0.02 ($\pm$ 0.05)	0.462
7	0.22 ($\pm$ 0.06)	-0.04 ($\pm$ 0.05)	<0.001
8	0.22 ($\pm$ 0.08)	-0.04 ($\pm$ 0.06)	0.004
24	0.23 ($\pm$ 0.08)	-0.03 ($\pm$ 0.04)	0.123

Table 4 Grouped means and SD of Lo/Hi ratio from an electrically evoked contraction for an interaction effect of time on Intervention arm.

Time Since Baseline (h)	Mean Lo/Hi ratio ($\pm$ SD)	Mean change from baseline ($\pm$ SD)	Change from baseline p-value
0	0.28 ($\pm$ 0.11)	--	--
1.25	0.22 ($\pm$ 0.11)	-0.06 ($\pm$ 0.08)	0.003
2.5	0.21 ($\pm$ 0.11)	-0.07 ($\pm$ 0.11)	0.012
3.75	0.20 ($\pm$ 0.10)	-0.08 ($\pm$ 0.10)	<0.001
5	0.21 ($\pm$ 0.10)	-0.07 ($\pm$ 0.09)	0.001
6	0.23 ($\pm$ 0.10)	-0.05 ($\pm$ 0.08)	0.034
7	0.22 ($\pm$ 0.09)	-0.06 ($\pm$ 0.08)	0.004
8	0.20 ($\pm$ 0.09)	-0.07 ($\pm$ 0.09)	<0.001
24	0.23 ($\pm$ 0.10)	-0.04 ($\pm$ 0.06)	0.004

Figure 13 illustrates the interaction effect of arm over time on Lo/Hi ratio. Lo/Hi ratio is normalized to baseline to remove between-participant-effects from the graph. The significant interaction effect of arm and time can be seen through time points 2-9 where normalized Lo/Hi ratio

in the intervention arm is significantly lower than baseline. Figure 14 illustrates normalized Lo/Hi ratio over time between protocol and arm but no significance is present.

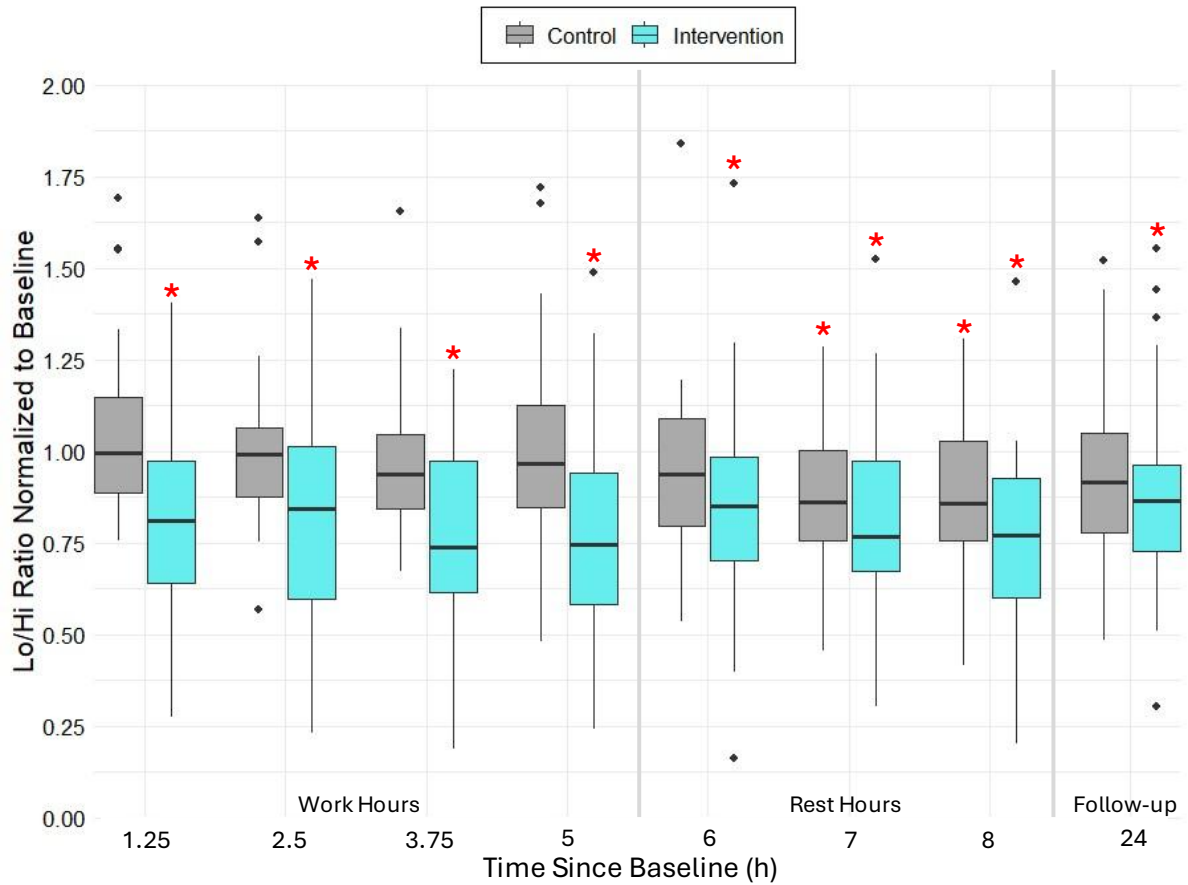


Figure 13 Normalized Lo/Hi ratio from an electrically evoked contraction over time grouped by arm across an intervention day and follow up visit broken down between work hours and rest hours. An asterisk (*) is shown over boxes that are significantly different from baseline

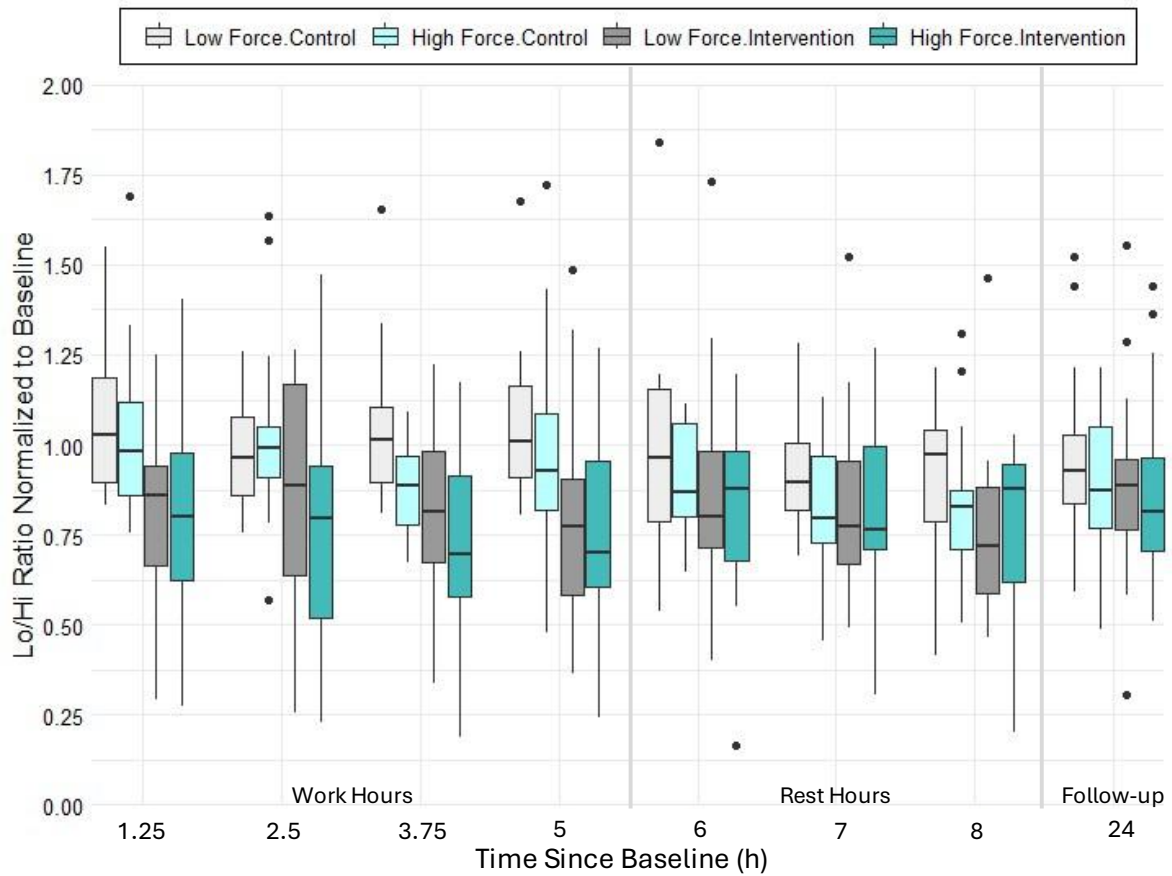


Figure 14 Normalized Lo/Hi ratio from an electrically evoked contraction over time grouped by protocol and arm across an intervention day and follow up visit broken down between work hours and rest hours.

A 4x2x2 (time x arm x protocol) repeated measures ANOVA was performed on MVF data. ANOVA assumptions of normality were met. The ANOVA revealed a significant main effect of time ($F_{(3, 54)} = 10.554, p < 0.001, \eta_p^2 = 0.370$) and a significant interaction effect of time and arm ($F_{(3, 54)} = 12.575, p < 0.001, \eta_p^2 = 0.411$). Mauchly's test for sphericity was significant for time, so the Greenhouse-Geisser correction was applied. Post-hoc testing of the main effect of time revealed that MVF was significantly different from baseline (271.6 ± 85.5 N) during post-work (255.8 ± 81.3 N, $p < 0.001$) and post-rest (265.1 ± 87.5 N, $p = 0.016$) assessments but not during the follow-up (267.9 ± 88.3 N, $p = 0.285$) visit. Post-hoc testing of the interaction effect of time on the control arm revealed

no significant differences compared to baseline (264.9 ± 81.3 N) in MVF across time (Post-work: 260.2 ± 81.0 N, $p = 0.640$; Post-rest: 266.9 ± 84.6 N, $p = 1.000$; Follow-up: 264.3 ± 84.4 N, $p = 1.000$). Post-hoc testing of the interaction effect of time on the intervention arm revealed that MVF was significantly different from baseline (278.3 ± 90.1 N) during post-work (251.4 ± 82.5 N, $p < 0.001$) and post-rest (263.2 ± 91.4 N, $p < 0.001$) assessments but not during the follow-up (271.5 ± 93.1 N, $p = 0.081$) visit. Figure 15 illustrates the interaction effect of arm over time on MVF. MVF is normalized to baseline to remove between-participant-effects from the graph. The significant interaction effect of arm and time can be seen in post-work and post-rest time points where MVF is significantly lower than baseline (which is 1.000). Figure 16 illustrates normalized MVF over time between protocol and arm but no significance is present.

