Examining the effects of a passive upper extremity exoskeleton on shoulder fatigue during a simulated automotive overhead weld inspection task

by

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A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Master of Science

in

Kinesiology and Health Sciences

Waterloo, Ontario, Canada, 2024

Authors 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

Exoskeletons are emerging as occupational assistive devices, and in particular passive upper extremity exoskeletons have been implemented in workplaces in situations where it is not possible to remove overhead work job elements. Previous studies have commonly reported the effects of exoskeleton usage on the deltoid muscles during short duration tasks, but these data incompletely characterized how exoskeletons may influence shoulder fatigue development and subsequent injury risk. The main purpose of this thesis was to quantify the exoskeleton's impact on psychophysical, localized muscle, and strength measures of fatigue in the shoulder throughout a two-hour simulated welding task. Ten male participants completed two in-lab sessions of the same task with and without the exoskeleton. Psychophysical measures of exertion, shoulder, elbow, and wrist discomfort were recorded along with surface electromyography (EMG) from bilateral supraspinatus, infraspinatus, upper trapezius, anterior and middle deltoids using a posture-controlled weighted reference task to calculate changes in mean power frequency (MPF) every 10 minutes throughout the 2-hour protocol. Maximum voluntary strength efforts (abduction and external rotation) were completed every 20 minutes to monitor changes in strength. The left and right sides were compared over time to assess potential changes in strategy throughout the task progression. The absence of significant hand by time interactions indicated there was no systematic change in strategy throughout the task protocol. The overhead weld inspection task caused increased markers of fatigue (decreased MPF) in the supraspinatus, infraspinatus, and upper trapezius over the 2-hour protocol. Wearing the exoskeleton resulted in significantly higher MPF compared to no exoskeleton in the supraspinatus ($p<0.001$), infraspinatus ($p<0.001$), and upper trapezius ($p<0.001$), with measures remaining at baseline in the EXO group, indicating a lack of fatigue development. Shoulder discomfort was reduced by

0.67 points (EXO = 1.97, NE = 2.64) when wearing the exoskeleton. Additionally, wrist discomfort was 0.4 points lower without the exoskeleton (EXO = 1.06, NE = 0.66), suggesting that the wrist and other body regions that are not targeted by the exoskeleton should be monitored if these devices are implemented. External rotation force was also lower with the exoskeleton than without, driven by a decrease in force output at the start of the collection period that returned to baseline values by the end of the 2-hour protocol. This could indicate that the exoskeleton may have affected cognitive fatigue in these non-expert users; however, cognitive fatigue was not directly measured in this thesis and should be investigated further in future work. Overall, this thesis provides novel findings regarding the effects of a passive upper extremity exoskeleton on muscular fatigue, particularly in the glenohumeral stabilizing muscles (supraspinatus, infraspinatus, and upper trapezius). This had not been previously explored during an extended duration task representative of the workplace.

Acknowledgements

First, I would like to thank my supervisor Dr. Clark Dickerson for inviting me to the DIESEL team during my undergraduate degree and teaching me how fascinating and complex shoulders are. Without your support and encouragement, I wouldn't be where I am today.

Thank you to my committee members Dr. Jack Callaghan and Dr. Andrew Laing for their invaluable feedback on this project.

To all the DIESEL lab students, and many volunteers, thank you for your support in this project. A special thank you to Kathryn Webster for her numerous hours spent in the lab with me troubleshooting equipment, collecting participants, and setting up for the experiment. To Meghan Hanton-Fong, thank you for all your help with collections and I'm grateful for the fun we had in the lab, especially on the long days. Thank you to Jeff Rice who helped recreate the manufacturing environment in our lab, and for helping troubleshoot mid-collection to keep things running smoothly. I would like to thank our industry partner who provided valuable insights and guidance, as well as financial support and a meaningful problem to investigate.

To Kendra McKellar – you're one of the biggest reasons I finished my undergrad with so many great memories and laughs, and even though we differed in our Kinesiology specializations post-undergrad you're still one of the biggest reasons I finished my master's with my sanity intact. You have shown up for me in so many ways over the years and I am forever grateful. To Kelsey, Courtney, and Taylor – thank you for being the best hype women and emotional supports when I needed it. And to my parents, Jack and Anne, thank you for your continued love and support, and for raising me to be a curious and kind person. I couldn't have done it without you.

Finally, thank you to my partner Robert Davis, who has supported me throughout this degree in so many ways. You listened to me teach you about the ‘bio’ side of mechanics while preparing for exams, helped me work through difficult concepts and ideas, and you were my rock through this whole process. Your unwavering belief in my success and support throughout my degree has been truly appreciated and essential. I’m excited to see what else is in store for us on this wild journey together.

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1.0 Introduction

Exoskeletons are wearable devices designed to support the body, and have grown in popularity in recent years, both in their use in industry and the growing body of literature (Nussbaum et al., 2019). They are used to augment the wearer's physical ability or decrease the physical load on the target body region. Exoskeletons typically target a specific body region, most commonly the back, lower limb, ankle, wrist, and shoulder (Bar et al., 2021), while others are whole body and target multiple body regions. Evidence for the benefits of exoskeleton use is stronger for exoskeletons used to support the back (Bar et al., 2021), whereas the shoulder is a newer area of research (McFarland and Fischer, 2019).

The shoulder complex has a high degree of flexibility that comes at the cost of stability, which can predispose it to unique injury. While other body regions benefit from passive contributions from ligamentous and bony stability, the shoulder has a shallow fossa and lacks ligamentous contributions until the end range of motion (Matsen et al., 1994), requiring muscle action for stability (Dickerson, et al., 2023). In 2022, the shoulder had the second highest number of workplace injuries, only second to the back (WSIB, 2022). Since these injuries occur in soft tissues, the recovery rate can be slow and they may therefore require substantial time off work, with an average 88 days off work for a shoulder injury (WSIB, 2022). The high frequency and cost of shoulder injuries results in a significant negative impact on both the cost to the employers, and the injured person's daily activities.

While the deltoids and rotator cuff are both required to facilitate arm elevation, they do not experience the same rates of injury. The rotator cuff is commonly injured, with the supraspinatus tendon tearing first, followed by infraspinatus and then subscapularis (Itoi et al., 1999). A common injury pathway includes the impingement of the supraspinatus tendon within the subacromial space, which can be provoked by external mechanisms of overhead work due to the relative position of the humerus in the glenoid fossa, and fatigue of the rotator cuff muscles (Michener, McClure, & Karduna, 2003; Brossman et al., 1996). The deltoids are larger muscles which contribute largely to shoulder elevation past the first 10-15 degrees, however they are rarely injured themselves as these muscles have a much larger cross-sectional area when compared to the rotator cuff muscles (Greenfield, Donatelli, & Brody, 2004).

Exoskeleton use has potential benefits in some cases where overhead work tasks cannot be avoided. According to the National Institute for Occupational Safety and Health (NIOSH), a hierarchy of controls can be used to reduce the exposure to known hazards (2015). Types of controls are categorized and ranked based on the effectiveness of the solutions from most to least effective as seen in **Figure 1**. Exoskeletons are commonly categorized as personal protective equipment, and as such they should be considered only after alternate methods of hazard reduction have been exhausted. In cases where the overhead work component cannot be removed or modified, passive upper extremity exoskeletons (PUEE's) are being explored as a solution to reduce the severity of the overhead work and reduce risk of injury.

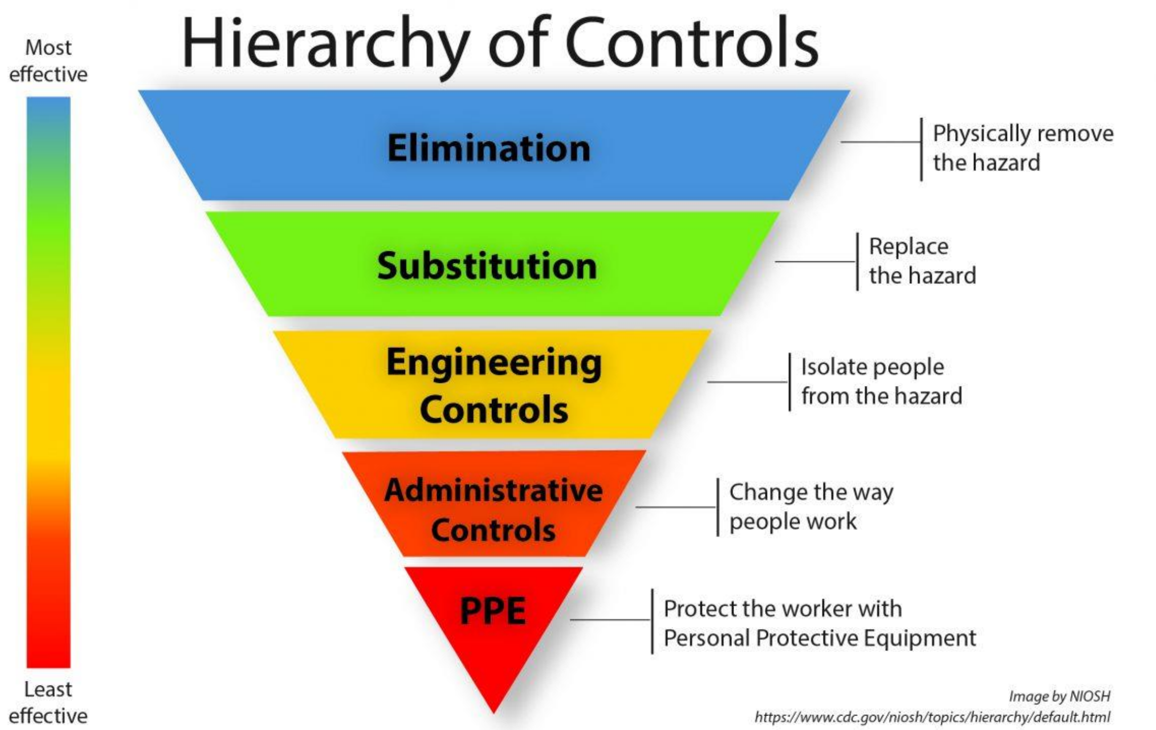

Figure 1. Hierarchy of controls figure showing the five tiers of controls, from most effective (top) to least effective (bottom). The most effective types of controls, such as elimination of the hazard, should be implemented first before exploring alternate options. Figure retirieved from https://www.cdc.gov/niosh/topics/hierarchy/default.html.

There is a need for exoskeletons to be evaluated in environments that are representative of workplace demands. Exoskeletons have been evaluated most frequently while completing short duration simple tasks in the lab environment, such as holding isometric overhead postures, simulated drilling or screwing (De Bock et al., 2022). However, different responses to wearing exoskeletons have been reported between simple tasks completed in the lab, and tasks completed in the field (De Bock et al., 2021). Workplace demands involve more complex movements that are completed over longer durations, and therefore there is a need to evaluate exoskeletons in environments that represent conditions encountered in the field.

Since the shoulder relies heavily on muscular contributions for stability, characterizing the impact of the passive upper extremity exoskeletons on key shoulder muscles is critical.

Strong evidence exists for PUEE's reducing deltoid muscle activity, primarily the anterior deltoid (Bar et al., 2021; McFarland & Fischer, 2019). However, the rotator cuff muscles have been studied less frequently when using PUEE's, with only two studies recording infraspinatus muscle response (Kim and Nussbaum, 2019; Van Engelhoven et al., 2019) and no data currently existing for the supraspinatus response. Understanding the impact on the rotator cuff alongside the deltoid muscle response to exoskeletons will help to provide a more comprehensive understanding of the impact of PUEE's on shoulder injury risk.

Studies have commonly recorded the exoskeleton for a short length of time, using time-domain surface electromyography to characterize the impact of the exoskeleton on muscle demands and predict the risk of developing fatigue. In some cases, frequency-based measures have been used to quantify fatigue directly (Rashedi et al., 2014; Schmalz et al., 2019), however these studies had a task duration of 5-10 minutes. One study investigated the use of a PUEE during a 1-hour task, however fatigue was assessed using a tissue oxygenation saturation index and the task consisted of repetitive force applications in constrained postures (Weston et al., 2022), which does not represent many occupational tasks.

This thesis contributes to the existing body of literature by examining the rotator cuff muscular response to the exoskeleton during a simulated automotive weld inspection task throughout a 2-hour protocol to measure the fatigue response.

1.1 Thesis Objective

1) To determine if wearing a passive upper extremity exoskeleton decreases psychophysical, local muscle and strength indicators of fatigue in the shoulder after completing a two-hour overhead work task.

1.2 Hypotheses

1) Mean power frequency percent change will be lower in the anterior deltoid, middle deltoid, upper trapezius, supraspinatus, and infraspinatus when wearing the exoskeleton compared to no exoskeleton.
2) Ratings of perceived exertion will be lower when wearing the exoskeleton compared to no exoskeleton.
3) Ratings of perceived shoulder, elbow, and wrist discomfort will be lower when wearing the exoskeleton compared to no exoskeleton.
4) Strength percent change will be lower in both elevation and external rotation when wearing the exoskeleton compared to no exoskeleton.
5) This task will cause fatigue over time in the 5 muscles examined.
6) There will be no change in strategy over time (measured by hand * time interaction) in the muscles examined.
7) The use of the exoskeleton would not change the strategy over time.

2.0 Literature Review

This section starts with a review of the literature on fatigue and the various methods to measure fatigue in human participants including force, electromyography, and psychophysical measures. It then discusses shoulder injuries and mechanisms, passive upper extremity exoskeleton evaluations, and a summary of knowledge gaps.

2.1 Fatigue

Many definitions of fatigue exist throughout the literature. Fatigue is commonly defined as the inability to maintain an expected force (Edwards, 1981), which is otherwise referred to as mechanical failure. This definition assumes fatigue is delayed and does not begin at the onset of muscle activity, as force can be maintained for a duration of time before failure occurs. Neuromuscular fatigue, also known as local muscle fatigue (Chaffin, 1973) has more recently been defined as a temporary reduction of the force generating capacity of a muscle to perform physical actions (Enoka & Duchateau, 2008; Bigland Ritchie & Woods, 1984), and includes the processes leading up to the mechanical failure, or the "transition to fatigue" (Al-Mulla, Sepulveda, & Colley, 2011).

Fatigue can be caused by a combination of both central and peripheral mechanisms (De Luca, 1997; Bigland-Ritchie & Woods, 1984; Enoka & Duchateau, 2008; Al-Mulla, Sepulveda, & Colley, 2011). Central fatigue mechanisms are due to a decrease in output from the central nervous system in an attempt to decrease risk of injury (Enoka & Duchateau, 2008, Al-Mulla, Sepulveda, & Colley, 2011). Central fatigue can be confirmed by applying an external electrical supramaximal twitch to compare the maximum force output from the twitch to the maximum voluntary contraction force. The impact of central fatigue can vary based on task type and demands, with a greater influence on longer duration tasks, which could be due to a lack of motivation or the inability of the individual to tolerate the discomfort associated with the development of fatigue (Bigland-Ritchie & Woods, 1984, Edwards, 1981). This is an important consideration during workplace tasks, as most tasks will require relatively low levels of activation that are completed over 2-8 hours in the workday.

2.1.1 Fatigue Measurement Methods

There are many different methods that can be used to measure fatigue, each giving slightly different insight into the effects of the task being performed. There are subjective measures like psychophysical ratings of exertion, which provide insight into the individual's perceived mental and physical load while completing the task. More objective measures include EMG recordings of the muscle, both in the amplitude and frequency domain to provide insight into the fatigue response of individual muscles, and force measurement methods which help gain insight into the global fatigue response over the targeted joint complex. These methods will be discussed in this section.

2.1.1.1 Force

One of the most common methods to quantify fatigue is by measuring a decline in maximum voluntary force over time (Edwards, 1981). This can be measured through constant force production, or by measuring intermittent maximum voluntary force contractions throughout the duration of a task (Enoka & Duchateau, 2008). This measure provides insight to determine the level of contractile fatigue as the motor units contributing to the force production are no longer able to produce the same amount of force throughout the fatiguing process. When looking at joints with redundant muscle action, measuring force provides a global measure of fatigue about the whole joint system, and provides little information about the fatigue state of individual muscles.

2.1.1.2 Electromyography (EMG)

To measure the impact of a fatiguing task on specific muscles, surface EMG is commonly used to quantify the local muscle fatigue. A combination of frequency domain and time domain surface EMG characteristics are commonly used to quantify the fatigue response in specific muscles (Cifrek et al., 2009). Mean and median power frequency have been used as the gold standard EMG measure of fatigue (Al-Mulla et al., 2012). A shift to the left on the power spectrum or decrease in the mean or median power frequency measures have been associated with the development of fatigue over time. This shift has been contributed to a decrease in conduction velocity (Cifrek et al., 2009; Bigland-Ritchie & Woods, 1984; De Luca, 1997). However, conduction velocity is not responsible for the entire shift to lower frequencies seen with fatigue. Krogh-Lund and Jorgensen found that conduction velocity remained constant in the final 50% of the fatiguing contraction, even as the power spectrum continued to shift to lower frequencies (1991). They hypothesized this could have occurred due to the gradual recruitment of larger motor units which have a faster conduction velocity compared to the smaller motor units at the start of the contraction (Krogh-Lund & Jorgensen, 1991).

Additionally, an increase in surface EMG signal amplitude has been associated with local muscle fatigue, and this has been used in combination with the shift in frequency spectral measures to determine the presence of fatigue in a muscle (Cifrek et al., 2009). This increase in signal amplitude is seen in surface EMG but not in fine wire EMG (Cifrek et al., 2009), in part due to tissue filtering. Since our tissues act as a low pass filter (Cifrek et al., 2009), when the frequency spectra shift to lower frequencies with fatigue, more of the signal power can reach the electrode. The increase in signal amplitude could also be attributed to the recruitment of additional motor units to maintain the same level of force during a submaximal contraction to replace the motor units that have succumb to contractile fatigue (Cifrek et al., 2009).

2.1.1.3 Rating of Perceived Exertion and Discomfort

Psychophysical measures provide valuable insight into what an individual is feeling throughout a task, and encompass both the physical sensations of peripheral fatigue, and central fatigue (Borg, 1990). The Borg-CR 10 scale has been shown to be sensitive to changes in general fatigue (Grant et al., 1999), and is an accessible assessment tool to use in occupational settings, making it a commonly used measure.

2.2 The Shoulder

The shoulder is a complex set of joints that allows the flexibility required to complete everyday tasks that require the upper extremity. In the workplace, the shoulder is commonly injured resulting in high costs to the employer and significant time off work. Both overhead work and muscle fatigue can decrease the subacromial space, which increases the risk of shoulder impingement and rotator cuff tears.

2.2.1 Shoulder Injuries in the Workplace

Workplace shoulder injuries are common, costly to employers, and can have significant negative impacts on affected individuals. According to WSIB, shoulder injuries are the second most costly workplace musculoskeletal injury after cranial region injuries (WSIB, 2022). Shoulder injury claims are considered high impact due to the high cost to employers, with rotator cuff tears in Ontario costing an average of $25,218, and an average of 88 days of lost time at work (WSIB, 2022). In addition to the financial burden on employers, shoulder injuries have a significant impact on the physical, economic, and psychological wellbeing of the person injured (Pranksy et al., 2000). Van der Molen et al. found an increased risk of shoulder pain to be associated with work in different sectors such as fish processing, slaughterhouse, sewing machine operation, manual labour, fishing, construction, metal work, nursing, and the army (2017). Common injury mechanisms in the shoulder have been attributed to repetitive work, vibration, manual handling, and arm elevation (Dickerson et al., 2023; van der Molen et al., 2017).

2.2.2 Shoulder Injury Mechanisms

The subacromial space (SAS) in the shoulder is a space that houses critical tissues, and decreasing this space is often involved in injury precipitation. The SAS is made up of the space between the acromion, coracoacromial arch, and the head of the humerus (Kamkar, Irrgang, & Whitney, 1993), and contains the supraspinatus tendon, the long head of the biceps brachii tendon, the shoulder capsule, and the subacromial bursa (Michener, McClure, & Karduna, 2003). This space at rest, in healthy individuals ranges from 6-14mm, with the tissues taking up to half the space (Michener et al., 2003). Both intrinsic and extrinsic factors can alter the size of the SAS, causing the tissues to be compressed. Intrinsic factors refer to factors within the body that cause the degradation of the tissues, leading to decreased SAS (Michener, McClure, & Karduna, 2003).

Extrinsic mechanisms that decrease the SAS are mechanisms that can be more readily modified to reduce likelihood of subacromial impingement, and therefore decrease the risk of injury. The SAS can be reduced by postural changes, altered glenohumeral or scapular kinematics due to fatigue or injury, or posterior capsule tightness (Michener, McClure, & Karduna, 2003). Arm elevation causes the SAS to decrease at elevation angles between 60-90 degrees, as well as during internal rotation (Brossman et al., 1996) due to the greater tuberosity of the humerus moving into the SAS. This is a critical location on the humerus as it is the attachment site of the supraspinatus tendon, causing increased risk of tendon compression as it passes through the space.

Superior humeral head translation is an external subacromial impingement mechanism and has been observed following fatigue protocols resulting in rotator cuff muscle fatigue. Chopp et al. (2010) quantified translation of the humeral head in a non-fatigued and fatigued cuff state. What they found was that in a non-fatigued state, the subacromial space decreased steadily until 90 degrees elevation, and then began to increase slightly at elevation angles above 90 degrees. However, when the cuff was fatigued, the space continued to decrease after 90 degrees elevation (2010), demonstrating that the effects of arm elevation and muscle fatigue on the SAS are additive. This has negative implications for the supraspinatus tendon as compression due to the decrease in subacromial space becomes more likely to occur when performing overhead movements in a state of rotator cuff fatigue.

One theory for why this upwards humeral head translation occurs is that an imbalance occurs between the rotator cuff and the deltoid muscles (Greenfield, Donatelli, & Brody, 2004), an example of differential fatigue theory (Kumar, 2001). The rotator cuff muscles, especially supraspinatus, are smaller, stabilizing muscles, responsible for maintaining humeral position relative to the scapula, and compressing the humerus into the glenoid (Greenfield, Donatelli, & Brody, 2004). Infraspinatus and subscapularis lines of action point inferiorly as they have fibers originating on the infraspinous and subscapular fossa’s and inserting on the greater and lesser tubercles (Criswell, 2010) resulting in the primary fiber direction pointing inferior and medially. Thus, the rotator cuff muscles provide a stabilizing compression force as well as a downward pull on the humerus, while the deltoid pulls upward on the humerus as seen in **Figure 2**. This theory is supported by Graichen et al. who reported that during active arm elevation of 90 degrees and 120 degrees the humeral head was centered in the glenoid; however, during passive arm elevation the humerus translated superiorly (2000), supporting the importance of muscle action to maintain humeral position in the glenoid. Since the rotator cuff muscles are smaller than the deltoids (Greenfield, Donatelli, & Brody, 2004), they may fatigue more quickly resulting in an imbalance between the upward pull of the deltoid and the stabilizing force of the rotator cuff in many postures.

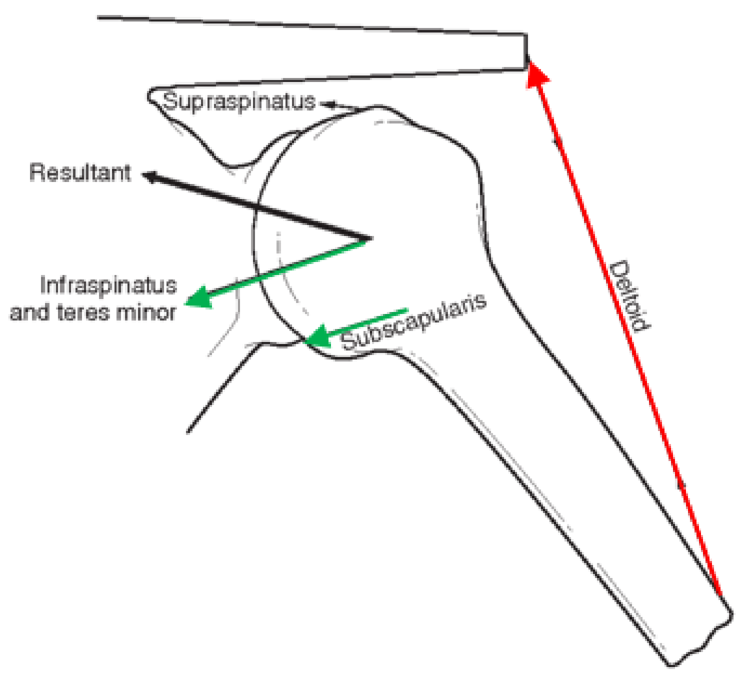

Figure 2. Modified from Greenfield, Donatelli, & Brody (2004). The arrows in the image show the force vectors and lines of actions of the rotator cuff muscles and deltoid. The green arrows represent forces that will prevent inferior translation of the humerus, as well as helpful compression. The red arrow represents forces that will result in superior translation.

Individual responses to shoulder fatiguing protocols vary throughout the population. One example of this was reported by Chopp-Hurley et al., where between 39% and 57% of the participants responded to a fatigue protocol with disadvantageous kinematic responses to fatigue, and other participants responded with advantageous kinematic changes which increase the SAS

(2016). Mulla, McDonald, and Keir observed muscular response at the shoulder varied both between participants and between testing days (2018). While most participants exhibited fatigue in the infraspinatus, there was a more variable response in the remaining shoulder muscles recorded between and within participants (Mulla, McDonald, & Keir, 2018). This, in part, could be due to the specificity of the fatigue protocol, which included different variations of internal and external rotation movements. As external rotation is not commonly completed to fatigue, and there is considerable kinematic redundancy at the shoulder, participants may have relied on contributions from different muscles to avoid task failure.