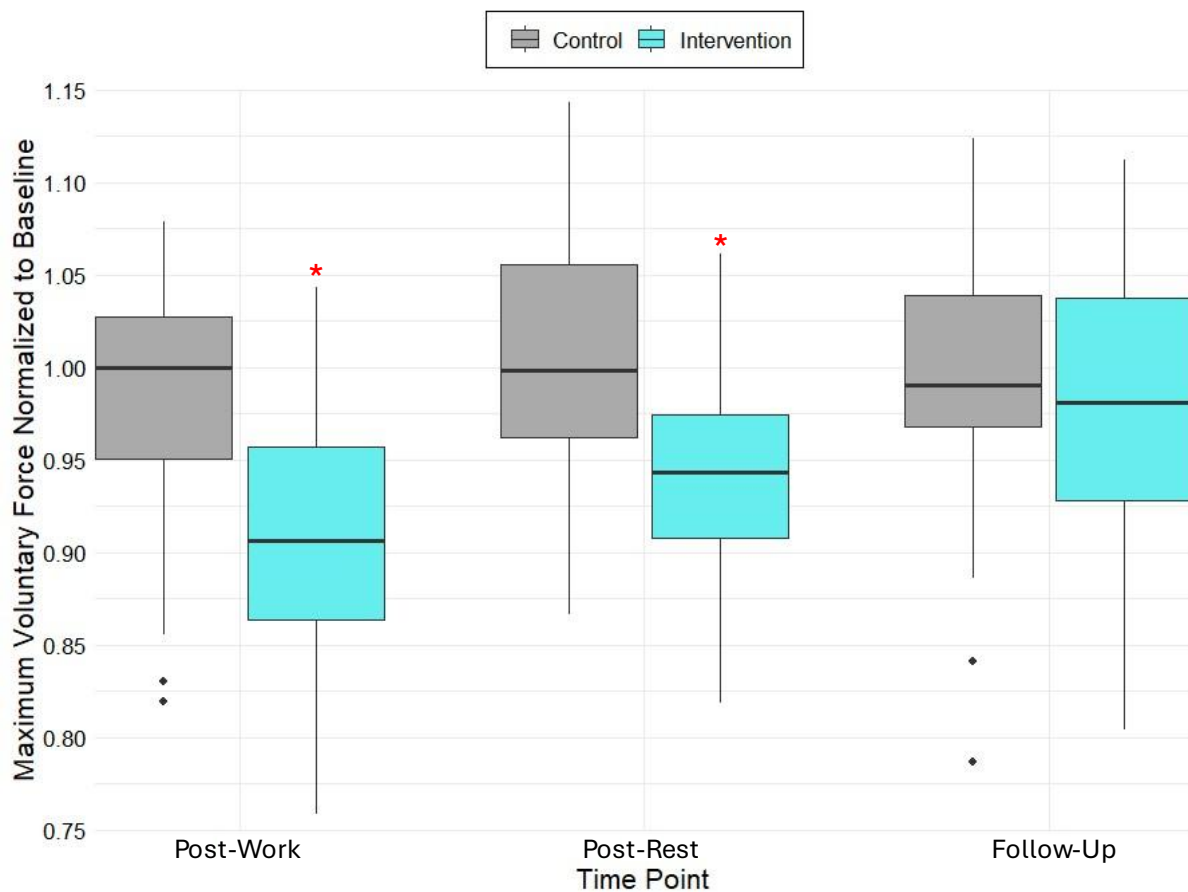


Figure 15 Normalized MVF over time grouped by arm across an intervention day and follow up visit. An asterisk (*) is shown over boxes that are significantly different from baseline

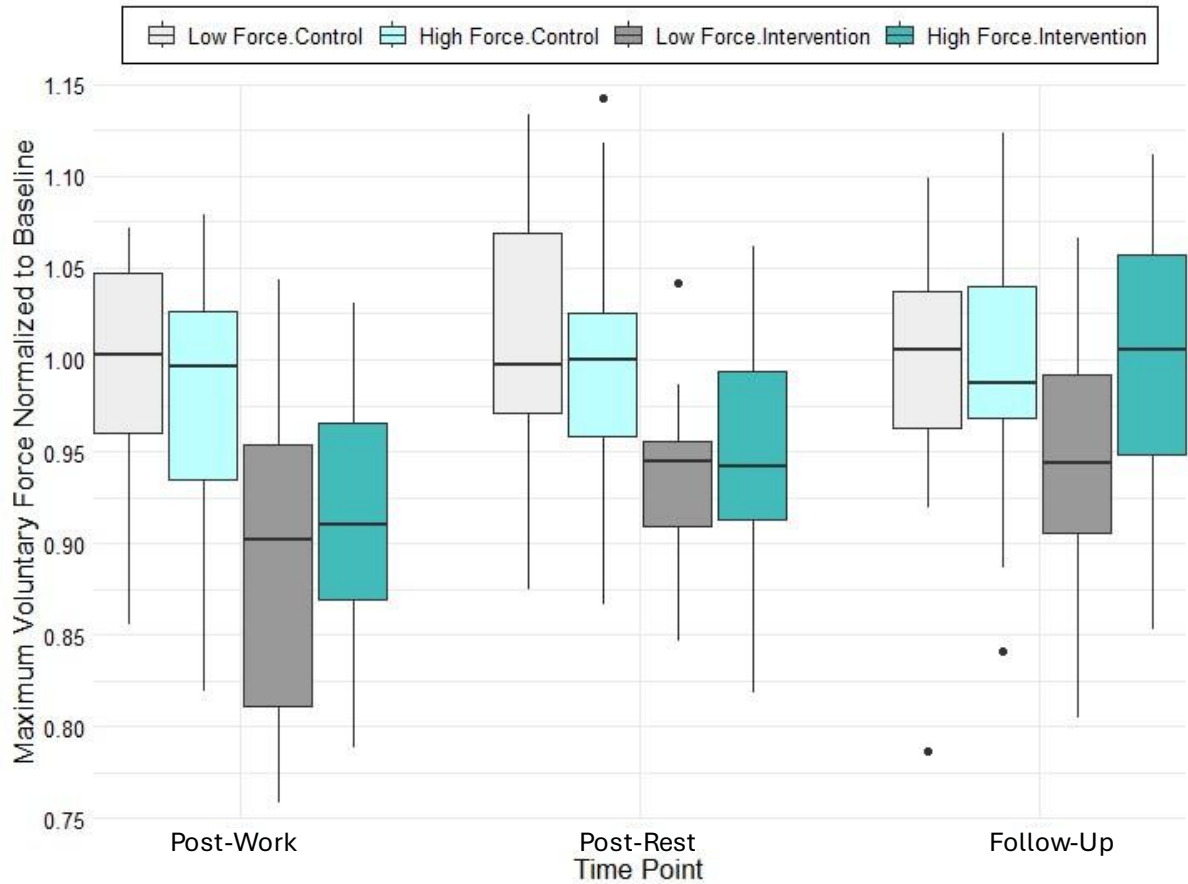


Figure 16 Normalized MVF over time grouped by protocol and arm across an intervention day and follow up visit.

All data used in regressions met core assumptions for performing a regression: Continuous & categorical predictors, continuous outcome, nonzero variance, mean of residuals was nearly zero, and there were many more observations than predictors. Some assumptions were not met, but could not have been, considering the study design: order effects and independence. Normalized Lo/Hi ratio, normalized MVF, normalized force variability, and normalized force unsteadiness had homoscedasticity and normality of residuals within bounds of acceptability. Normalized force variability and normalized force unsteadiness had outliers but did not have highly influential points.

The fitted regression model was: Normalized Force Variability = $1.293 - 0.131 * (\text{Normalized Lo/Hi Ratio}) - 0.062 * (\text{Protocol})$ where protocol was coded as 0 for the low force protocol and 1 for the high force protocol. The overall regression was statistically significant ($R^2 =$

0.010, $F_{(2, 637)} = 3.083$, $p = 0.046$). Normalized lo/hi ratio did not significantly predict normalized force variability ($p = 0.056$). Protocol did not significantly predict normalized force variability ($p = 0.078$). Normalized force variability and Lo/Hi ratio are plotted in Figure 17 with lines of best fit for the data grouped by protocol.

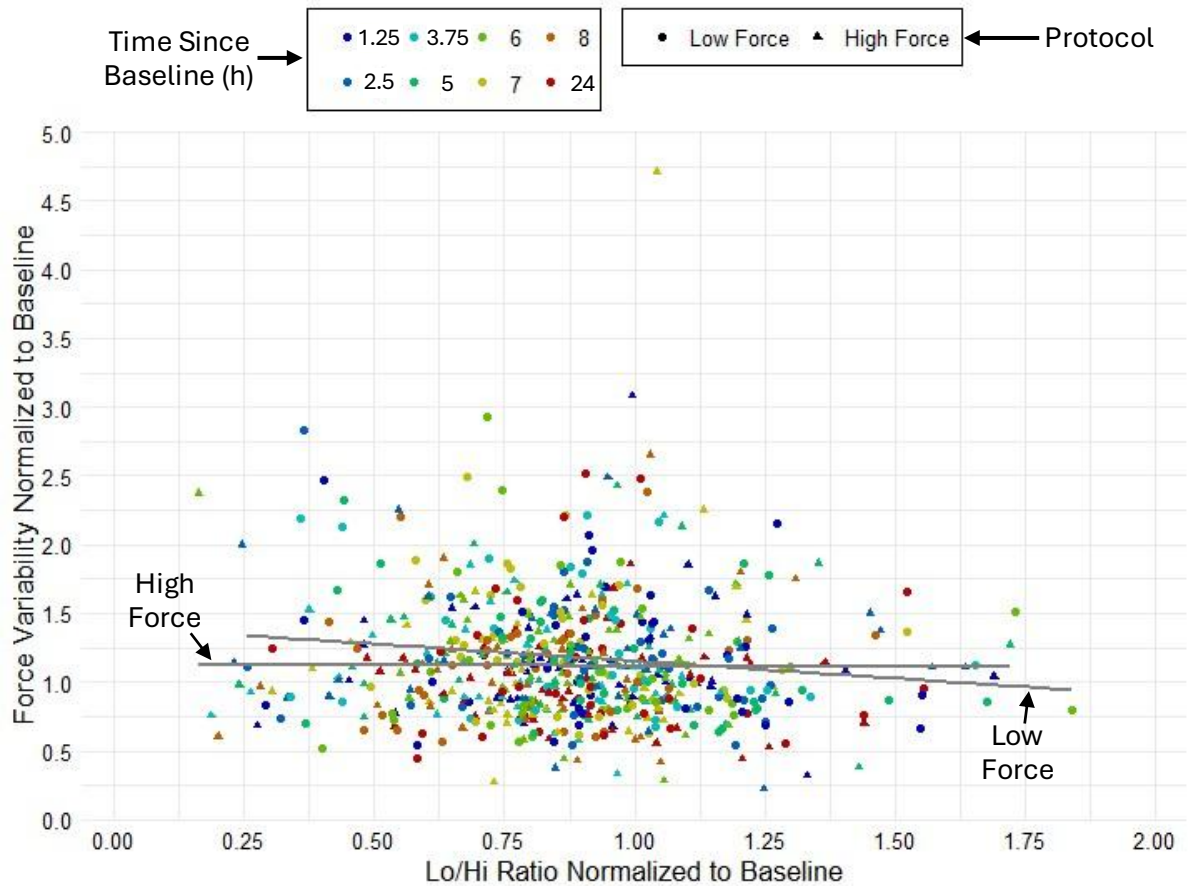


Figure 17 Normalized force variability during a force matching task plotted against normalized Lo/Hi ratio from an electrically evoked contraction grouped by protocol and time since baseline where each point on the figure is a single force matching task from a participant. Lines of best fit represent the regression model of normalized Lo/Hi ratio and protocol predicting force variability.

The fitted regression model for normalized force unsteadiness was: Normalized Force Unsteadiness = $1.330 - 0.232 * (\text{Normalized Lo/Hi ratio}) + 0.034 * (\text{Protocol})$ where Protocol was coded as 0 for the low force protocol and 1 for the high force protocol. The overall regression was statistically significant ($R^2 = 0.035$, $F_{(2, 637)} = 10.39$, $p < 0.001$). Normalized lo/hi ratio significantly

predicted normalized force variability ($p < 0.001$). Protocol did not significantly predict normalized force variability ($p = 0.230$). Normalized force unsteadiness and Lo/Hi ratio are plotted in Figure 18 with lines of best fit for the data grouped by protocol.