2.3 Passive Upper Extremity Exoskeletons Previous Research

Exoskeletons have been designed with the goal of reducing risk of injury to individuals in occupational settings completing physically demanding tasks. As discussed in the shoulder injury mechanism section, two important contributors to risk of injury at the shoulder are posture and muscle fatigue; the goal of the PUEE is to reduce the latter when the former cannot be modified. To do this, the PUEE is designed to transfer energy from the exoskeleton to the upper arm while in elevated arm postures, therefore reducing shoulder muscle demands and prolonging time to fatigue for the individual. This section will discuss the different types of PUEE designs, where exoskeletons have been previously evaluated, and previous work quantifying the effects of the PUEE’s on muscle demands and fatigue.

2.3.1 Exoskeleton Design

Exoskeletons can be divided into two categories: active and passive, depending on where they get their power source. Active exoskeletons get their energy from things like mechanical actuators, and passive exoskeletons used stored energy, like springs to provide support to the desired body part (de Looze et al., 2016; Bar et al., 2021). Passive exoskeletons used to support the upper extremity, such as the technology used by the Levitate © Airframe (**Figure 3**) use a spring-based mechanism store elastic energy when the arm is at rest. This elastic energy will begin to transfer to the upper arm as the wearer elevates their arm, peaking at approximately 90 degrees of elevation (Doyle, 2017). The PUEE is designed to provide the arm support to offset gravity that will interfere minimally with the wearer's motion (Doyle, 2017, McFarland & Fischer, 2019).

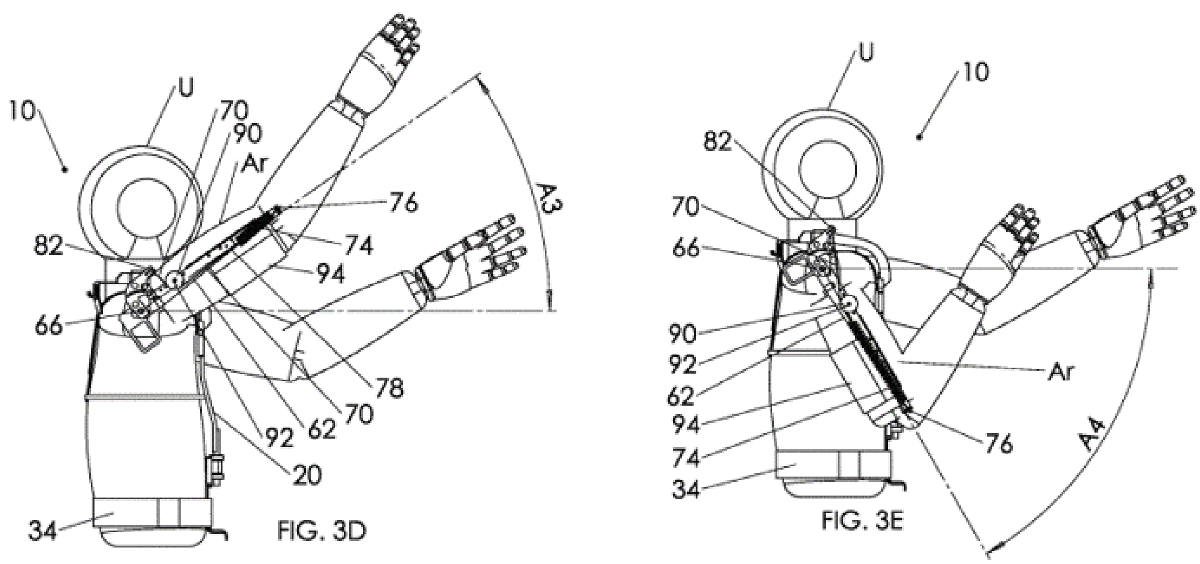

Figure 3. Side view of the passive support system located within the AIRFRAME exoskeleton support cassette, including the spring and pulley mechanisms used to generate passive force from the Levitate Technologies Inc. patent 9737374B2 (Doyle, 2017).

2.3.2 Types of Passive Upper Extremity Exoskeletons (PUEE).

Passive exoskeletons have been designed for many different uses, including their use in industrial settings to decrease injury risk, hospital settings for rehabilitation, consumer use in sport, and in the military (Dao et al., 2022). Some commonly studied PUEE's include the EksoBionics © EksoVest (Weston et al., 2022; Smets 2019; Kim and Nussbaum 2019; Kim et al., 2018a & 2018b), the Levitate AIRFRAME ® (Weston et al., 2022; Irzano et al., 2020; Liu et al., 2018; Gilette & Stephenson 2019; Tetteh, Hallbeck,, & Mirka, 2022, McFarland et al., 2022), the SuitX © ShoulderX (Alabdulkarim & Nussbaum 2019; Weston et al., 2018; Pinho & Forner-Cordero 2022; Van Engelhoven et al., 2019), the SkelEx (de Vries, Krause, & de Looze 2021; Jorgensen, Hakansson, & Desai, 2022; de Vries et al., 2019; Debrosses, Schwartz, & Theurel, 2021), the Fawcett Exovest ™ (Weston et al., 2022; Alabdulkarim & Nussbaum 2019; Rashedi, Kim, Nussbaum, & Agnew 2014), the Ottobock PAEXO (Jorgensen, Hakansson, & Desai 2022; Schmalz et al., 2019; Maurice et al., 2020), the EXHAUSS ® Stronger (Theurel et al., 2018, Debrosses, Schqartz, & Theurel, 2021), the EksoBionics © EVO (Jorgensen, Hakansson, & Desai 2022), and the FORTIS (Alabdulkarim & Nussbaum, 2019). These exoskeletons can be further divided into two main categories: mechanical arm exoskeletons and PUEE's that directly support the arm (McFarland et al., 2019). The Fawcett Exovest™ and the EXHAUSS ® Stronger models are mechanical arm exoskeletons, meaning they are worn like a backpack, and they have a mechanical arm that directly supports tools. The FORTIS exoskeleton is a full body exoskeleton, supporting the lower body and has a mechanical arm to support tool use. The remaining PUEE's are upper body exoskeletons that have similar features: they are worn like a backpack, with straps over the shoulders and a waist support belt, and create a moment about the shoulder to offset forces of gravity and external tools both at rest and with a hand load, typically through direct contact with the upper arm of the wearer.

The mechanical arm PUEE's have a backpack-type of design with straps over the shoulders, and a mechanical arm attached to the waist belt of the exoskeleton. These exoskeletons may be used in situations where an overhead tool support or lift assist may not be feasible due to the workstation design or dynamic nature of the task. However, these devices do not support the weight of the arm and therefore decrease risk to the shoulder due to external hand load, but not gravitational forces. Rashedi et al. found that the EXHAUSS Stronger exoskeleton increased right iliocostalis lumborum pars lumborum activity, which could be due to the additional moment created by the tool support attached to the left side of the body in this exoskeleton design (2014). Weston et al. also found when using the Fawcett with a mechanical arm that torso extension forces and muscle activation were significantly increased when using the exoskeleton (2022). This contrasts with results from arm supporting PUEE's, as they have showed no significant difference in low back activity (McFarland & Fischer, 2019). These differing results could be due to the exoskeleton design, and the location of the external tool weight, since the tool and mechanical arm mass are located farther from the body when using a tool support exoskeleton, which creates a larger moment and demand on the low back.

Exoskeletons that directly support the upper arm are the more common design. These PUEE's are worn like a backpack, secured around the waist and create a shoulder moment opposite to gravity by supporting the arm directly (McFarland & Fischer, 2019). While most of the arm support PUEE's have a similar design, there are differences including the location of the passive force generator, mass, mass distribution, and range of support. Some PUEE's, such as the Levitate © Airframe have interchangeable cassettes that allow the user to modify the support level, while others have a dial to change support level, like the PAEXO. Others have a single level of support.

While the exoskeletons have the same goal of reducing demand to the shoulder, differences have been found experimentally between designs. Alabdulkarim and Nussbaum compared a full body exoskeleton (FORTIS™), an arm support exoskeleton (SuitX™ ShoulderX™), and an exoskeleton with a mechanical arm (Fawcett Exsovest™ with a zeroG^2 arm) during an overhead drilling task in a lab environment (2019). The arm support exoskeleton had significantly lower peak and median loading of the left deltoid. Additionally, all exoskeletons had decreased upper arm rating of perceived discomfort (RPD) than the control conditions, and the full body exoskeleton had significantly lower shoulder RPD than the arm cuff exoskeleton (Alabdulkarim & Nussbaum, 2019).

Studies investigating exoskeletons of similar arm cuff design have also noted differences between exoskeletons. Jorgensen, Hakansson, and Desai compared the SkelEx, PAEXO, and EVO PUEE’s during overhead aircraft manufacturing sealing tasks (2022). Anterior and medial deltoid, upper trapezius, latissimus dorsi, and biceps brachii muscle activity were not significantly different between exoskeletons, except for one instance at the shoulder height condition where EVO had no significant difference in muscle activity, while the SkelEx and PAEXO both significantly decreased (Jorgensen, Hakansson, & Desai, 2022). However, Weston et al. evaluated the EksoVest, Airframe, and ShoulderX PUEE’s – 3 arm support exoskeletons with a similar design, during a one-hour repetitive overhead task (2022). They found the Levitate Airframe and Ekso shoulder and upper arm discomfort to be significantly lower than the ShoulderX, but neither exoskeleton caused a significant difference when compared to no exoskeleton (Weston et al., 2022). Debrosses, Schwartz, and Theurel compared two arm support exoskeletons (SkelEx and EXHAUSS) during short 15 second overhead exertions (2021). They found some differences in muscle activity between exoskeletons in the anterior deltoid, upper trapezius, and biceps brachii, but overall, both exoskeletons had significantly lower muscle activity compared to no exoskeleton (2021).

2.3.3 Exoskeleton Evaluation Settings

Exoskeletons have been studied both in lab environments and in the field. Most commonly, exoskeletons have been studied in the lab, using a range of different types of simulated overhead work tasks. These task types range from basic movement patterns like single plane arm elevation (de Vries et al., 2019), to more representative task types like lifting and carrying (De Bock et al., 2021), and finally to workplace simulations (Jorgensen, Hakansson, & Desai, 2022; de Vries, Krause, & de Looze, 2021; Pinho & Forner-Cordero, 2022). The range of task types augments the understanding of the efficacy of exoskeletons; however, it does not provide a measure of effectiveness.

There is some evidence that the efficacy results seen in lab may not fully transfer directly into the occupational environment. De Bock et al. (2021) investigated the use of two exoskeletons, SkeleX and ShoulderX both in the lab and in the field. They completed isolated static tasks in the lab, including isometric overhead holds, lifting, and squatting tasks, as well as a materials handling task involving a dynamic overhead reach component and some trunk flexion. They found that the ShoulderX performed better than the SkeleX during the overhead isolated upper arm tasks in the lab, and they found a significant 3% increase in upper trapezius activity and a 11% increase in erector spinae activity during the squatting isolated tasks using SkeleX. In the field, they found that the SkeleX performed better than the ShoulderX, causing an insignificant decrease by ~50%MVC in upper trapezius activity, and significantly increasing the erector spinae muscle activity compared to SkeleX (De Bock et al., 2021). A few differences between the exoskeletons may have contributed to these results, including a difference in support moment of the upper arm (ShoulderX = 15Nm, SkeleX = 6Nm) and weight (ShoulderX = 5.3kg, SkeleX = 4.0kg). These results may indicate that the benefits of the PUEE's investigated are task-specific; having a greater positive effect on sustained overhead tasks compared to dynamic, short bursts of overhead work.

In-lab investigations that more accurately represent the work task completed in the field may provide greater insight into the applicability of the PUEE effect to an occupational environment. Recent studies have simulated automotive assembly (Pinho and Cordero, 2022), aircraft assembly work (Jorgensen, Hakansson, & Desai, 2022) to understand the applicability of the PUEE in specific job tasks. Jorgensen, Hakansson, & Desai tested three arm support exoskeletons by simulating aircraft assembly tasks at two overhead work heights, and one below shoulder height. They recorded anterior and middle deltoids, latissimus dorsi, upper trapezius, biceps, and triceps from the upper body. They reported significant reductions in the anterior and middle deltoids both above and below shoulder height, and significantly decreased latissimus dorsi and biceps activity at the overhead task height but not at the lower task height (2022). These results demonstrate the differences in muscle activity between the deltoids and additional muscle groups such as the latissimus dorsi and biceps, however they do not include rotator cuff muscle activity. Additionally, the task duration in this study was less than 1 minute for each task, and therefore could only identify early changes in muscle activity with the exoskeleton.

Pinho and Cordero created a mock-up of a screwing assembly task completed in an automotive plant at four different hand heights and two different force directions (2022). They reported that exoskeleton use decreased anterior deltoid muscle activity by 23-34%, with greater decreases in activity at greater shoulder flexion angles and no change in muscle activity in a neutral shoulder position (Pinho & Cordero, 2022). In this study the maximum voluntary isometric contractions for the anterior and middle deltoids were performed with the shoulder in a neutral posture, which may have resulted in an underestimated maximum voluntary contraction and an overestimated percent reduction of deltoid muscle activity with the exoskeleton. Additionally, the same level of support was used for each participant regardless of their height or weight, so there may have been individual differences in response to the exoskeleton based on support level.

Fewer studies have been conducted outside of the lab environment to evaluate the effectiveness of the PUEEs. Liu et al. evaluated the Levitate Airframe worn by surgeons throughout an entire shift with and without the exoskeleton, using two surgical operative days matched for type and number of operations. They reported a significant decrease in shoulder pain scores (0.143 vs 1.143) at the end of the operative shift when wearing the exoskeleton using a 5-point pain inventory scale (2018). This study provides valuable information about the effects of the exoskeleton over the course of a full day operating in the participant's work environment. However, it is not possible to tell which muscles were most affected by exoskeleton usage and therefore driving the differences in pain reporting. Smets evaluated the EksoBionics arm cuff exoskeleton in four participants over a three-month period and found lower reports of back and arm discomfort when wearing the exoskeleton (2019), however these data were not statistically tested due to small sample size (N = 3). Participants reported the greatest perceived benefits of the exoskeleton at overhead work heights, and difficulty with any non-neutral back postures (Smets, 2019) which is consistent with the muscular demand findings from De Bock et al.

(2021). While these studies used more subjective measures of quantifying exoskeleton use, they are critical to understanding the effectiveness and application of the equipment in the field.

Other studies have been completed in the field using more objective measures like EMG. Gillette and Stephenson evaluated the Levitate Airframe over a full work shift in an automotive facility. They reported a significant increase in the anterior deltoid muscle activity by 4.2% over the course of a shift without the exoskeleton, and no significant change in activity with the exoskeleton (2019). This may indicate signs of fatigue in the anterior deltoid over the course of a shift without the exoskeleton that were mitigated with the use of the exoskeleton. Biceps, upper trapezius, and lumbar erectors were recorded as well, and no significant changes were seen from the beginning to the end of the shift in these muscles (Gilette & Stephenson, 2019), which could be in part due to the small sample size (N = 6) as slight but insignificant decreases were noted. This study provides insight into the full shift effects of the Levitate exoskeleton during automotive manufacturing tasks, however the response of additional muscles like supraspinatus and infraspinatus are critical to gain a better understanding of the effect on underlying shoulder injury mechanisms.

Irzano et al. also investigated the use of the Levitate Airframe worn by automotive manufacturing employees during two different shifts while completing overhead automotive assembly work – one shift wearing the exoskeleton and one shift without. They reported decreases in 50th percentile muscle activity in the anterior deltoid by 34%, and upper trapezius by 18-21% when wearing the exoskeleton compared to no exoskeleton (2020). The authors noted that maximum voluntary contractions were not collected from participants, and instead were estimated using the collected trial data and biomechanical models due to time restrictions during collections (Irzano et al., 2020). Additionally, it was not indicated when throughout the shift the

EMG was collected, which could influence the results as differences in anterior deltoid activation may increase over the time of the shift as previously reported by Gillette and Stephenson (2019).

2.3.4 Muscle Fatigue in PUEE Studies

Studies investigating the impact of PUEE's frequently use muscle activation to predict the effects of the exoskeleton on fatigue throughout a work shift. Maurice et al. investigated the use of an exoskeleton in a lab setting, during five 2-minute blocks of an overhead simulated screwing task with 30 seconds of rest between blocks. They recorded EMG from the anterior deltoid both with and without the PAEXO PUEE. They reported no significant change in amplitude of the anterior deltoid over the course of the 12-minute task when using the exoskeleton, however without the exoskeleton the amplitude increased significantly by 30% from the first to last block (2020). These results suggest the use of the exoskeleton was beneficial, potentially reducing the effects of fatigue. However, in this study it was noted that the amplitude values were normalized to the session maximum muscle activity, which could inflate the true percent change from the first to final task blocks, making it difficult to compare these results to other studies. Muscle activity normalized to maximum voluntary contractions, paired with additional measures of fatigue such as mean and median power frequency over a longer task duration would provide further insight into the effects of the PUEE and application in occupational settings.

Alternate methods of fatigue measurement have been used to evaluate the PUEE's as well. Weston et al evaluated three PUEE's throughout a simulated work task of 6 exertions per minute of 10 pounds of force for a duration of one hour (2022). They quantified local muscle fatigue in the middle trapezius and anterior deltoid using near infrared spectroscopy to measure changes in tissue saturation index (TSI). They reported that there were no significant changes in

TSI between the exoskeleton and no exoskeleton conditions, however the anterior deltoid and middle trapezius trended closer to zero when using the exoskeleton (2022), indicating the muscle required less oxygen consumption when using the exoskeletons. While the percent MVC was not known for the shoulder muscles in these tasks, the average discomfort rating for the shoulders was 2.3 points on a 1-10 scale (Weston et al., 2022), which could contribute to the lack of significance in the change in TSI ratings. While changes in the oxygenation levels in the muscle can provide valuable information about the oxidative metabolism demands, it cannot be directly compared to frequency and amplitude measures of muscle fatigue using sEMG (Al-Mulla, Sepulveda, & Colley, 2011).

Other studies have investigated changes in fatigue using frequency domain measures as well. Rashedi et al. evaluated the use of a mechanical arm exoskeleton using mean power frequency and normalized RMS over a 10-minute task and found the exoskeleton did not have a significant effect on the rate of decline of mean power frequency but did have a significant effect on the change in normalized RMS values over time (2014). Slight differences in posture were noted throughout the task when EMG was collected, which could have contributed to the differences seen over the 10-minute period. Schmalz et al. used mean power frequency and amplitude measures to quantify fatigue during a 5-minute continuous overhead work task. They found the slope of the change in mean power over time approached values closer to zero without the exoskeleton in the deltoids, biceps, serratus anterior, indicating reduced progression of fatigue. In the latissimus dorsi and external obliques, they found small but significant decreases in the slope of the change in mean power frequency over time, indicating increased progression of fatigue, and no significant change in the trapezius muscle. They also found a significant decrease in the mean EMG amplitude for all muscles when wearing the exoskeleton (Schmalz et al., 2019).

These results suggest that the PAEXO exoskeleton used in this study decreased local muscle fatigue in the measured shoulder muscles.

2.4 Literature Review Summary

In summary, many of the previous PUEE studies provide useful information regarding muscle activation levels in specific shoulder muscles, most commonly the deltoids and upper trapezius, during short duration tasks used to make predictions about fatigue. Other studies have used subjective measures like Borg's RPE scale and pain reporting scores over the course of a full work shift to provide information about the effectiveness of the device in a workplace setting. However, most of the studies previously mentioned did not measure fatigue directly using measures like mean and median power frequency, and those that did recorded exoskeleton use during a short duration static task in the lab.

As mentioned previously in the shoulder injury mechanism section, decreasing or delaying fatigue of the deltoids does not directly reduce risk of injury in the shoulder without additional context on how it is affecting other surrounding muscles. If the rotator cuff muscles experience fatigue and the deltoids do not, this can lead to additional upwards translation of the humeral head into the subacromial space during arm elevation, and in turn increase risk of impingement of the supraspinatus tendon. Gaining a better understanding of how the exoskeleton affects both the primary shoulder elevators along with the stabilizers (rotator cuff) is critical to determine how the exoskeleton can modify risk of injury in the workplace.

3.0 Methods

3.1 Participants

10 males (age; 23.8 ± 4.1 years, height; 178.3 ± 7.6cm, weight 80.7 ± 13.1kg) participated in 2 sessions, spaced a minimum of 7 days apart. Participants were recruited as a convenience sample from the university population. All participants were right-handed. Males were chosen to be representative of the population of workers completing the weld inspection task in industry.

3.1.1 Exclusion Criteria

Anyone with shoulder pain or injury in the last year was excluded as the overhead work may exacerbate current shoulder injuries and symptoms. Anyone with allergies to adhesives could not participate. Anyone under the age of 18, or over the age of 40 could not participate due to University of Waterloo COVID-19 restrictions at the time of ethics approval. Additionally, before the start of the first collection, the participants were asked to don the exoskeleton to ensure it would fit. There were no issues with the exoskeleton fit in the volunteers for this study.

3.1.2 Recruitment Methods

Recruitment occurred through posting on Twitter, a poster board, and a poster on the lab door. Consent was collected prior to starting the experimental procedures. Participants were remunerated $14/hour for their time, along with a lab t-shirt at the end of the final session.

3.2 Experimental Design

3.2.1 Pre-experimental Procedures

Once participants expressed interest in the study, they were emailed the consent forms and screening questionnaire. The researcher then scheduled a call with the participants to address any questions about the screening forms, confirm eligibility, and schedule their sessions. Sessions were scheduled with a minimum of seven days between to reduce chances of crossover effects from previous sessions, similar to other studies testing passive exoskeletons (Theurel et al., 2018; Rashedi et al., 2014). Additionally, during the piloting phase, there were individuals who reported some residual muscle fatigue in the shoulders up to 5 days post-completion of the overhead work task. This validated the need for the 7-day separation between sessions to decrease crossover effects.

The study design is a repeated measures design, with the same participant completing the overhead work tasks for two sessions: with the exoskeleton (EXO) and without the exoskeleton (NE). A total of two experimental sessions were completed and took approximately 4-5 hours per session, including pre-experimental setup, collections and the 2-hour task protocol. EXO and NE sessions were completed on separate testing days and spaced as mentioned. The order of the sessions (EXO, NE) was randomized with equal numbers of participants starting with and without the exoskeleton. Participants were asked to refrain from vigorous upper extremity activity that would cause residual shoulder discomfort the day before and day of the session to decrease risk of shoulder fatigue. This was discussed during the call before participants came to the lab for their first session.

3.2.2 Experimental Protocol

Study sessions consisted of two main parts: the experimental set-up and baseline measures, and the 2-hour task protocol where the participants performed the static overhead work task. After consent forms were gathered, electromyography and kinematic markers were placed, the exoskeleton was donned and fit, and baseline strength measures were taken. Following strength baselines, the participant learned the task and familiarized themselves with the exoskeleton (for the EXO session), then reference tasks were completed, and baseline ratings of exertion and discomfort were collected (**Figure 4**). If the participant's RPE was > 0, they were asked if they needed additional rest before starting the task.

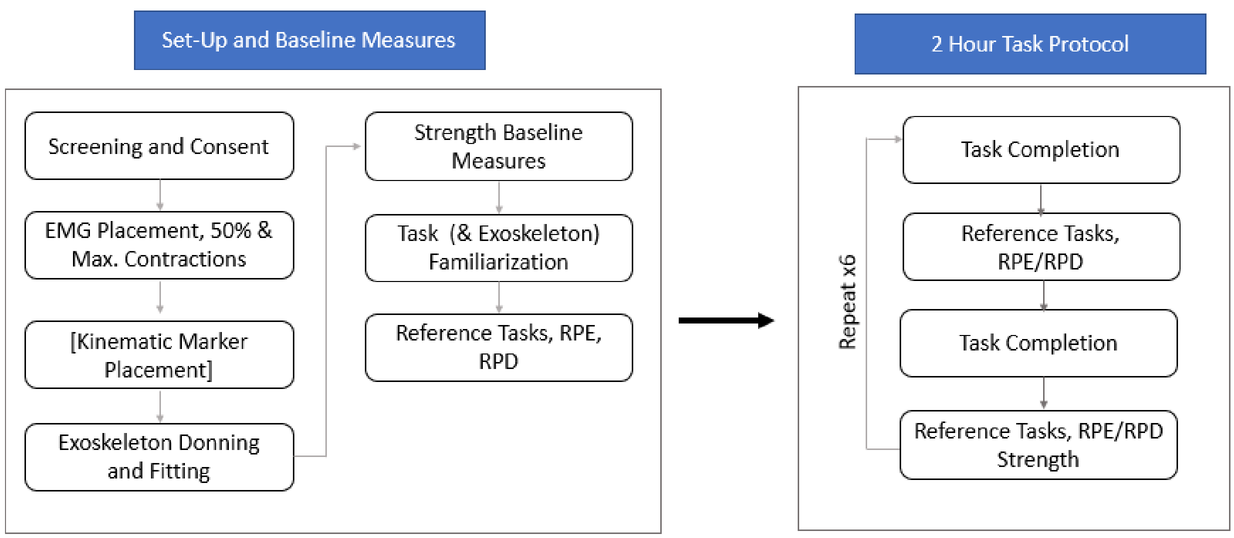

Figure 4. Single lab session collection overview, including kinematic marker placement, examination of which is not included in this thesis. In NE conditions, exoskeleton donning and fitting is omitted.