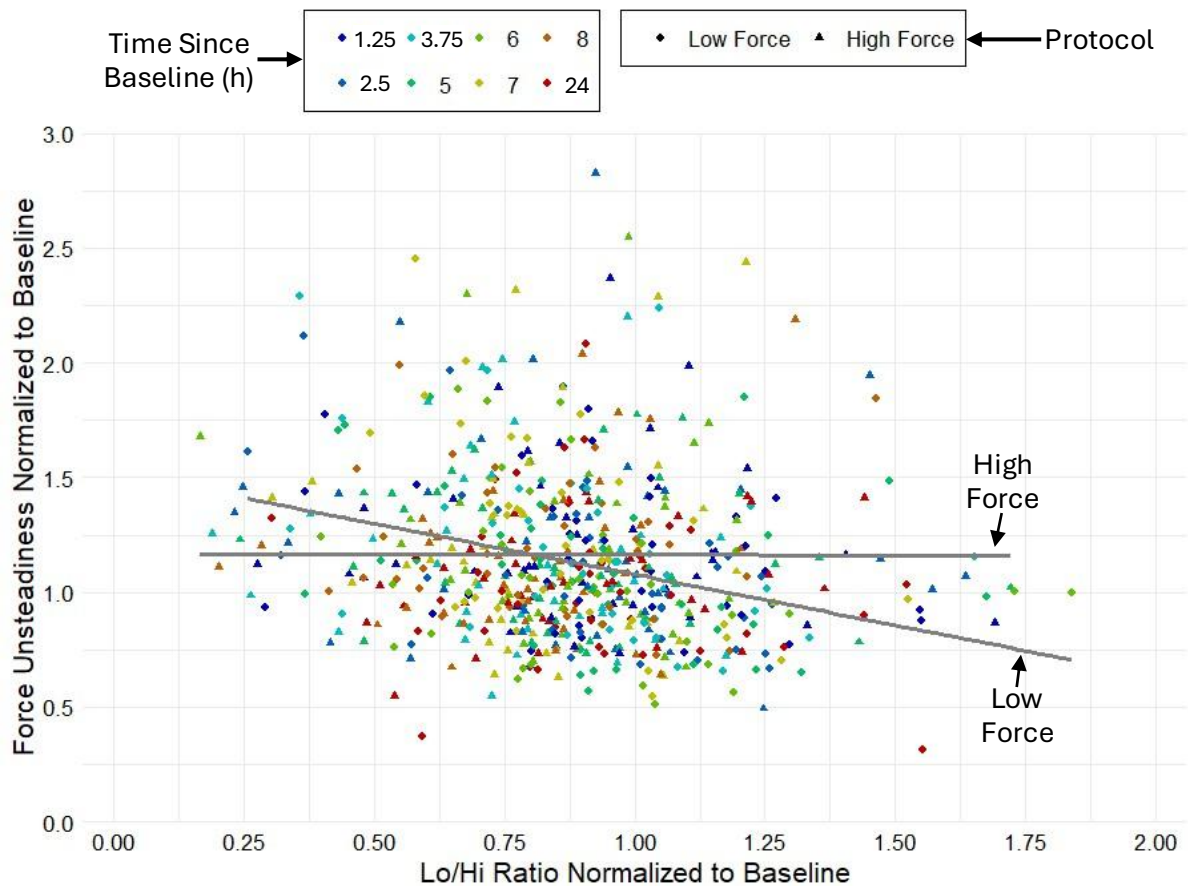


Figure 18 Normalized force unsteadiness during a force matching task plotted against normalized Lo/Hi ratio from an electrically evoked contraction grouped by protocol and time since baseline where each point on the figure is a single force matching task from a participant. Lines of best fit represent the regression model of normalized Lo/Hi ratio and protocol predicting force unsteadiness.

A secondary analysis was performed on force stability data using MVF measures as a predictor in conjunction with protocol. Two multiple regressions were performed to determine how well MVF and protocol predict force normalized variability and normalized force unsteadiness.

The fitted regression model was: Normalized Force Variability = $2.153 - 1.033 * (\text{Normalized MVF}) - 0.076 * (\text{Protocol})$ where Protocol was coded as 0 for the low force protocol and

1 for the high force protocol. The overall regression was statistically significant ($R^2 = 0.047$, $F_{(2, 225)} = 5.591$, $p = 0.004$). Normalized maximum voluntary force significantly predicted normalized force variability ($p = 0.003$). Protocol did not significantly predict normalized force variability ($p = 0.163$). Normalized force variability and MVF are plotted in Figure 19 with lines of best fit for the data grouped by protocol.

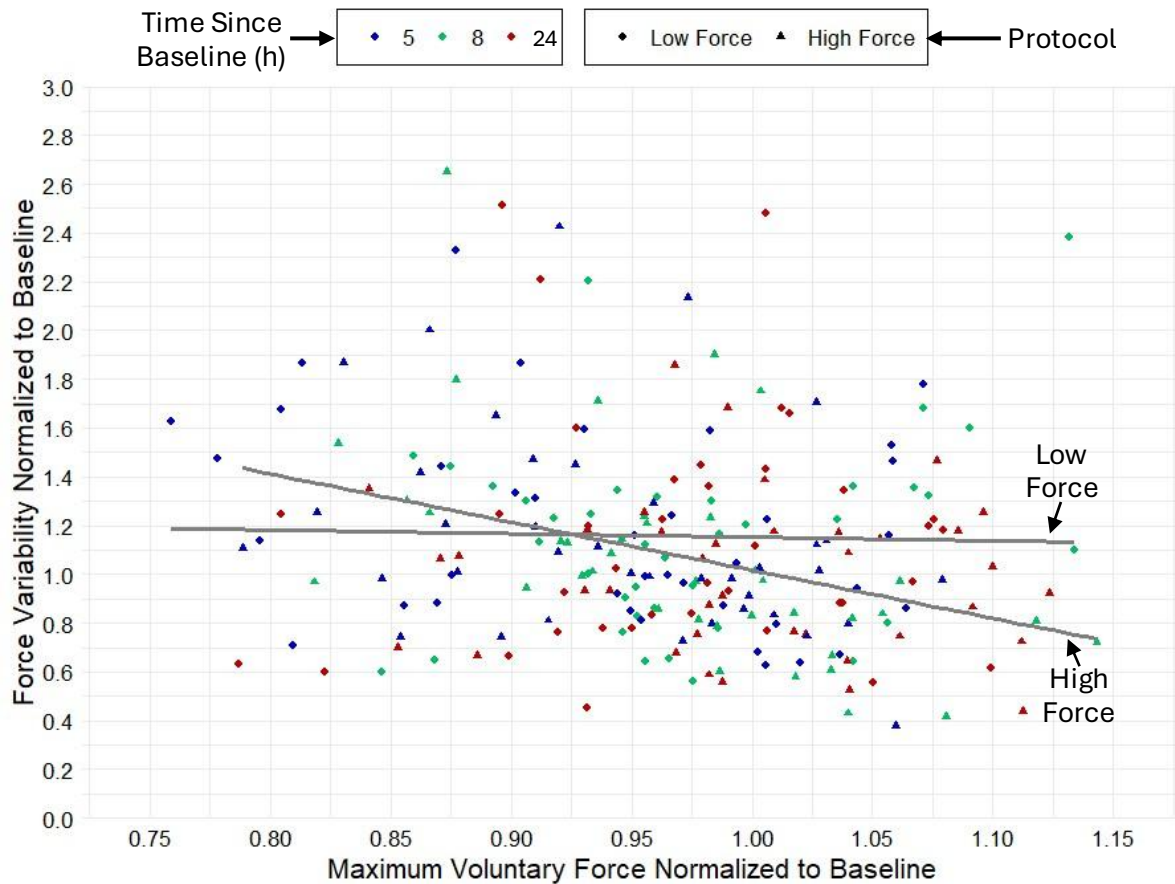


Figure 19 Normalized force variability plotted against normalized MVF grouped by protocol and time since baseline where each point on the figure is a single MVF from a participant. Lines of best fit represent the regression model of normalized MVF and protocol predicting force variability.

The fitted regression model was: Normalized Force Unsteadiness = $2.390 - 1.327 * (\text{Normalized MVF}) + 0.004 * (\text{Protocol})$ where Protocol was coded as 0 for the low force protocol and 1 for the high force protocol. The overall regression was statistically significant ($R^2 = 0.116$, $F_{(2, 225)} = 14.78$, $p < 0.001$). Normalized maximum voluntary force significantly predicted normalized

force unsteadiness ($p < 0.001$). Protocol did not significantly predict normalized force unsteadiness ($p = 0.907$). Normalized force unsteadiness and MVF are plotted in Figure 20 with lines of best fit for the data grouped by protocol.

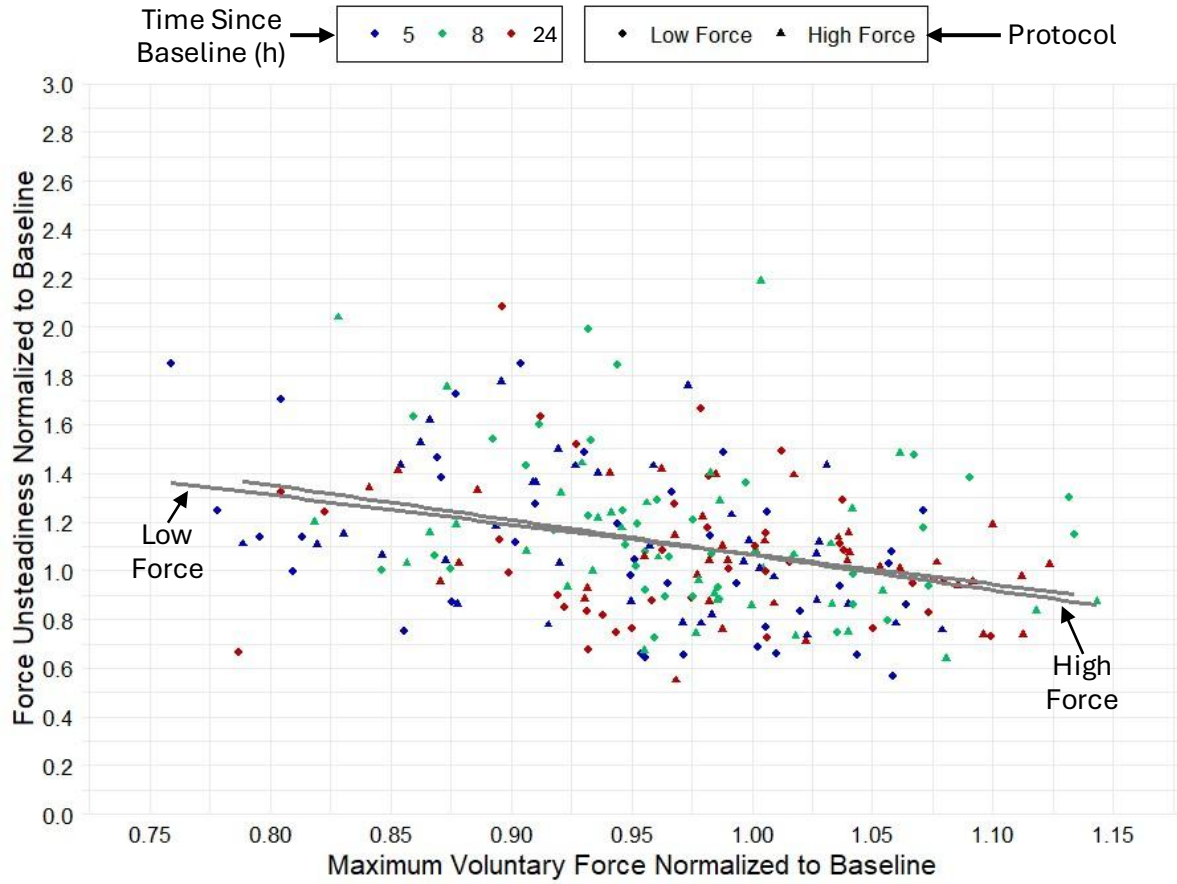


Figure 20 Normalized force unsteadiness plotted against normalized MVF grouped by protocol and time since baseline where each point on the figure is a single MVF from a participant. Lines of best fit represent the regression model of normalized Lo/Hi ratio and protocol predicting force unsteadiness. A tertiary analysis was performed on force stability data by using a 9x2x2 (time x arm x protocol) repeated measures ANOVA to detect differences across time points between arms and protocol on non-normalized force variability and non-normalized force unsteadiness data.

The non-normalized force variability data met the ANOVA assumptions of normality. The ANOVA detected a significant main effect of arm ($F_{(8, 152)} = 11.059$, $p = 0.004$, $\eta_p^2 = 0.370$) and a significant interaction effect of time and arm ($F_{(8, 152)} = 3.187$, $p = 0.015$, $\eta_p^2 = 0.144$) on force

variability. Mauchly's test for sphericity was significant for the interaction effect of time and arm, so the Greenhouse-Geisser correction was applied. The intervention arm (0.0185 ± 0.0087) had a significantly different force variability compared to the control arm (0.0158 ± 0.0058). Post-hoc testing of the interaction effect of time and arm on force variability resulted in no significant differences from baseline in either arm (Table 5 and **Error! Reference source not found.**).

Table 5 Grouped means and SD of force variability during a force matching task for an interaction effect of time on Control arm.