3.2.2.1 Task Familiarization

Once fitted with the exoskeleton, participants had time to get used to the exoskeleton, and practice completing the task to meet industry partner determined performance goals. The tasks were required to be completed accurately, and quickly to keep up with production demand, so the participants were required to complete the task within the designated cycle time, and without disrupting the flow of the tasks. For each task, there were key functions represented by touch points on the car underbody which were labeled in numerical order for the participants to follow (**Figure 5**). First, the tasks were demonstrated by the researcher with verbal instructions given. The tasks were repeated by the researcher multiple times with the participant following along until they were comfortable with the workflow. Following the researcher's demonstration, the participant walked through the task, explaining the task order back to the researcher. Participants were asked to avoid prolonged arm elevation while learning the task to ensure participants did not begin to fatigue before the 2-hour task protocol began. The participant could begin the experimental trials when they could follow the task workflow. The researcher and research assistant observed the participant completing the tasks and provided auditory or physical prompts to the participant as needed to maintain workflow.

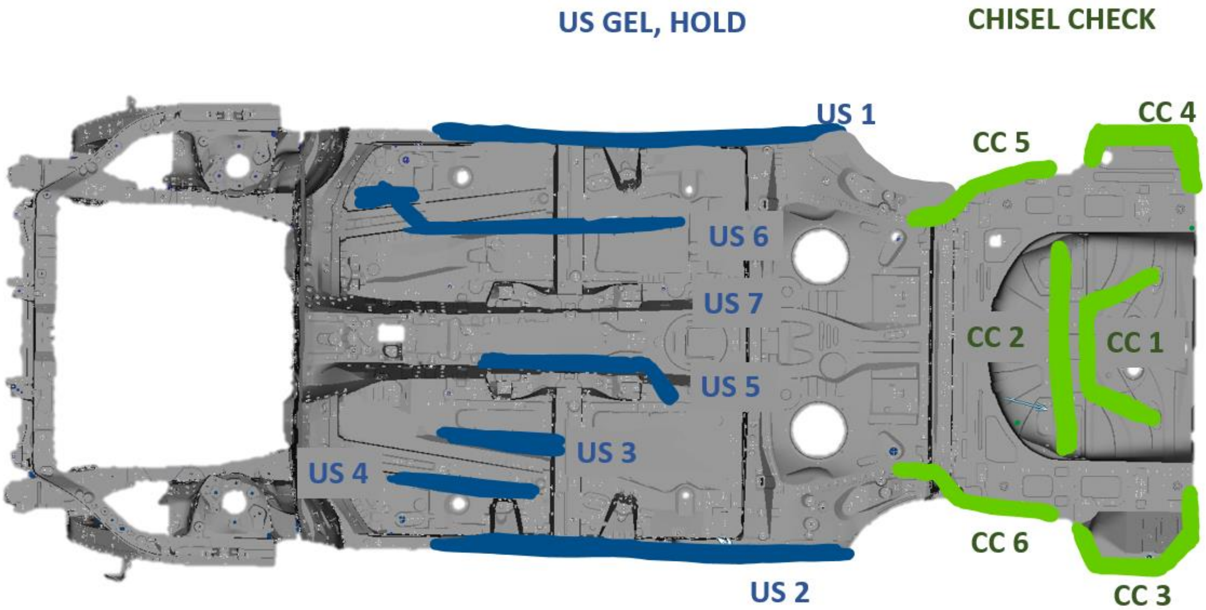

Figure 5. Weld locations labelled by grouping on the car underbody. In blue, the ultrasound gel and hold groupings (US) are indicated, with a total of 7 groupings. There are 6 groups of holds: US 1 (1-15), US 2 (16-29), US 3 (30-35), US 4 (36-40), US 5 (41-46), US 6 (47-57), and US 7 (58-63). The chisel check (CC), subtask c, is located at the back of the car to the right of the image and is indicated in green. There are 6 groups of welds: CC 1 (1-8), CC 2 (9-16), CC 3 (17-27), CC 4 (28-35), CC 5 (36-41), CC 6 (42-47).

Participants were not given specific instructions regarding which arm they had to use for the task and were able to switch arms at any point throughout the task based on preference. This was done to emulate the environment in the automotive industry, where employees are not instructed specifically about which arm to use and are instead focused on task objectives and performance goals.

3.2.2.2 Static Inspection Task

The static weld inspection task was representative of an inspection operation from an industry partner where employees are required to inspect the quality of welds on the underbody of a vehicle. The total cycle time for one weld inspection task was 20 minutes, and this consisted of three sub-tasks. Since work shifts are broken into 2-hour segments, the task protocol was 2 hours long, until the participant indicated they could not continue, or they reached an RPE/RPD 8 or higher on the Borg CR-10 scale (Borg, 1982).

The three sub-tasks were: (a) ultrasound (US) gel application, (b) US hold, and (c) chisel checks (**Figure 6**). During the US gel application, the participant was instructed to tap each touch point on the underbody of the car to the beat of a metronome set to 60 beats per minute. Once they touched all 63 touch points, they moved to the US hold subtask. The participant used the US scanner to touch and hold on each touch point for a duration of 8 seconds. The ultrasound scanner used for inspection was re-created out of wood in lab to mimic the scanning device used in industry (**Figure 7**).

Figure 6. Static weld sub tasks. US gel and US hold shown on the left, Chisel check (HIT) on the right.

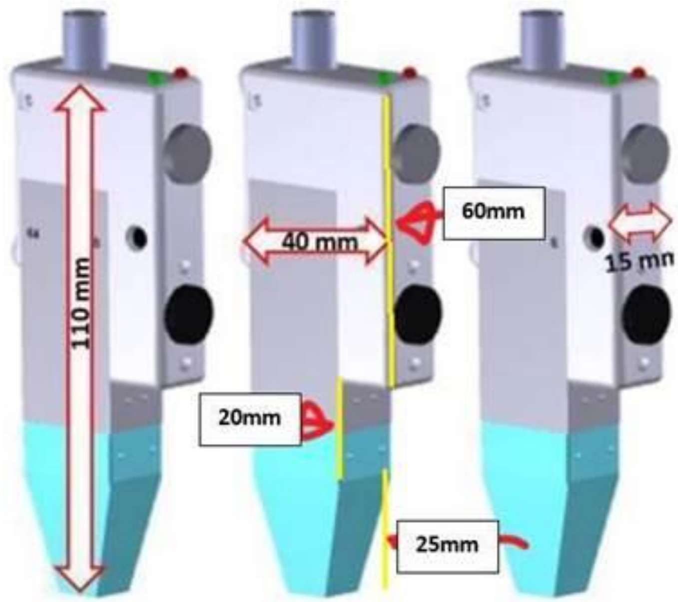

Figure 7. Ultrasound scanner with dimensions in millimeters, recreated out of wood for the static inspection task.

Participants were prompted to move to the next touch point by an audible cue, which beeped during the last 3 seconds of the hold to prepare the participant and provided a distinct whistle or bell sound to move to the next weld location. These cues were provided using a mobile Tabata Timer application (Serhiienko, 2022).

Once the static inspection task was complete, the participant retrieved the hammer and chisel to complete task c), the chisel check. During this subtask, the participant was instructed to complete the task with precision – lining up the chisel directly over the numbered locations, and then tapping the chisel with the hammer when the countdown began. The participant was given 5 seconds per chisel check, and there were 47 total weld locations that required these checks. Weld locations were grouped into six groupings and labelled with coloured tape on the underbody. This indicated the start of a series of welds that was followed linearly, and each grouping consisted of 6-11 weld points (**Figure 5**). Arrows were placed on the underside of the car body to visually prompt the participant to move to the start of the next grouping of welds to streamline workflow.

3.3 Instrumentation

3.3.1 Exoskeleton

One Airframe exoskeleton (Levitate Technologies Inc., San Diego, CA) was used for this study. The researcher was trained on how to fit the exoskeleton to the user virtually by the manufacturer to ensure the equipment was being used in accordance with manufacturer guidelines. When fitting the exoskeleton to the participant, the adjusted elements were the waist band and hip supports, superior/inferior adjustment, lateral/medial adjustment, and the shoulder adjustment (**Figure 8**). According to the manufacturer and the industry partner, the exoskeleton is adjusted primarily to ensure the comfort of the wearer. However, specific anatomical landmarks were used for reference when adjusting the exoskeleton: the shoulder adjustment over the acromion, the superior portion of the waist band just below the iliac crest of the participant, and when the participant raises their arms, there should be no contact between the skin and point D on the exoskeleton. The last adjustment is on the arm cuff (point E) which was adjusted so the arm cuff (point F) was superior to the medial and lateral epicondyles.

Figure 8. Levitate exoskeleton with labelled adjustable parts. (A) Waist belt, (B) superior inferior back, (C) medial lateral, (D) shoulder rotation, (E) cuff length adjustment, and (F) end of cuff. Images from: https://www.levitatetech.com/

Once the researcher completed the initial fitting, the participant was asked to raise and lower their arms, mimicking the movements completed during the task protocol. Adjustments were made based on the researcher's observations and participants feedback to ensure wearer comfort. The same researcher fit the exoskeleton for each participant to ensure consistency. Level of exoskeleton assistance was determined based on the cassette installed on the device. The cassette is shown in Figure 8 and contains the spring-based mechanism that transfers passive energy to the user. Exoskeleton support cassettes were initially selected by approximating the participant's arm weight, as a portion of their total body weight (Winter, 2009).

$$
\begin{aligned}
\text{Arm weight} &= (\text{upper arm} + \text{forearm} + \text{hand})*\text{Total body mass} \\
&= (0.028+0.016+0.006)*\text{TBM} \\
&= 0.05*\text{TBM}
\end{aligned}
$$

Equation 1. Arm weight calculation (Winter, 2009).

Calculated arm weight was rounded up to match the nearest cassette support level (cassette maximum support levels = 2.72, 3.63, or 4.54kg). Once this was calculated, the cassette was installed onto the exoskeleton during the familiarization period, and the participants were asked to raise their arms 90° in front of them, with elbows extended and then to relax their muscles. If the exoskeleton support was too low, the arms would fall to their sides, and the cassette support was then increased to fully support the arms. This method for cassette selection is in accordance with methods used by the industry partner to replicate the task conditions and exoskeleton fit as closely as possible and approximates methods used in previous research to select exoskeleton support levels (Maurice et al., 2020; Jorgensen, Hakansson, & Desai, 2022).

Once the exoskeleton was properly fitted, the hip pads and back pad location were marked on the participant with washable marker to ensure the exoskeleton position remained consistent throughout the two-hour task protocol. Special attention was paid to the exoskeleton position after the participant completed a sit to stand movement, as forward flexion of the torso increases risk of the hip pads shifting on the participant.

3.3.2 Electromyography

The anterior deltoid, middle deltoid, upper trapezius, supraspinatus, and infraspinatus were recorded bilaterally via surface electromyography. Placement of the electrodes is described in **Table 1**, based on published electrode placements (Criswell, 2011). Each electrode placement site was prepped by lightly shaving with a disposable razor and cleaning the skin’s surface with isopropyl alcohol to decrease skin impedance (Yasojima et al., 2008). Disposable bipolar

Ag/AgCl pre-gelled surface electrodes (Noraxon, USA Inc., Arizona, USA) with fixed 2cm inter-electrode distance were used to record each muscle. EMG was sampled using a wireless 16-channel Noraxon TeleMyo 2400R G2 unit (Noraxon 2 USA Inc., Arizona, USA) at a rate of 1500 Hz, and was collected using Nexus software version 1.8.5 (Vicon, Oxford, UK). An analog band-pass filter of 10-500 Hz was applied, with a base gain of 500.

After electrode placement, participants were asked to complete a submaximal contraction of approximately 50% maximum to visually inspect signals, adjust gain settings for the maximum voluntary contractions (MVC), and to familiarize the participants with the MVC postures. Gain was adjusted individually for each muscle based on this initial 50% contraction to prevent signal clipping and optimize signal resolution.

Two MVC trials were completed for each muscle with 2 minutes of rest between trials to prevent fatigue (DeLuca, 1997). Participants were asked to ramp up to their max, hold the max for approximately 1-2 seconds, and then ramp back down. Researchers provided verbal encouragement throughout the MVC trial, unless requested by participants to remain silent (Bingboga et al., 2013). Trials were collected for 5 seconds to ensure the full burst of muscle activity was captured.

Table 1. Summary of EMG placements and MVC trials based on Criswell (2010). Upper trapezius placement slightly modified.

Muscle	Electrode Placement	MVC Details
Infraspinatus	The spine of the scapula is palpated, and the electrode is placed about 4cm below the spine on the muscle belly in line with the muscle fibers.	Participant is seated, with their arm at their side in 0° elevation, with the elbow flexed to 90°. The participant will externally rotate their arm against manual resistance from this position.
Supraspinatus	The spine of the scapula is palpated, locating the lateral distal portion. The muscle belly location is confirmed by participant exerting force in elevation. The electrode is placed directly above the scapula over the suprascapular fossa.	1) Side lying: Participant lies on their side, with their arm raised 5° with elbow extended. Force is exerted in elevation. 2) Seated: Participant is seated, with their arm elevated 90° in the scapular plane, in the full can position with elbow extended. Force is exerted in elevation (Alenabi et al., 2018).
Anterior Deltoid	The electrode is placed over the muscle belly, approximately 4cm distal to the clavicle parallel to the muscle fibers.	Participant is seated and arm elevated in the sagittal plane to 90° with elbow extended. Force is exerted in elevation.
Middle Deltoid	The electrode is placed over the muscle belly in line with the muscle fibers, approximately 3cm distal to the acromion.	Participant is seated with arm elevated to 90° in the coronal plane with elbow extended. Force is exerted in elevation.
Upper Trapezius	Electrode is placed over the muscle belly, on the line between C7 and the acromion, approximately 3cm lateral to C7 (modified).	Participant is prone with arm elevated to 90° in the coronal plane. Force is exerted in elevation.

After piloting, it was determined that the upper trapezius electrode placement required a more medial location than recommended by Criswell (2011), to accommodate the exoskeleton straps and avoid motion artifact. McLean et al. demonstrated that multiple placements can be used for the upper trapezius muscle (2003), however due to limited space distal to the exoskeleton straps, the electrode was placed medially. When placing the electrode, C7 and the acromion were palpated and marked with washable marker, and the muscle belly was palpated during contraction prior to the electrode being placed. The electrode was placed approximately 3cm from C7 over the muscle belly. The signals were visually inspected using a 50% muscle contraction prior to completing the MVC.

3.3.3 Force

Force was collected using an AMTI 6-degree-of-freedom force transducer (MC3A; AMTI, Watertown, MA), attached securely to a custom moveable jig with a clamp to allow the force cube to be moved up and down on a steel column to accommodate each participant's individual anthropometrics, and the difference in height requirements between the two force positions. Force was sampled at 1500 Hz using Nexus 1.8.5 software (Vicon, Oxford, UK). Two maximal force exertions were completed bilaterally: elevation and external rotation.

Participants were instructed how to avoid compensatory movements during the maximal voluntary force (MVF) exertions, such as torso rotation and side-bending. The researcher visually monitored the participant and force trace for compensation, and if it occurred the trial was repeated. Participants completed a sub-maximal exertion prior to the MVF to familiarize themselves with the movement, and ensure they were exerting force in the correct direction. The chair participants were seated on was attached to a wooden platform to prevent chair movement during the exertions. If chair movement occurred during the exertion, weight was added to the wooden platform to ensure the contraction remained static. The chair location and vertical height of the force jig was marked with tape for each force posture for each participant to ensure a consistent static posture was maintained throughout the task protocol.

3.3.3.1 Elevation

Participants' were seated, with their arm raised to 90° of abduction, with their hand gripping the force handle (**Figure 9**A). Elevation angle was verified using a goniometer. They were seated with their low back touching the back of the chair, head up looking forward, shoulders aligned with the chair back and perpendicular to the force handle. A researcher visually monitored each force exertion to ensure correct posture was maintained during the static maximum voluntary force trials. Force was measured in elevation to determine changes in strength primarily related to the shoulder elevators (deltoids, supraspinatus). Of note, grip strength may have affected the maximum values obtained in this posture. The workplace task challenged primarily participants shoulder elevators required to raise the arm, so minimal changes in grip strength over time due to the task demands were expected.

3.3.3.2 External Rotation

The participant was seated, with their upper arm at 0° elevation and externally rotated 45°, elbow flexed to 90°, and dorsal hand against the force handle (**Figure 9**B). A neutral arm elevation angle was maintained using a custom 1" foam block placed between the upper arm and torso to prevent elevation of the humerus during the maximum voluntary force trial. External rotation angle was verified using a goniometer. The participants were instructed to externally rotate their arm against the force handle, while maintaining a neutral torso posture and head position. Force was measured in this posture to measure changes in strength primarily related to the shoulder external rotators (infraspinatus).

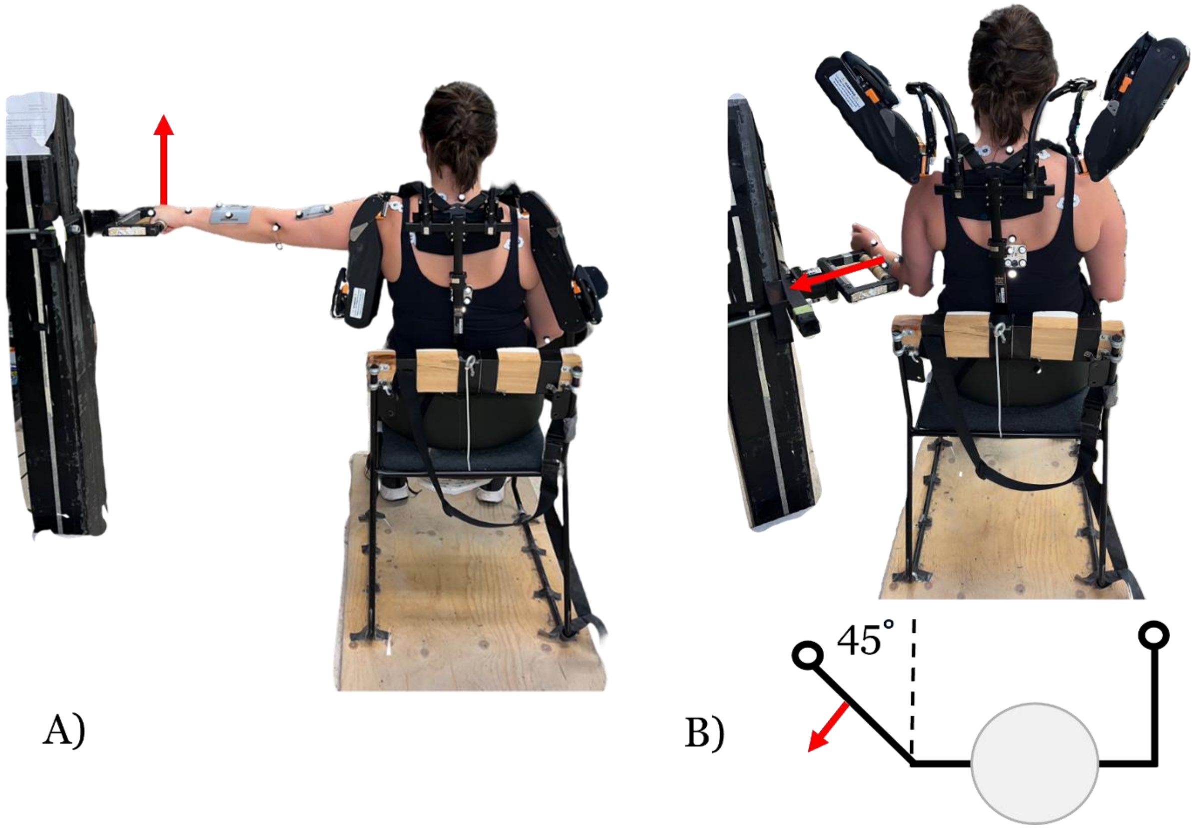

Figure 9. Elevation (A) and External Rotation (B) force tasks. The red arrow depicts the direction of force exerted by the participant onto the force handle.

Three repetitions of the force tasks were completed (DeLuca, 1997) prior to the two-hour task protocol to determine the daily maximum force. At least 30 seconds rest was given between repetitions, and 2 minutes rest was given between force postures to reduce the effects of fatigue (DeLuca, 1997). The researcher asked the participant if they were ready to complete the next exertion, and if not, additional rest was provided. Once the task protocol began, the participants completed one repetition bilaterally for each force posture every 20 minutes throughout the protocol. Reasoning for force postures is given in **Table 2**.

Table 2. Force postures and descriptions.

Posture	**Reasoning**
External rotation	To quantify fatigue in the rotator cuff, specifically infraspinatus.
Elevation	To quantify fatigue in the rotator cuff (supraspinatus) and arm elevators (anterior and middle deltoid, upper trapezius).

3.3.4 Electromyography Reference Task

A reference task was completed at baseline and repeated once every 10 minutes throughout the duration of the 2-hour task protocol. Participants stood with their elbow fully extended and arm elevated to 90° (**Figure 10**), thumb facing the ceiling, holding an anthropometrically scaled weighted bottle for 5 seconds.

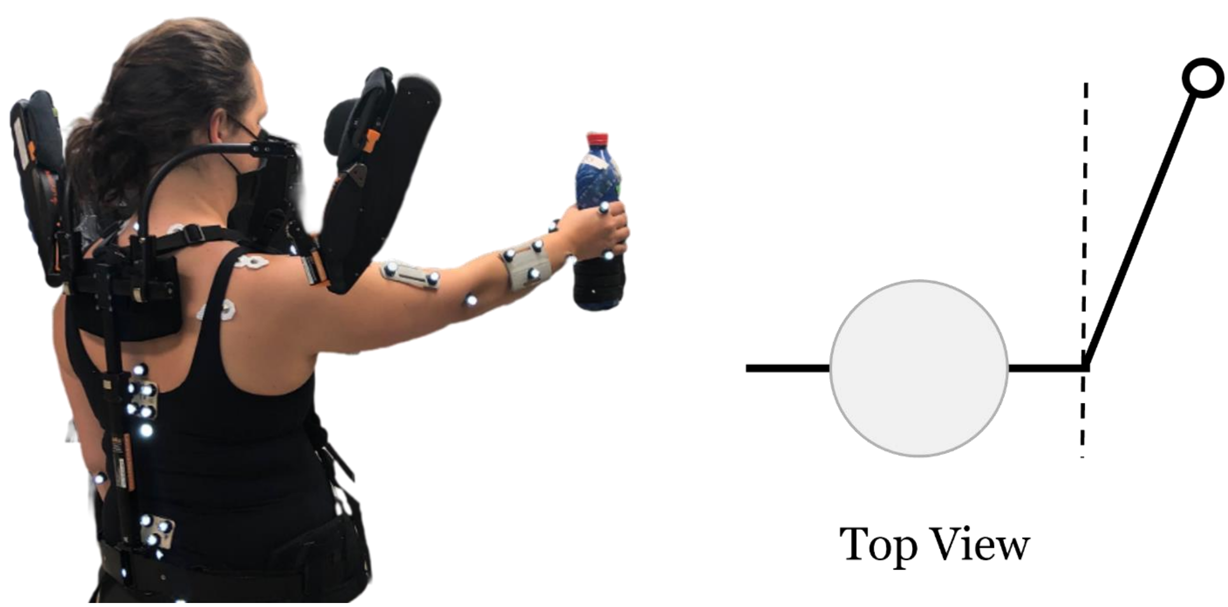

Figure 10. Representative EMG reference task (left), with a top view of the participant's arm posture (right). The top view shows the arm deviated 30 degrees clockwise from the sagittal plane.

The bottle weight was scaled in 0.5kg increments to the participant's maximum strength in the sagittal and coronal planes. To scale the bottle weight, force was measured on the right and left sides during the anterior deltoid and middle deltoid MVC's for a total of 8 force exertions (Chopp et al., 2010). A handheld ErgoFet 300 force dynamometer (Hoggan Scientific, Salt Lake City, UT, USA) was used to measure the peak force during the 8 MVC's. During the anterior deltoid MVC, force was measured with the padded foam extension on the ErgoFet placed superior to the radial styloid to avoid discomfort. During the middle deltoid MVC, the ErgoFet was placed superior to the ulnar styloid on the wrist. These 8 exertions were averaged and used to represent the maximum strength for the reference task. 10% of the maximum strength was calculated, and this number was rounded up to the nearest 0.5kg to determine the bottle weight for the reference task. This bottle weight and reference task were selected as it is similar to previous shoulder fatigue protocols (Chopp et al., 2010; Chopp-Hurley et al., 2016) and to avoid causing additional fatigue outside of the task protocol. Additionally, the bottle had to be held static during the 5 second contraction (DeLuca, 1997; Phinyomark et al., 2012) and as the participants were predicted to fatigue during the 2-hour protocol, compensatory movements are more likely to occur to maintain bottle position at higher bottle weights. The bottle weight for the two sessions was the same. The bottle was placed on a height-adjustable shelf with the bottle location marked for participant reference and to maintain the same bottle location throughout the 2-hour protocol. Once the participants' posture had been set relative to the shelf, the researcher also taped the floor to ensure consistent foot placements.

3.3.5 Ratings of Perceived Exertion and Discomfort

Ratings of perceived exertion and discomfort were measured using a Borg-CR10 scale (Borg, 1990). The Borg CR-10 scale has been used to determine the perceived intensity of different variables including physical exertion and discomfort (Borg, 1990). The CR-10 scale includes verbal anchors at different levels of exertion from 0 to 10. Zero on the scale represents no exertion at all, 0.5 represents a feeling of exertion that is extremely weak or just noticeable. These cues continue until the scale reaches 10, which is anchored by the cues ‘extremely strong’ or ‘almost max’ (**Figure 11**). This was described as the highest amount of exertion someone has ever experienced (Borg, 1990). Prior to recording baseline measures, the anchors of the Borg CR-10 scale were explained for whole body exertion, and also for specific body region discomfort. It was explained to participants that whole body exertion should not be heavily influenced by a single pain in the arm or leg, but representative of how someone is feeling overall. The rating of discomfort measures described the discomfort felt in specific body regions using the CR-10 scale, in this case in the left and right shoulders, elbows, and wrists.