Time Since Baseline (h)	Mean force variability ($\pm$ SD)	Mean change from baseline ($\pm$ SD)	Change from baseline p-value
0	1.61e-2 (± 7.6 e-3)	--	--
1.25	1.69e-2 (± 5.8 e-3)	+0 (± 7.8 e-3)	1.000
2.5	1.61e-2 (± 5.2 e-3)	+0 (± 7.8 e-3)	1.000
3.75	1.56e-2 (± 4.5 e-3)	-5e-4 (± 6.9 e-3)	1.000
5	1.62e-2 (± 6.3 e-3)	+1e-4 (± 7.6 e-3)	1.000
6	1.44e-2 (± 5.2 e-3)	-1.7e-3 (± 7.2 e-3)	1.000
7	1.60e-2 (± 6.3 e-3)	-1e-4 (± 8.4 e-3)	1.000
8	1.64e-2 (± 5.8 e-3)	+3e-4 (± 7.4 e-3)	1.000
24	1.50e-2 (± 5.2 e-3)	-1.1e-3 (± 6.8 e-3)	1.000

Table 6 Grouped means and SD of force variability during a force matching task for an interaction effect of time on Intervention arm.

Time Since Baseline (h)	Mean force variability ($\pm$ SD)	Mean change from baseline ($\pm$ SD)	Change from baseline p-value
0	1.62e-2 (± 5.9 e-3)	--	--
1.25	1.78e-2 (± 6.2 e-3)	+1.6e-3 (± 5.8 e-3)	1.000
2.5	1.90e-2 (± 7.2 e-3)	+2.8e-3 (± 6.6 e-3)	0.358

3.75	1.92e-2 ($\pm 8.8\text{e-}3$)	+3.0e-3 ($\pm 7.5\text{e-}3$)	0.415
5	2.02e-2 ($\pm 1.13\text{e-}2$)	+4.0e-3 ($\pm 8.0\text{e-}3$)	0.112
6	1.97e-2 ($\pm 6.8\text{e-}3$)	+3.5e-3 ($\pm 7.2\text{e-}3$)	0.118
7	2.09e-2 ($\pm 1.45\text{e-}2$)	+4.7e-3 ($\pm 1.28\text{e-}2$)	0.683
8	1.67e-2 ($\pm 6.9\text{e-}3$)	+6e-4 ($\pm 5.6\text{e-}3$)	1.000
24	1.66e-2 ($\pm 5.9\text{e-}3$)	+4e-4 ($\pm 5.7\text{e-}3$)	1.000

Figure 21 displays force variability over time between arm normalized to baseline to remove between-participant-effects from the graph. The significant main effect can be seen where the intervention arm as a group has a higher force variance than the control arm. No significant

interaction effects are present. Figure 22 displays normalized force variability over time between protocol and arm but no significance is present.

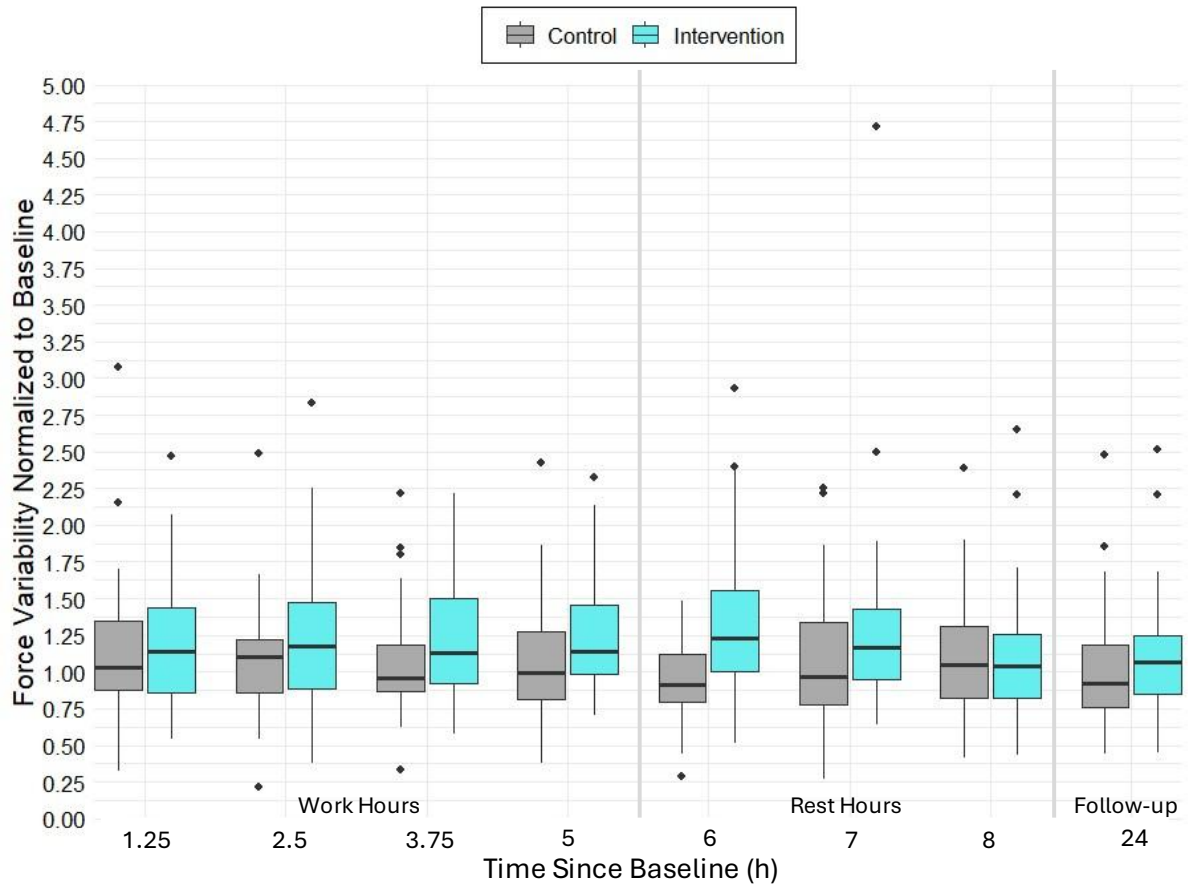


Figure 21 Normalized force variability during a force matching task over time grouped by arm across an intervention day and follow up visit broken down between work hours and rest hours. No significant time-arm interaction is present.

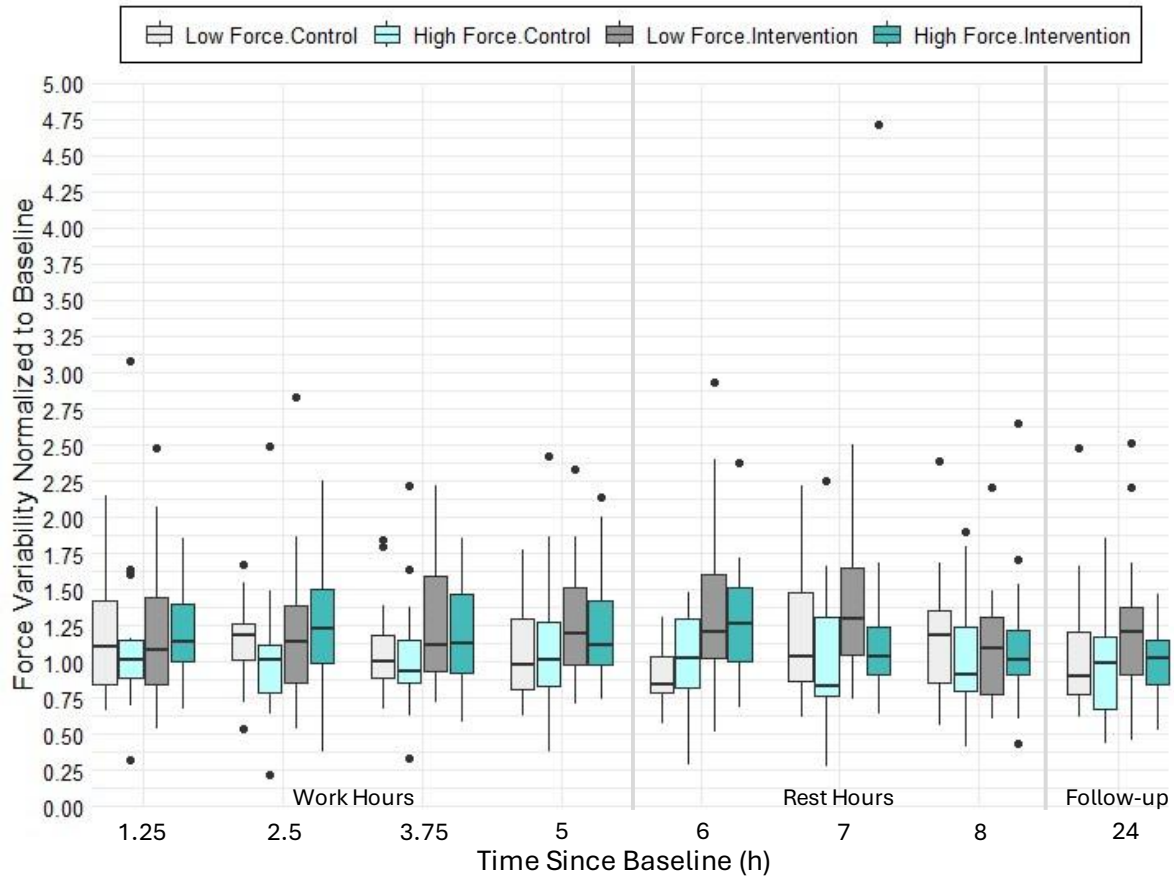


Figure 22 Normalized force variability during a force matching task over time grouped by protocol and arm across an intervention day and follow up visit broken down between work hours and rest hours.

The non-normalized force unsteadiness data met the ANOVA assumptions of normality. The ANOVA detected significant main effects of arm ($F_{(1, 19)} = 8.109$, $p = 0.001$, $\eta_p^2 = 0.299$) and time ($F_{(8, 152)} = 3.093$, $p = 0.022$, $\eta_p^2 = 0.140$) and a significant interaction effect of time and arm ($F_{(8, 152)} = 6.372$, $p < 0.001$, $\eta_p^2 = 0.251$) on force unsteadiness. Mauchly's test for sphericity was significant for the main effect of time and interaction effect of time and arm, so the Greenhouse Geisser correction was applied. The intervention arm (26.368 ± 18.291 N/s, $p < 0.001$) had a significantly different force unsteadiness compared to the control arm (19.740 ± 12.002 N/s). Post-hoc testing of the main effect of time on force unsteadiness revealed a significant difference between baseline and time point 2 (See **Error! Reference source not found.** in Appendix C). Post-hoc testing of the interaction effect of time on the control arm revealed that force unsteadiness was not significantly different from baseline

at any time points (Table 7). Post-hoc testing of the interaction effect of time on the intervention arm revealed that force unsteadiness was different from baseline at all time points aside from time point 9 (Table 8).

Table 7 Grouped means and SD of force unsteadiness during a force matching task for an interaction effect of time on Control arm.

Time Since Baseline (h)	Mean force unsteadiness (N/s) ($\pm$ SD)	Mean change from baseline (N/s) ($\pm$ SD)	Change from baseline p-value
0	21.1 ($\pm$ 13.8)	--	--
1.25	20.7 ($\pm$ 12.5)	-0.4 ($\pm$ 4.7)	1.000
2.5	19.1 ($\pm$ 11.5)	-2.0 ($\pm$ 5.7)	0.989
3.75	19.5 ($\pm$ 11.5)	-1.5 ($\pm$ 5.4)	1.000
5	18.7 ($\pm$ 10.9)	-2.4 ($\pm$ 5.9)	0.521
6	18.9 ($\pm$ 11.8)	-2.2 ($\pm$ 6.0)	0.880
7	19.9 ($\pm$ 12.1)	-1.1 ($\pm$ 6.5)	1.000
8	20.4 ($\pm$ 12.5)	-0.6 ($\pm$ 5.8)	1.000
24	19.5 ($\pm$ 12.3)	-1.6 ($\pm$ 6.0)	1.000

Table 8 Grouped means and SD of force unsteadiness during a force matching task for an interaction effect of time on Intervention arm.

Time Since Baseline (h)	Mean force unsteadiness (N/s) ($\pm$ SD)	Mean change from baseline (N/s) ($\pm$ SD)	Change from baseline p-value
0	21.9 ($\pm$ 15.6)	--	--
1.25	27.2 ($\pm$ 17.1)	+5.3 ($\pm$ 7.0)	<0.001
2.5	28.4 ($\pm$ 21.0)	+6.5 ($\pm$ 11.4)	0.030
3.75	28.2 ($\pm$ 21.5)	+6.3 ($\pm$ 11.7)	0.045
5	28.2 ($\pm$ 22.0)	+6.3 ($\pm$ 9.5)	0.006

6	26.5 (± 16.6)	+4.6 (± 8.4)	0.037
7	28.1 (± 18.1)	+6.2 (± 10.0)	0.011
8	26.5 (± 17.5)	+4.6 (± 5.7)	<0.001
24	22.3 (± 14.0)	+0.4 (± 8.0)	1.000

Figure 23 illustrates the interaction effect of arm over time on force unsteadiness. Force unsteadiness is normalized to baseline to remove between-participant-effects from the graph. The significant interaction can be seen from time points 2 to 8 where the intervention arm has

significantly higher normalized force steadiness than baseline (which is 1.000). Figure 24 displays normalized force unsteadiness over time between protocol and arm but no significance is present.

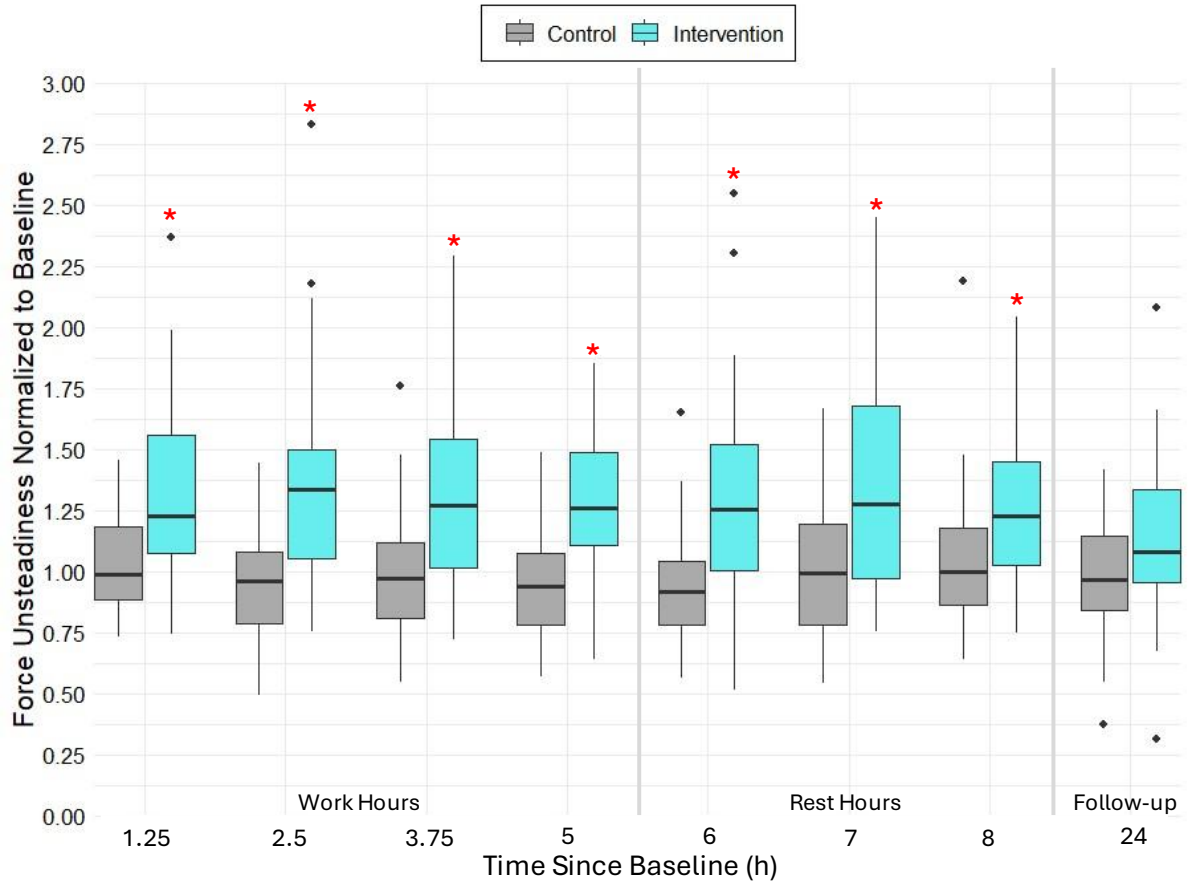


Figure 23 Normalized force unsteadiness during a force matching task over time grouped by arm across an intervention day and follow up visit broken down between work hours and rest hours. An asterisk (*) is shown over boxes that are significantly different from baseline.

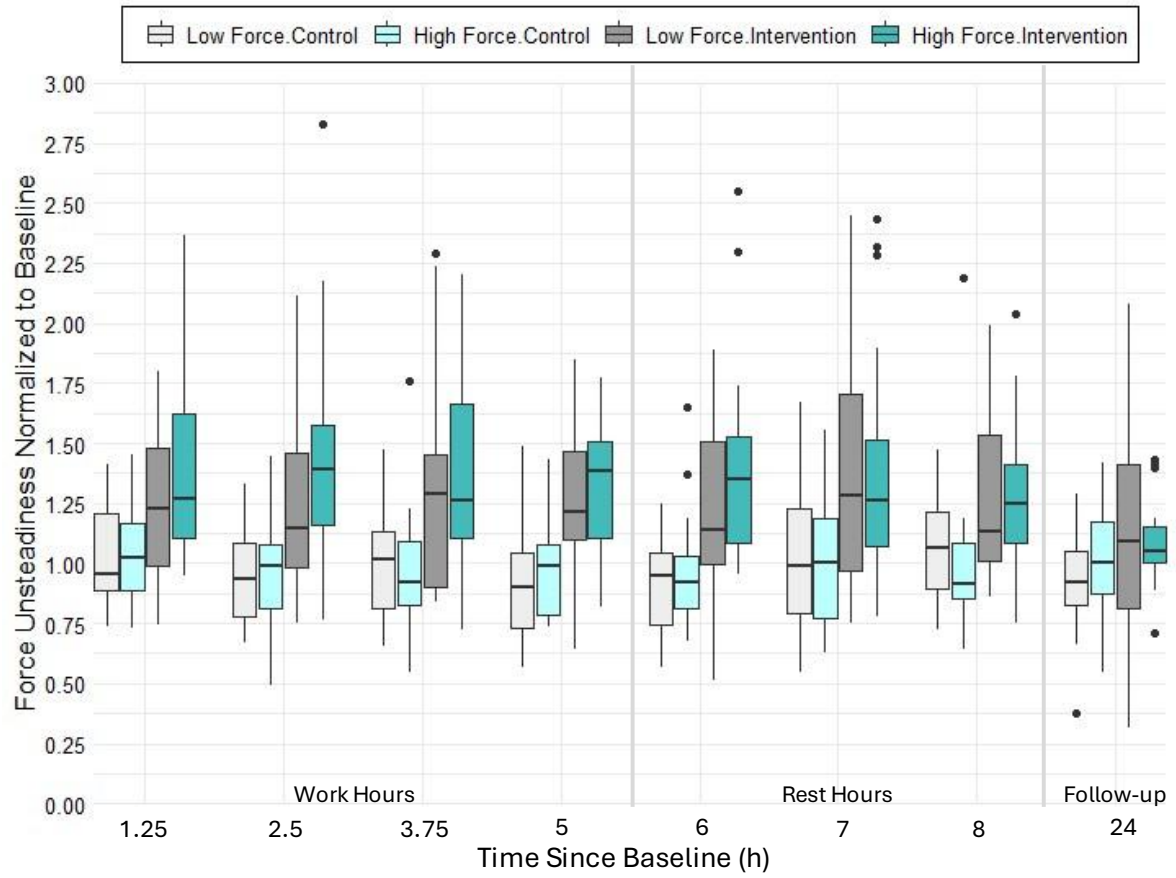


Figure 24 Normalized force unsteadiness during a force matching task over time grouped by protocol and arm across an intervention day and follow up visit broken down between work hours and rest hours.

Chapter 5 Discussion

The results from this study reinforce the null hypothesis that force-magnitude does not influence PLFFD progression and PLFFD does not influence force stability metrics. Hypothesis 1 of this thesis was “the Lo/Hi ratio will be different between work protocols during recovery on the same day and at the start of the next day”. No significant interaction effects of protocol and time were found in Lo/Hi ratio. This suggests there is no difference in recovery of PLFFD between protocols and the null hypothesis is retained. The reasoning behind the hypothesis was that larger motor units (those more likely to be recruited during higher force contractions) recover from muscle fatigue more quickly than smaller motor units, and thus PLFFD may follow the same trend. The null findings may be explained by the difference in mechanism between muscle fatigue and PLFFD. PLFFD is likely caused by altered function of the sarcoplasmic reticulum and changes in cytosolic Ca^{2+} whereas muscle fatigue is caused by metabolic byproducts interfering with crossbridge function and decreased available ATP. Depending on the muscle fibre type, muscle fibres can recover from muscle fatigue at different rates, likely due to differing pathways of ATP generation (Allen et al., 2008). While fibre type is known to align with different isoforms of SR Ca^{2+} pumps (which are influenced by PLFFD), the function between the two isoforms is believed to act similarly (Lytton et al., 1992). Therefore, the difference in mechanism between PLFFD and muscle fatigue may explain the lack of interaction effect seen in data, and that force magnitude does not impact recovery rate of PLFFD.

Changes in Lo/Hi ratio in the Intervention and Control arms indicate that PLFFD accumulated in response to the intervention. Lo/Hi ratio in the intervention arm was significantly different from baseline during all time points, including the follow up visits. The difference in Lo/Hi ratio between baseline and follow-up indicate the long-duration effect of the accumulation of PLFFD in response to the intervention. The Lo/Hi ratio of the control arm was significantly different from baseline at time points 7 and 8, and the Lo/Hi ratio of the intervention arm was not significantly different from the control arm at those time points. PLFFD may have accumulated in the control arm throughout rest, as indicated by the control arm being significantly different from baseline and the intervention arm being not significantly different from the control arm. Active use of the control arm while the intervention arm recovered during rest hours may have caused an accumulation of PLFFD in the control arm. If the control arm did not experience any work (even during rest hours) but experienced a change in Lo/Hi ratio, the fact that it is not significantly different from the intervention

arm may indicate that there is a natural progression of PLFFD through the day independent of work. Therefore the intervention arm may not have been under the effect of PLFFD despite being significantly different from baseline during rest hours, due to the control arm representing an arm that did not experience the intervention. However, for the duration of rest hours, participants were encouraged to rest and be inactive, but their exact level of activity was not constrained. Changes in the Lo/Hi ratio of the control arm align more closely with activity during rest hours than any natural progression throughout the workday. Therefore, it is more likely that PLFFD accumulated in the control arm throughout the rest hours and both arms were under the effect of PLFFD during the rest hours, but further investigation into the topic with a tightly constrained control arm may reveal the driving factor of this effect.

The investigation onto the subject of PLFFD progression factors were sparked by non-significant trends in Lo/Hi ratio recovery post-intervention in studies by Dennerlein et al. (2003) and Hruschka (2003). In these studies, protocols of different force-magnitudes had non-significant differences in Lo/Hi ratio accumulation within a day and between days. The objective of this research was to use a higher temporal resolution of PLFFD progression over protocols designed to be workload matched and varying in force-magnitudes. Null findings in this study suggest there is no influence of force-magnitude on PLFFD progression. Therefore, findings from this study clarify the non-significant differences seen in previous literature and refines our understanding of factors that influence PLFFD progression as a whole.

In addition to evaluating the results within the scope of the studies that sparked this research, comparison with past literature with similar setups of stimulation measuring Lo/Hi ratio serves to validate that measures from this study are consistent. Studies applying transcutaneous stimulation setups on the biceps (with 20:100 Hz ratio) (Dundon et al., 2008) and on the quadriceps (with 10:100 Hz ratio) (Pignanelli et al., 2024) had similar absolute values in Lo/Hi ratio. Post-intervention, the Lo/Hi ratio measures decreased to between 0.2 and 0.3 which are similar to the absolute values seen in this study, however there are larger differences between baseline and post-intervention in those studies than this study. The difference in total workload may explain the larger effect of the intervention seen in those studies. Pignanelli et al. (2024) and Dundon et al. (2008) intentionally fatigued the muscle of interest to a point defined by task failure (Pignanelli et al., 2024) or a target reduction in MVF (Dundon et al., 2008). The intervention in this study was designed to be submaximal and not as extremely fatiguing, which can be seen by the smaller reductions in MVF

post-intervention compared to baseline than Dundon et al. (2008) and Pignanelli et al. (2024). The high workload interventions in past research is likely the reason for the larger change in Lo/Hi ratio from baseline to post-intervention, whereas in this research the effect is relatively small. Therefore, absolute values seen in this study are similar in absolute magnitude to those in previous literature and the smaller effect sizes pre- and post-intervention are due to using a less-intense intervention.