Borg's CR-10 scale

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

Figure 11. The Borg CR-10 scale from Borg (1990), otherwise known as the category ratio (CR) scale. This scale was printed and affixed to the wall for participants to use as a reference when asked for their rating of whole-body exertion, shoulder, elbow, and wrist discomfort at baseline and at each 10-minute increment throughout the 2-hour task protocol.

A poster was located on the wall for participants to reference when these ratings were recorded at baseline and every 10 minutes during the 2-hour protocol. Before starting the task, the researcher explained how to use the scale, and asked the participant if they had any questions about the ratings. These ratings were recorded at baseline, before the task started, and at 10-minute intervals throughout the task protocol.

These ratings were also used to monitor the 2-hour task intensity and provide a subjective measure of fatigue progression during the protocol. The task was ended before the 2-hour limit if the participant recorded a rating of 8 or higher for any of the recorded measures (Whittaker et al., 2019). Participants could also verbally indicate they could no longer continue the task at any time. If the task was completed before the 2-hour mark, final RPE and RPD measures were taken, and final reference tasks and strength measures were completed. Two participants ended the task early (after the 80- and 100- minute time points), both in the NE group.

3.4 Analysis

3.4.1 Reference Task

Change in mean power frequency over time was calculated to assess local muscle fatigue progression throughout the 2-hour task protocol. A decrease in mean power frequency from baseline indicates muscular fatigue progression (Oberg, Sandsjo, & Kadefors, 1990). Mean power frequency (MPF) was calculated during each 5 second static reference task throughout the 2-hour task protocol. EMG was collected for 5 seconds during each static reference task for the right and left arms. This signal was used to perform a Fast Fourier Transform (FFT) for 0.5 second epochs (Oberg, Sandsjö, & Kadefors, 1994), resulting in 10 epochs. The MPF of the epochs was calculated as the sum of the spectral moment at each frequency divided by the total spectral moment, to determine the MPF of each epoch. Epoch 1, 2, 9, and 10 were removed, and epoch 3-7 were averaged to calculate an average MPF value for each trial (10 minutes, 20 minutes, etc). This was done to select the epochs with the most stable EMG data, as there were a few instances where the EMG fluctuated during the first and last second of recording as the participant steadied the bottle or anticipated putting it down. Trials were completed at baseline, and every 10 minutes throughout the 2-hour task protocol. Signals recorded during EMG reference task trials throughout the 2-hour task protocol were normalized to the baseline measure and expressed as a percent difference.

3.4.2 Force

Force trials were filtered using a 4 Hz low pass Butterworth filter. Most of the signal power of repetitive movements is below 6 Hz (Winter, 2009), and since the strength tasks were static, the signal frequency would be below 6 Hz. Therefore, the filter cutoff frequency chosen was 4 Hz.

The peak force was extracted from the filtered force data. After filtering, the maximum force value from the three baseline measures was extracted, and the maximum of those values was used to represent the session maximum force for each posture. The session maximum was calculated for each posture for the left and right arms. The maximum force was then extracted from each maximum force trial completed every 20 minutes during the 2-hour protocol, and normalized to the baseline trial, expressed as a percentage difference.

3.4.3 Rating of Perceived Exertion and Discomfort

Participants were given instruction on how to rate perceived exertion and discomfort using the Borg CR-10 scale (Borg, 1990). Rating of perceived exertion and rating of perceived discomfort for the left and right shoulders, elbows, and wrists were measured at baseline and at 10-minute intervals throughout the task protocol. Baseline measures > 0 were subtracted from the in-task trials to remove bias.

3.4.4 Statistics

Three-way, two-tailed repeated measures ANOVAs were used, with a Bonferroni correction applied to a p-value of <0.05 to determine significance for the psychophysical, force, and mean power frequency variables. For each dependent variable, there were three factors: exoskeleton, time, and hand. Each factor had multiple levels. Exoskeleton has two levels: exoskeleton (EXO) and no exoskeleton (NE). Time had multiple levels, based on the dependent variable tested. For strength measures, time had 7 levels (0, 20, 40, 60, 80, 100, and 120 minutes). For the remaining dependent variables, time has 13 levels (0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, and 120 minutes). Hand had two levels, LEFT and RIGHT.

If there was an interaction between two factors, this was interpreted first before the main effects. The main effects, if significant, indicate if there was an influence of each specific factor.

The main effect of exoskeleton tells us whether there was a significant difference between wearing the exoskeleton or not, regardless of time or hand. The main effect of time tells us whether the dependent variables changed over the course of the 2-hour protocol, regardless of the influence of the exoskeleton or hand. This provides the most insight into how the task itself affected the participants. The main effect of hand, if significant, indicates if there was a difference between the participants right and left sides. The interaction between hand and time will determine if the participants significantly changed their strategy to complete the task over time. Exoskeleton by hand interaction, if significant, indicates that there was a difference in response between the left and right sides that was dependent on if the participants were wearing the exoskeleton or not.

4.0 Results

Results are discussed below in the order of psychophysical measures including RPE, RPD of the shoulder, wrist, and elbow, force in abduction and external rotation, and mean power frequency of five muscles (**Table 3**). Significant interactions are interpreted first, and if no significant interactions exist, main effects are discussed. The results revealed a significant decrease in RPE and shoulder RPD, and an increase in wrist RPD with EXO use. External rotation force was significantly lower in the EXO group. Mean power frequency decreased over time in the supraspinatus, infraspinatus, and upper trapezius, indicating these muscles experienced fatigue due to the 2-hour protocol. The use of the exoskeleton decreased markers of fatigue in these muscles.

Table 3. Dependent variables statistical tests, factors, and levels included in this thesis. Main effects and interactions tested for outlined.

Dependent Variable	Statistical test	Factors	Levels	Main effects and interactions
RPE	Two-way ANOVA	Exoskeleton	EXO, NE	Exoskeleton Time Exoskeleton*Time
		Time	0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120	
Elbow RPD Wrist RPD Shoulder RPD Upper trapezius MPF Supraspinatus MPF Anterior deltoid MPF Middle Deltoid MPF Infraspinatus MPF	Three-way ANOVA	Hand	Left, right	Exoskeleton Time Hand Exoskeleton*Time Exoskeleton*Hand Time*Hand Exoskeleton*Time*Hand
		Exoskeleton	EXO, NE	
		Time	0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120	
Abduction force External rotation force	Three-way ANOVA	Hand	Left, right	
		Exoskeleton	EXO, NE	
		Time	0, 20 40, 60, 80, 100, 120	

4.1 Rating of Perceived Discomfort and Exertion

No significant interactions occurred for the shoulder, elbow, or wrist, and therefore the main effects will be interpreted below. Main effects of time and hand were significant for the shoulder, and main effects of time were significant for the wrist, elbow, and RPE. Main effects of exoskeleton was significant for the shoulder and wrist (**Table 4**). Baseline measures > 0 were subtracted from the in-trial data to remove bias, and occurred for only one participant (NE baseline RPE = 1, EXO baseline RPE = 2, EXO baseline shoulder RPD = 1). All other participants had a baseline RPE and RPD of 0.

Table 4. Summary of p-values for main effects and interactions for the three-way ANOVA for dependent variables of rating of perceived exertion of the shoulder, elbow, and wrist. Significant effects (p<0.002) denoted with an **asterisk***.

	Main Effects			Interactions			
Dependent Variable	Exo	Time	Hand	Exo* Time	Exo* Hand	Hand* Time	C*T*H
Shoulder	**<0.0001***	**<0.0001***	**<0.0001***	0.0842	0.846	0.2082	0.999
Elbow	0.1537	**<0.0001***	0.0113	0.1398	0.9104	0.8362	0.9998
Wrist	**<0.0001***	**<0.0001***	0.0073	0.1147	0.8745	0.9957	0.9975
RPE	**<0.0001**	**<0.0001**	n/a	0.1164	n/a	n/a	n/a

4.1.1 Main Effect of Time

Main effects of time for ratings of perceived exertion, shoulder, wrist, and elbow discomfort are discussed below. Summary of post-hoc results are provided in **Table 5-8**.

Table 5. Summary of post-hoc tests completed for the main effect of time on RPE. Letters not connected by the same number are significantly different as per the Tukey HSD.

Time	Mean	SD	DF	F Ratio	P Value	Tukey HSD
10	1	0.888523	11	10.0042	<0.0001	E
20	1.875	1.588404				CD
30	1.375	1.086702				DE
40	1.975	1.282216				BCD
50	1.8	1.361114				CDE
60	2.3	1.399248				ABC
70	2.0625	1.404586				BCD
80	2.4875	1.606883				ABC
90	2.25	1.556795				ABC
100	2.671053	1.637352				AB
110	2.416667	1.888432				ABC
120	2.916667	2.095162				A

The RPE data over time reveals an interesting trend in the data, described as a ‘saw-tooth’ pattern. The light blue markers (**Figure 12**) indicate the testing intervals that were collected post unilateral US hold task. The black dots indicate the 20-minute intervals which were collected post bilateral hit check task. In each case, there is a positive slope from the 10 to 20-minute intervals (blue to black markers), indicating that RPE was increasing, and from the black to blue markers there was a negative slope indicating some recovery in RPE after the unilateral task.

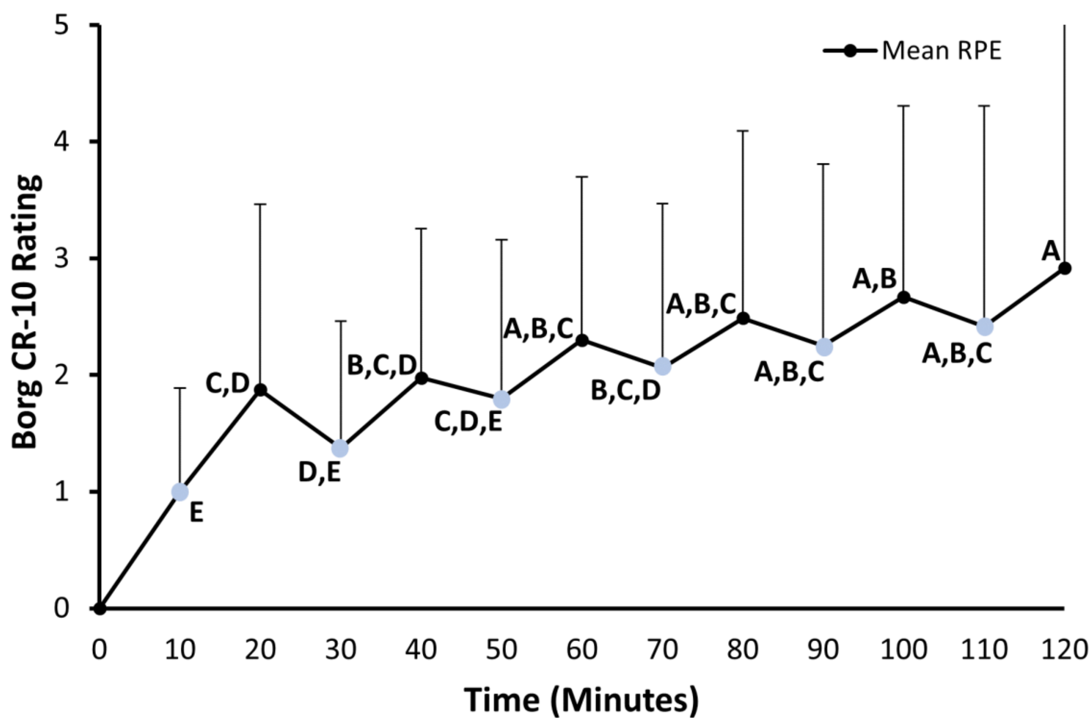

Figure 12. Mean rating of perceived exertion (RPE) over the 2-hour protocol, measured every 10 minutes. Levels not connected by the same letter are significantly different as per the post-hoc Tukey HSD test results (**Table 5**). The 10-minute levels, indicated with a light blue marker, were recorded post US hold subtask, and the 20-minute levels were recorded post hit check subtask.

Further, when looking at the Tukey HSD results, the 10-, 30-, and 50-minute intervals share the letter E, indicating their statistical similarity, while the remaining 20-minute intervals do not. As time progresses, RPE continues to increase, with the final 120-minute recording being statistically higher than the 10-50 and 70-minute time points with an increase of 1.92 points from 10 to 120 minutes. Overall, it appears there is a pattern that as time goes on, the RPE will increase at the 20-minute intervals, decrease slightly at the next 10-minute interval, and then continue to increase thereafter with a general upward trend of the data.

Table 6. Summary of post-hoc test on main effect of time for shoulder RPD.