Hypothesis 2 of this thesis was “decreased Lo/Hi ratio will be associated with decreased force stability, independent of protocol”, and while statistically significant models of Lo/Hi ratio and protocol were created, low R^2 values provide room to consider alternative explanations. Secondary models using normalized MVF as a predictor, instead of Lo/Hi ratio, explained more variance. An ANOVA revealed that force unsteadiness was significantly different from baseline throughout the intervention day, but not during the follow up visit. MVF was similarly different from baseline throughout the intervention day but not on the follow up visit and so is likely a more accurate predictor for stability metrics when compared to PLFFD. Force stability being well-predicted by changes in MVF aligns with previous literature (Missenard et al., 2008). The correlation between Lo/Hi ratio and force stability metrics may be an artifact of collinearity between Lo/Hi ratio and MVF, where both decrease throughout the intervention and increase through rest. Therefore, despite the result that Lo/Hi ratio is associated with changes in force stability metrics, correlations were very low and supplementary evidence from an ANOVA revealed that MVF was likely a more effective predictor.

PLFFD’s impact in force stability was believed to be related to the altered relationship between central drive and submaximal force production of motor units, where the central drive needed to achieve a target force would be different than normal when under the effect of PLFFD (Allen et al., 2008). Due to this modified relationship between central drive and applied force, it was hypothesized that PLFFD would reduce an individual’s force stability. However, the low R^2 of the regressions suggest that PLFFD is a very weak predictor of force stability metrics. One explanation is that PLFFD may not be meaningfully impactful to force stability because the body is already adjusting its central drive-applied force relationship due to potentiation, muscle fatigue, and muscle length (Del Valle & Thomas, 2004). If PLFFD is not impactful to create a functional difference in force stability metrics, PLFFD may not be of concern when considering effects that limit quality of work. A secondary explanation of the low explained variance is that an individual’s relationship

between Lo/Hi ratio and force stability metrics are unique to them, and at a population level, normalized metrics are not sufficient to be able to predict force stability metrics with Lo/Hi ratio.

Comparison with past literature on force stability metrics serves to validate that measures from this study are consistent and reasonable. The absolute value of force variability is similar to what Missenard et al. (2008) found at the 30% MVF task level (Appendix D). Interestingly, Missenard et al. (2008) found a larger change in force variability between pre- and post-intervention compared to baseline than this study. The more fatiguing intervention seen in Missenard et al. (2008) may provide an explanation on the larger effect on force variability pre- and post-intervention. The intervention of Missenard et al. (2008) was defined by task failure and induced a much larger effect of muscle fatigue than this study as seen in changes in MVF pre- and post-intervention. Force unsteadiness is a recently defined term (Yacoubi & Christou, 2024) and sufficient data is not present in the literature to define whether it is in the bounds of normality during force matching tasks, however literature does show that values found in this study are well within the magnitudes seen during precision tasks at the wrist (Werremeyer & Cole, 1997). Force stability metrics in this study align in magnitude with previous literature but there is a lack of studies examining force unsteadiness during submaximal force matching tasks with which to compare the data collected in this study.

As muscle fatigue accumulated, both force variability and force unsteadiness increased, however force unsteadiness seemed to be more impacted by muscle fatigue than force variability. The mechanisms behind force stability metrics may explain why force unsteadiness may be more affected by muscle fatigue than force variability. As muscle fatigue accumulates, high threshold motor units drop out and higher threshold motor units are recruited to compensate for the difference (Gordon et al., 2004; Zajac & Faden, 1985). Because higher threshold motor units have a faster rate of force production and are less capable of producing precise forces, the body's corrections for variations in force are faster and less precise. These more rapid adjustments may result in overshooting targets or overcompensating for feedback, making an oscillatory pattern around the force target and increasing force unsteadiness. However, if the oscillation around the target force increases in frequency as the rate of change of force increases, the standard deviation of the force will remain similar to an unfatigued state, thus force variability remains relatively similar. Therefore, the recruitment of higher threshold fibres causes greater rates of change of force which oscillate around the target force, maintaining a similar standard deviation of the signal but increasing force unsteadiness. So, despite

force variance increasing in conjunction with muscle fatigue, as seen in previous literature (Missenard et al., 2008), force unsteadiness was observed to increase even more so.

The broad application of this research was to examine factors that influence the progression of PLFFD to inform the design of recovery models of PLFFD and muscle fatigue. Synthesizing the results of this study and previous research, PLFFD is workload-driven and not effected by force-magnitude. Models estimating PLFFD should focus on the total workload performed rather than the force level at which work is performed. Secondly, this study examined the possible impact of PLFFD on task performance to understand whether the accumulation of PLFFD should be of concern to workplace designers. This study revealed that PLFFD has a very low correlation with changes in force stability and the collinearity between Lo/Hi ratio and MVF changes were the driving factor in the correlation between Lo/Hi ratio and force stability metrics. Within the scope of task performance, PLFFD should not be of concern to ergonomists and workplace designers. Incidentally, relationships between muscle fatigue and force stability metrics were discovered, opening the door for new research looking at muscle fatigue and force unsteadiness. Prescriptive models such as the Liberty Mutual manual materials handling (LM-MMH) equations (Potvin et al., 2021) provide a maximum acceptable load based on task variables and anthropometrics. In circumstances where an individual is working at the maximum acceptable load, muscle fatigue-induced increases in force variability and unsteadiness may cause applied forces to increase past the limit prescribed by the tool. This is not to say that exceeding prescribed limits immediately puts an individual at increased MSD risk, but to illustrate the fact that even when designing workplaces where applied forces are at maximum acceptable loads, the inherent inaccuracy of individuals and muscle fatigue-induced force variability will cause workers to transiently apply loads greater than and less than the maximum acceptable loads. Therefore, workplace designers and ergonomists should consider muscle fatigue accumulation and its impact on force stability when using tools that determine maximum acceptable loads, and that future research should be performed to see if increases in force variability and unsteadiness alter the effectiveness of such tools.

Chapter 6 Limitations

This study was designed with feasibility and reliability in mind, and as such, design aspects of this study impose limitations to the applicability of results. Firstly, healthy university-age students were recruited for this study which does not accurately reflect the population in the workplace. Participants were required to be uninjured and not be experiencing pain in their arms and shoulders prior to the study. Individuals in the workplace have the possibility of being injured despite continuing to work, which may influence how they do their tasks and how their muscles respond to it. Maximum force, force stability, and PLFFD measurements may all be impacted by injuries in the upper limb.

Secondly, the type of work performed was relatively tightly controlled. Despite representing a simple force application, this task can be extrapolated to represent a small range of workplace tasks. The force curve during an “on” period of the tasks is likely more complex than a square wave at the target force, meaning muscles are exposed to sub-target forces for more of the duration of the task. A square-wave style of force application was chosen so that the total workload between the two protocol conditions could be easily compared and contrasted without worry that participant behaviour would change between the two weeks. However, the intervention task was not as tightly controlled as a force-matching task with visual feedback. In order to facilitate participant engagement with a minimally demanding task, we chose to avoid force matching. Force matching would have provided a more concrete foundation to reason that the two weeks had an identical workload, however the participants would likely accrue large amounts of boredom and eventually have even worse performance compared to this study’s task (Randall et al., 2014). Lastly, a force matching task would have provided learning for the force matching task used in force stability measurements. A learning effect could have diminished smaller, yet significant effects of PLFFD, MVF changes, and protocol on force stability metrics.

Similar to the task itself, the duration of work did not represent the phases of work seen in industry, such as an 8-hour day with a half-hour break. A shorter “workday” was chosen as to track recovery from PLFFD post-intervention, however changes seen in PLFFD and force stability may have been larger in magnitude had the work lasted 8 hours, instead of 4. This segmentation of the day was chosen so that the participant would not have to do two intervention days in a row, nor stay in the lab for more than 8 hours at a time.

The force matching task used to measure force stability can be influenced by participant attention. After a long collection day of repeated work, attention may wane and performance may decrease. Such effects may be represented by an increase in force stability on the follow up visit. Identical verbal instructions were presented to the participant throughout the duration of the collections to ensure the environment was not a factor in available focus for the participant.

Chapter 7 Conclusion

The purpose of this research was to investigate the accumulation and recovery of PLFFD and how its interactions with force magnitude, muscle fatigue, and force stability may be implicated in MSD risk. Using a novel method of isometrically supporting a mass from the forearm for a segment of each minute, this study induced muscle fatigue and PLFFD in the participant's biceps brachii muscle over the course of a four-hour workload. Recovery was assessed through measuring the stimulated Lo/Hi ratio of the muscle, MVF, and force stability metrics. Neither hypothesis from this study was supported by the data collected. Firstly, no significant effect of protocol was detected in the Lo/Hi ratio metric. The difference in mechanism between muscle fatigue and PLFFD was likely the driving factor in the lack of force-magnitude effect. Secondly, Lo/Hi ratio predicted very little of the variation in force variability and force unsteadiness data. This study did, however, find that muscle fatigue influenced force stability metrics more than Lo/Hi ratio, which aligns with previous literature (Missenard et al., 2008) and opens the door to further research connecting muscle fatigue to force unsteadiness and its possible impact to the effectiveness of workplace design tools. Therefore, despite neither of the hypotheses being correct, this study revealed effects that are both important to the realm of PLFFD progression and MSD risk research.

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Appendix A

Survey Instruments

Introduction of the Rating-of-Fatigue Scale (Micklewright et al., 2017)

“A response of 0 would indicate that you do not feel at all fatigued. An example of this might be soon after you wake up in the morning after having a good night’s sleep. Now try to think of a similar occasion in your past where you have experienced the lowest feelings of fatigue and use this as your reference.”

“A response of 10 would indicate that you feel totally fatigued and exhausted. An example of this might be not being able to stay awake, perhaps late at night but equally could include situations such as sprinting until you can no longer physically continue. Again, try to think of a similar example that you have actually experienced in the past.”

Appendix B

EMG Data

EMG data were collected as a secondary measure to confirm findings if MVF measurements were unclear. Data for EMG is presented with no statistical testing, and only time points 1-8 are present because time point 9 was on the follow up day with no EMG. Three total participants were removed from EMG data plots (for a total of 17 participants with acceptable EMG data): EMG data of a participant was corrupted, EMG data of another participant was not recorded, and lastly an EMG sensor turned off during a participant's measurement. Figure 25 illustrates EMG amplitude over the course of the intervention day. The intervention arm boxes (regardless of protocol) increase in response to work and decrease back to baseline at the end of the day, reinforcing fatigue trends seen in MVF data. The control arm decreased in amplitude throughout the course of the day, especially during work hours in which the control arm was prohibited from engaging in activity. Figure 26 illustrates EMG frequency over the course of the intervention day. No trends are seen in the frequency data, likely due to only a small amount of muscle fatigue in the muscle. Consistent, physiological frequency data reinforces the concept that this data is reasonable and reliable.

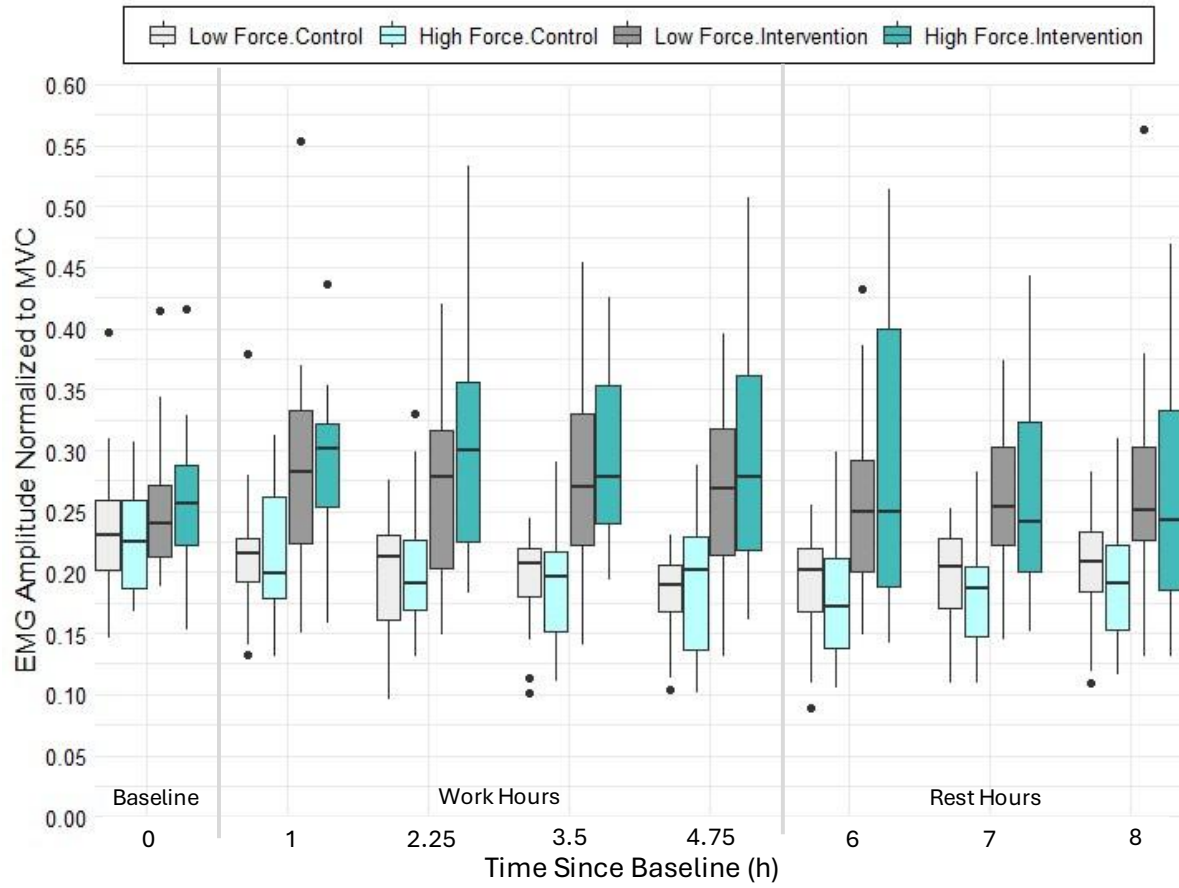


Figure 25 EMG Amplitude normalized to baseline MVF activation over an intervention day broken down by arm and protocol

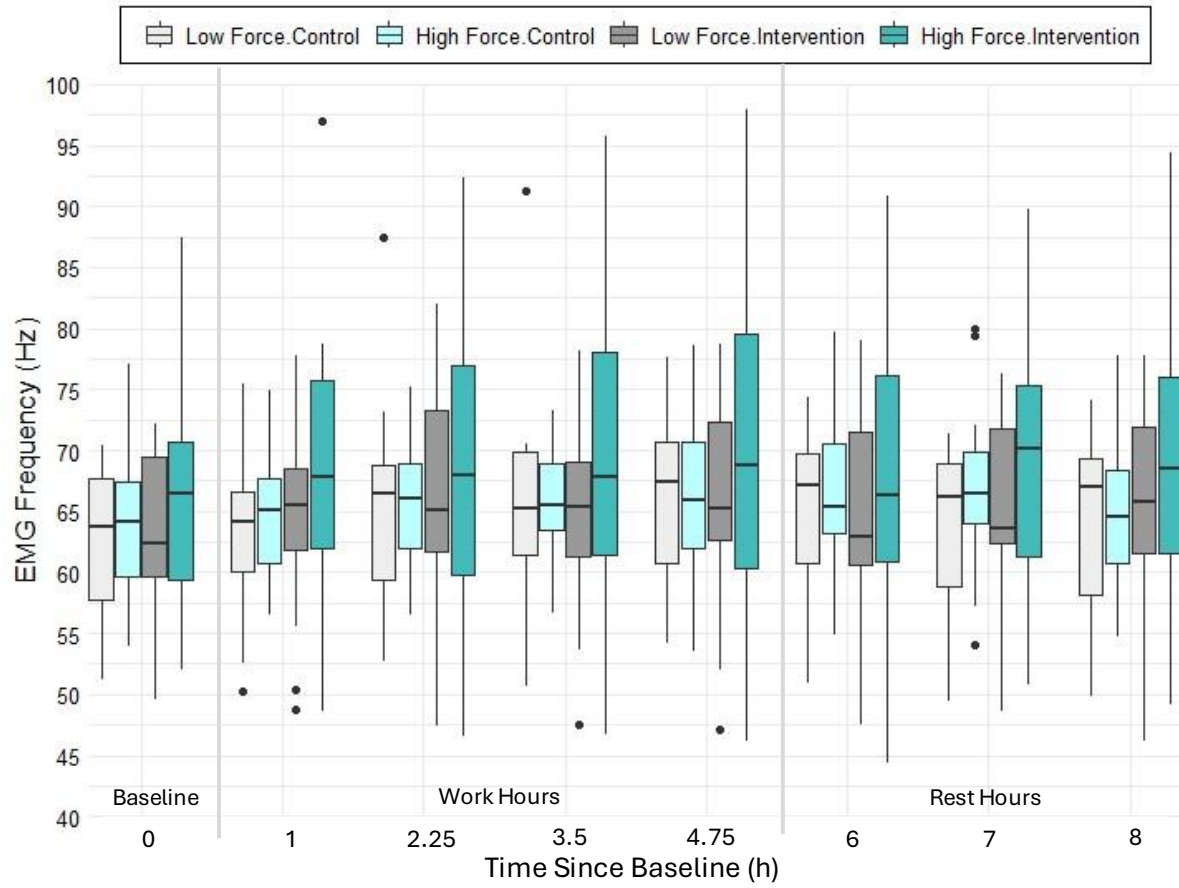


Figure 26 EMG frequency over an intervention day broken down by arm and protocol

Appendix C

Additional Pairwise Comparison Tables

Main effect comparisons are presented for clarity and completion. **Error! Reference source not found.** and **Error! Reference source not found.** list pairwise comparisons for the main effect of time for the Lo/Hi ratio and force unsteadiness respectively.

Table 9 Grouped means and SD of Lo/Hi ratio from an electrically evoked contraction for a main effect of time

Time Since Baseline (h)	Lo/Hi ratio mean ($\pm$ SD)	Change from baseline mean ($\pm$ SD)	Change from baseline p-value
0	0.27 ($\pm$ 0.10)	--	--
1.25	0.24 ($\pm$ 0.10)	-0.03 ($\pm$ 0.07)	0.022
2.5	0.23 ($\pm$ 0.10)	-0.04 ($\pm$ 0.07)	0.016
3.75	0.22 ($\pm$ 0.08)	-0.05 ($\pm$ 0.08)	<0.001
5	0.23 ($\pm$ 0.08)	-0.04 ($\pm$ 0.08)	0.004
6	0.24 ($\pm$ 0.09)	-0.03 ($\pm$ 0.07)	0.003
7	0.22 ($\pm$ 0.08)	-0.05 ($\pm$ 0.07)	<0.001
8	0.21 ($\pm$ 0.09)	-0.05 ($\pm$ 0.07)	<0.001
24	0.23 ($\pm$ 0.09)	-0.03 ($\pm$ 0.06)	<0.001

Table 10 Grouped means and SD of force unsteadiness during a force matching task for a main effect of time

Time Since Baseline (h)	Mean force unsteadiness (N/s) ($\pm$ SD)	Mean change from baseline (N/s) ($\pm$ SD)	Change from baseline p-value
0	21.4 ($\pm$ 14.7)	--	--
1.25	23.9 ($\pm$ 15.2)	+2.4 ($\pm$ 6.5)	0.047

2.5	23.7 (± 17.5)	+2.2 (± 9.9)	1.000
3.75	23.9 (± 17.7)	+2.4 (± 9.9)	0.928
5	23.4 (± 17.9)	+2.0 (± 9.0)	1.000
6	22.7 (± 14.8)	+1.2 (± 8.0)	1.000
7	24.0 (± 15.8)	+2.6 (± 9.2)	0.470
8	23.5 (± 15.4)	+2.0 (± 6.3)	0.177
24	20.9 (± 13.2)	-0.6 (± 7.1)	1.000

Appendix D

Data Extracted From Missenard et. al, 2008

Mean SD of force data was extracted from Missenard et al. (2008) for the unfatigued and fatigued groups. SD of force data (as a %MVF) was converted to force variability because target force was known. As seen in Table 11, the force variability during the 33% MVF force matching task was similar to the average force variability measured in this study ($1.72e-2$) during the 30% MVF force matching task.

Table 11 Data extracted from Missenard et. al (2008) and converted to force variability

	Target force (%MVF)	SD of force (%MVF)	SD converted to force variability
Unfatigued	7.81	0.12	$1.51e-2$
	13.82	0.21	$1.52e-2$
	33.04	0.53	$1.61e-2$
	51.97	0.88	$1.69e-2$
Fatigued	7.51	0.17	$2.28e-2$
	13.82	0.33	$2.38e-2$
	33.51	0.75	$2.24e-2$
	52.59	1.16	$2.21e-2$

Appendix E

Sex Differences

The sample collected for this study was unbalanced between 11 females and 9 males. This study was not powered to detect sex-based difference, and as such, differences between the two groups may be caused by small sample sizes rather than true differences between groups. Data for females and males are presented here for completeness, but conclusions about sex should not be drawn from this data due to unbalanced samples and small sample sizes. Additionally, stature, total body mass, and MVF for females were lower than males, so differences between females and males could be driven by any of these factors independent of sex. Maximum forces for females (200.2 ± 37.2 N) were higher than maximum forces for males (354.2 ± 40.9 N). Normalized MVF decreased to a similar amount between sexes post-work, however females seemed to recover more slowly than males (Figure 27).

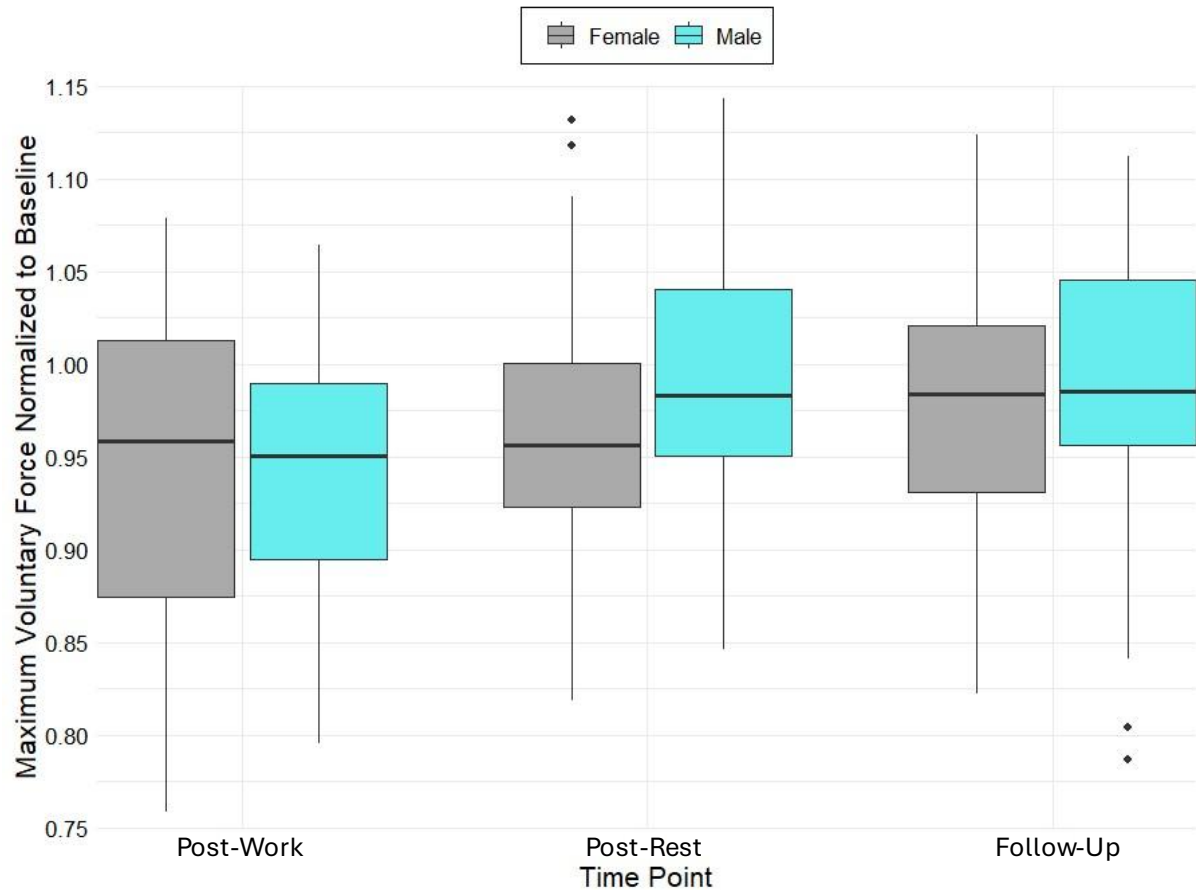


Figure 27 Normalized maximum voluntary force of both arms over time grouped by sex across an intervention day and follow up visit.

Lo/Hi ratio normalized to baseline was broken down by sex and arm to show the progression of PLFFD throughout the workday in Figure 28. Lo/Hi ratio was similar between females (0.236 ± 0.095) and males (0.228 ± 0.079). Lo/Hi ratio decreased in response to work and increased through rest hours. Throughout recovery females had a lower normalized Lo/Hi ratio, however on the follow up visit, males had a lower normalized Lo/Hi ratio.

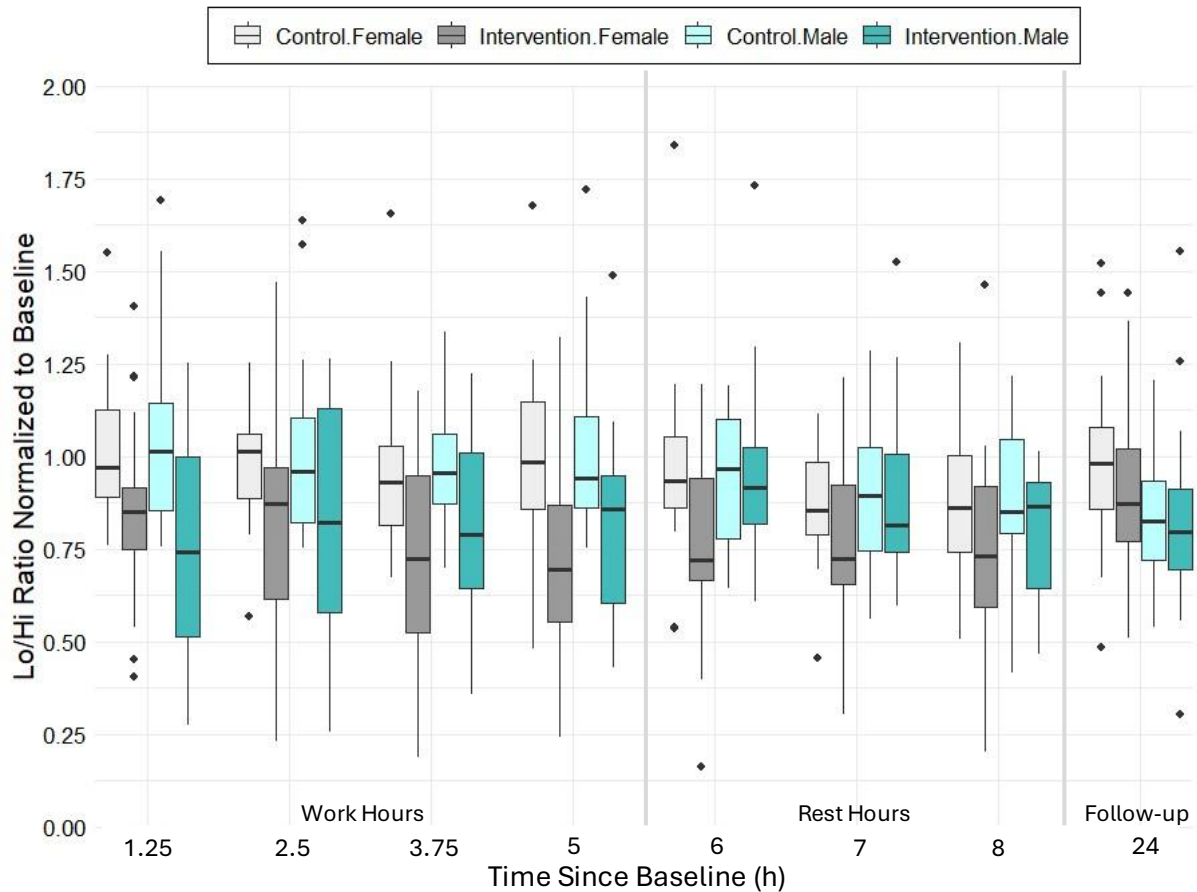


Figure 28 Normalized Lo/Hi ratio from an electrically evoked contraction over time grouped by sex and arm across an intervention day and follow up visit broken down between work hours and rest hours.

Force variability trends over time were similar between females and males for their control and intervention arms, respectively (Figure 29). Absolute force variability values were lower in females ($1.580\text{e-}2 \pm 5.187\text{e-}3$) than males ($1.880\text{e-}2 \pm 9.324\text{e-}3$), however when normalized to baseline, females had higher force variability compared to males throughout the entire protocol. Similarly, force unsteadiness increased in response to work and decreased through rest hours similarly between sexes (Figure 30). Females had lower force unsteadiness ($13.8 \pm 6.3 \text{ N/s}$) than males ($34.3 \pm 16.7 \text{ N/s}$), however when normalized to baseline, females had a larger response to the intervention.

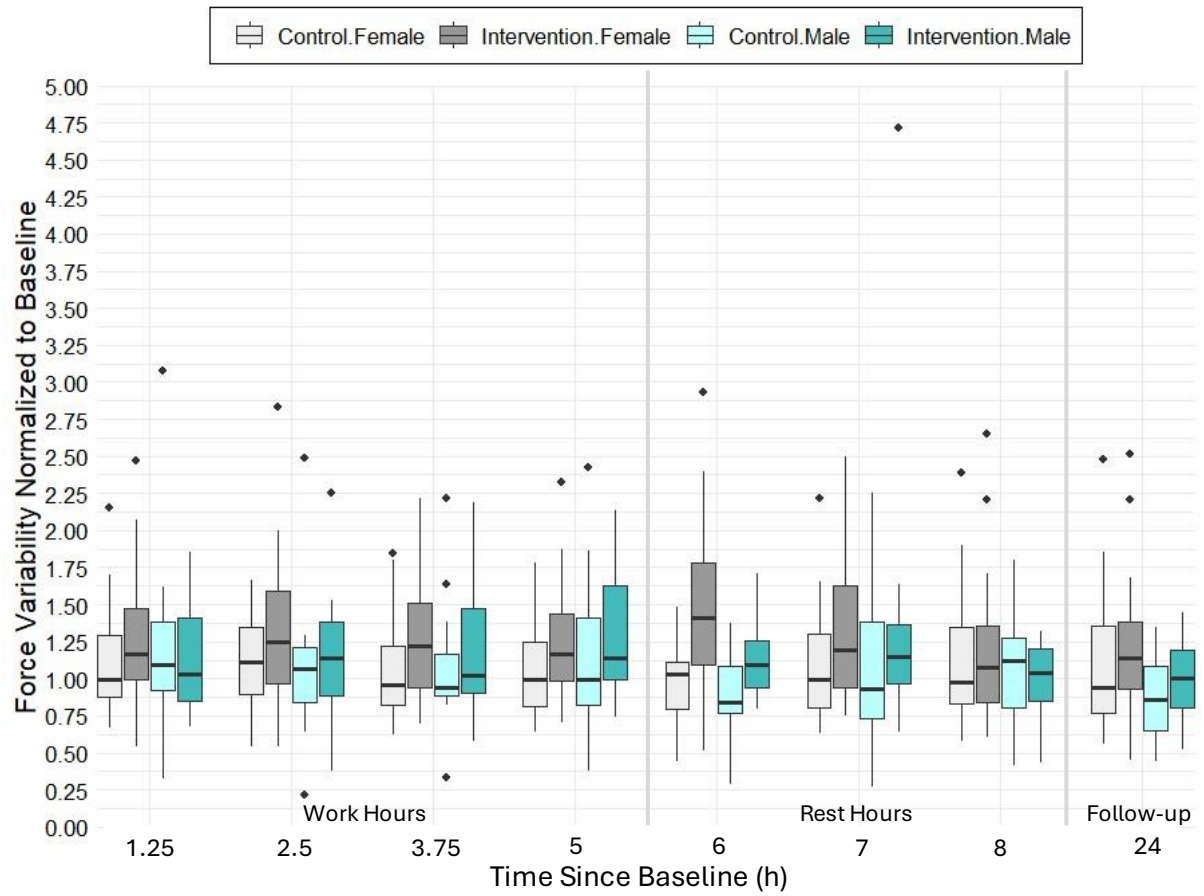


Figure 29 Normalized force variability during a force matching task over time grouped by sex and arm across an intervention day and follow up visit broken down between work hours and rest hours.

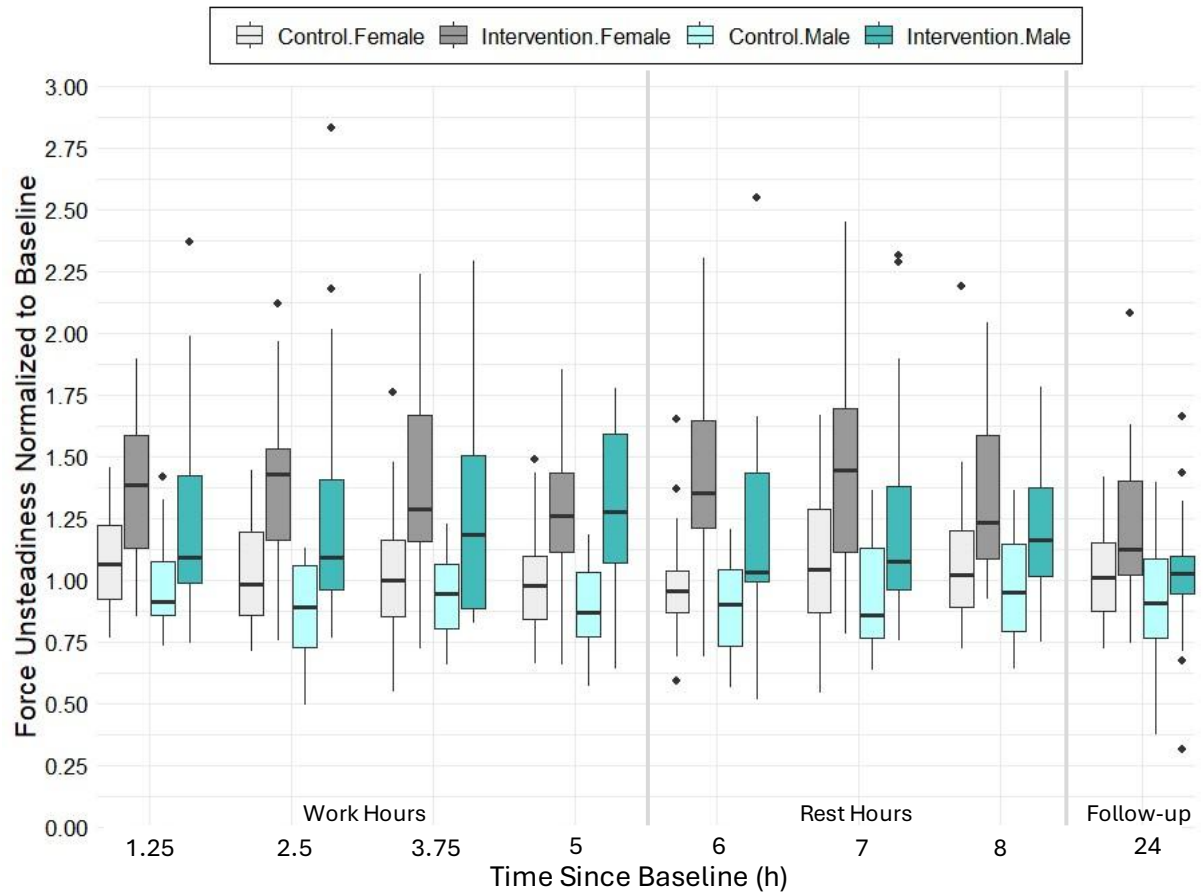


Figure 30 Normalized force unsteadiness during a force matching task over time grouped by sex and arm across an intervention day and follow up visit broken down between work hours and rest hours.