Time	Mean	SD	DF	F Ratio	P Value	Tukey HSD
10	1.35	1.277016	11	19.5103	<0.0001	E
20	2.1125	1.542091				CD
30	1.625	1.169867				DE
40	2.2875	1.484482				C
50	2.0875	1.440653				CD
60	2.475	1.559504				BC
70	2.325	1.748809				C
80	3	1.963611				AB
90	2.328947	1.669586				BC
100	2.855263	1.822932				AB
110	2.236111	1.545667				BC
120	2.972222	1.927042				A

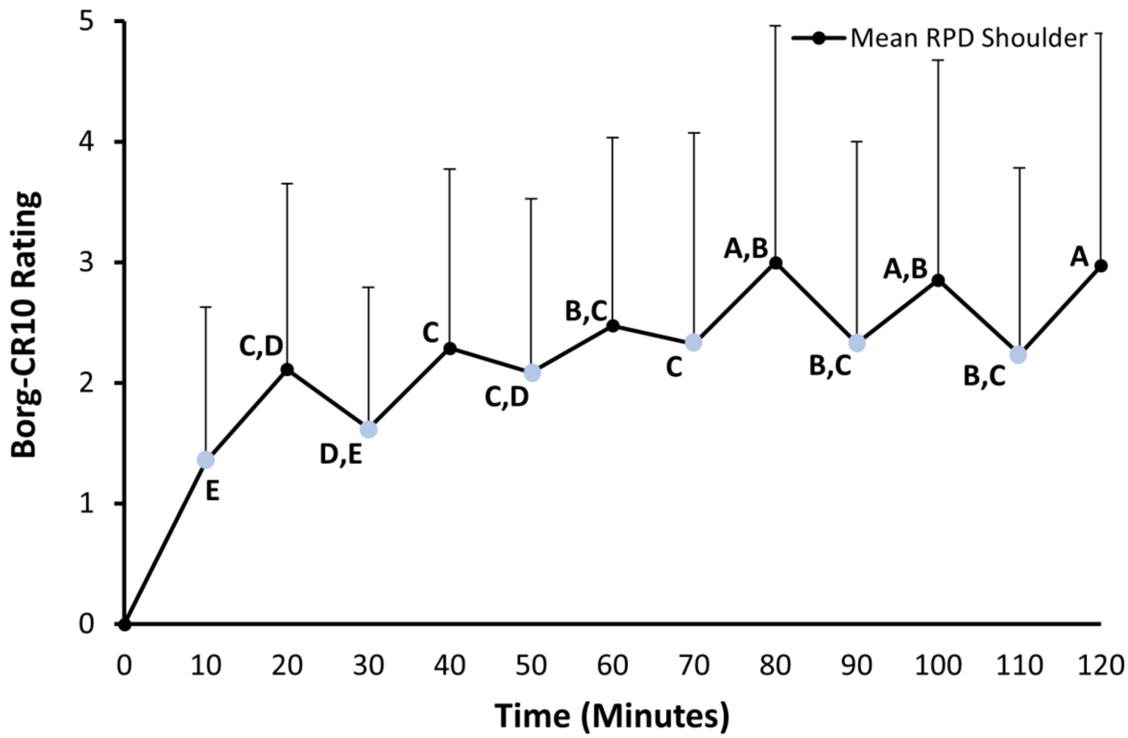

Figure 13. Mean rating of perceived shoulder discomfort (RPD) over the 2-hour protocol, measured every 10 minutes. Levels not connected by the same letter are significantly different as per the post-hoc Tukey HSD test (**Table 6**). The 10-minute levels, indicated with a light blue marker, were recorded post US hold, and the 20-minute levels were recorded post hit check.

A similar 'saw-tooth' trend can be observed in the shoulder RPD data presented in **Figure 13**. Mean shoulder RPD increased significantly from the 10 to the 120 minutes by 1.62 points. In the shoulder, the 120-minute time point is statistically similar to the 100- and 80-minute times, while the 90- and 110-minute marks are lower than at 120 minutes, indicating that there was a significant decrease or recovery of shoulder RPD during the unilateral task. Overall, there appeared to be a similar pattern as that observed with the RPE data (**Figure 13**), where the RPD increased over time, with some recovery occurring after the unilateral task but a consistent trend upwards.

Table 7. Summary of post-hoc test on main effect of time for wrist RPD.

Time	Mean	SD	DF	F Ratio	P Value	Tukey HSD
10	0.25	0.41				D
20	0.74	0.91				BC
30	0.55	0.75				CD
40	0.93	1.18				ABC
50	0.89	1.05				ABC
60	0.99	1.22	11	9.66	<0.0001	AB
70	0.83	1.07				BC
80	1.16	1.41				AB
90	0.86	1.06				ABC
100	1.04	1.14				AB
110	1.00	1.13				AB
120	1.21	1.36				A

The mean wrist RPD increased significantly from 10 to 120 minutes of 0.96 points (**Figure 14**), however the overall rating of discomfort was lower for the wrist (mean = 1.2) than it was for the RPE (mean = 2.9) or the shoulder RPD (mean = 3.0). The final RPD at 120 minutes was significantly higher than the RPD at the 10-30 minute and 70 minute marks, and there was a slight saw-tooth pattern but less pronounced than shoulder RPD or RPE (**Figure 12**, **Figure 13**) indicating that the bilateral hit check was more demanding on the wrist than the unilateral task but the tasks were less demanding overall on the wrist.

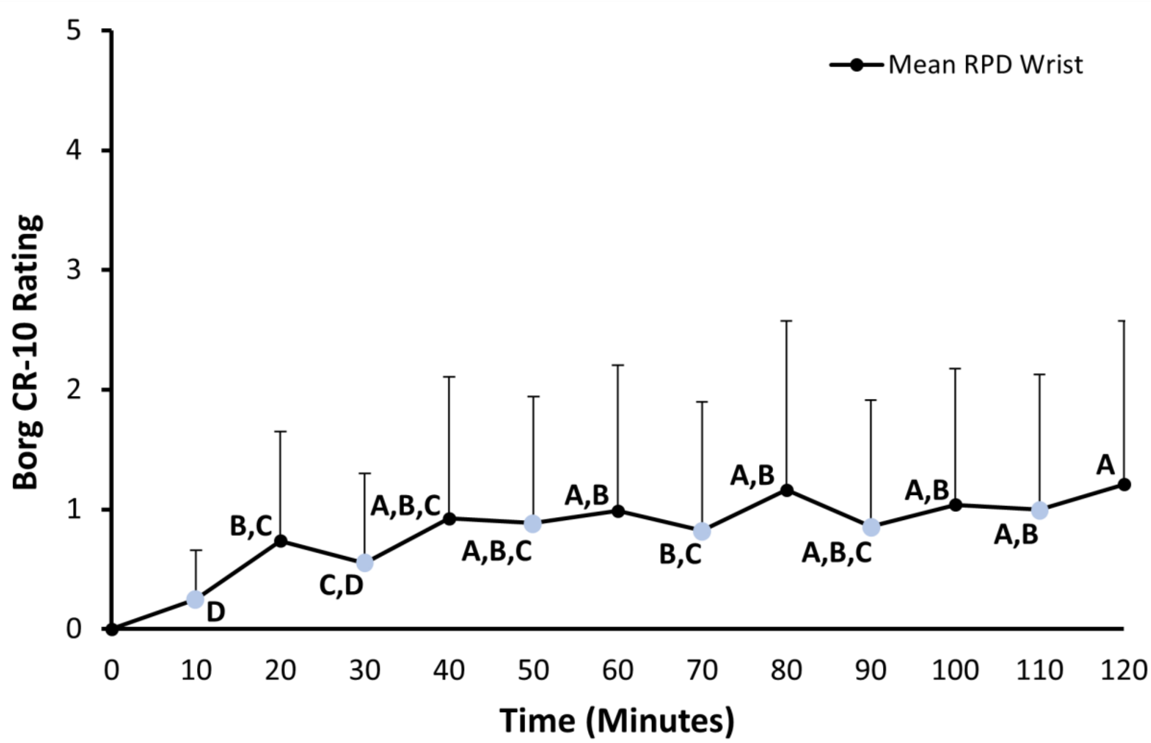

Figure 14. Mean rating of perceived wrist discomfort (RPD) over the 2-hour protocol, measured every 10 minutes. Levels not connected by the same letter are significantly different as per the post-hoc Tukey HSD test (**Table 7**). The 10-minute levels, indicated with a light blue marker, were recorded post US hold, and the 20-minute levels were recorded post hit check.

Table 8. Summary of post-hoc test for main effect of time on elbow RPD.

Time	Mean	SD	DF	F Ratio	P Value	Tukey HSD
10	0.20	0.39	11	15.37	<0.0001	F
20	0.48	0.57				EF
30	0.58	0.75				DE
40	0.74	0.83				CDE
50	0.71	0.93				CDE
60	0.88	0.88				BCD
70	0.88	1.00				BCD
80	1.05	1.16				ABC
90	0.96	1.04				ABC
100	1.04	1.04				AB
110	1.00	1.02				ABC
120	1.25	1.33				A

There was a significant increase in Elbow RPD from 10 to 120 minutes of 1.05 points. The final time point is significantly higher than the 10–70-minute time points and is statistically the same as the 80–100-minute time points (**Figure 15**). Time points 50-110 all share the letter B, indicating that they are statistically the same, and there is no noticeable fatigue or recovery between the unilateral and bilateral tasks. This could be due to the nature of the task not being demanding on the elbow, as evident from the overall low RPD scores (**Table 8**).

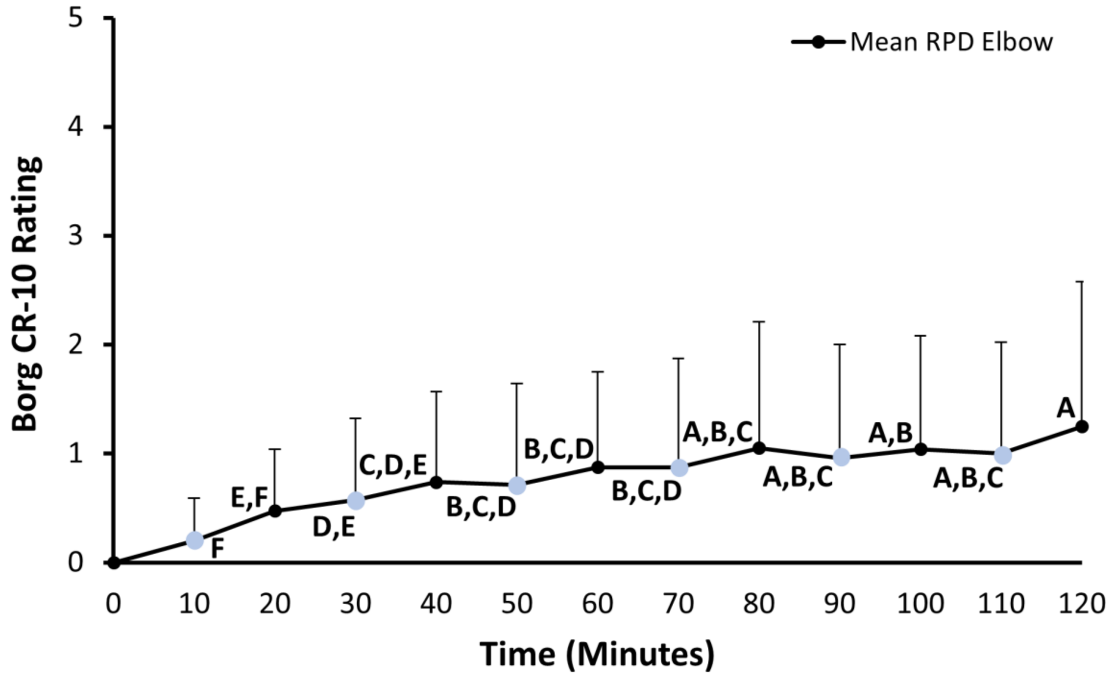

Figure 15. Mean rating of perceived elbow discomfort (RPD) over the 2-hour protocol, measured every 10 minutes. Levels not connected by the same letter are significantly different as per the post-hoc Tukey HSD test (**Table 8**). The 10-minute levels were recorded post US hold, and the 20-minute levels were recorded post hit check.

4.1.2 Main Effect of Exoskeleton

The main effect of exoskeleton (EXO vs NE) was significant for psychophysical measures of RPE ($p<0.0001$), shoulder RPD ($p<0.0001$), and wrist RPD (<0.0001). There was no significant effect of the exoskeleton on the elbow (**Figure 16**).

Table 9. Summary of mean and standard deviations (SD) for RPE, shoulder, wrist, and elbow RPD for the main effect of exoskeleton.

	RPE		Shoulder RPD		Elbow RPD		Wrist RPD	
Exoskeleton	Mean	SD	Mean	SD	Mean	SD	Mean	SD
EXO	1.87	1.48	1.97	1.42	0.87	0.90	1.06	1.15
NE	2.30	1.61	2.64	1.82	0.73	1.03	0.66	1.02

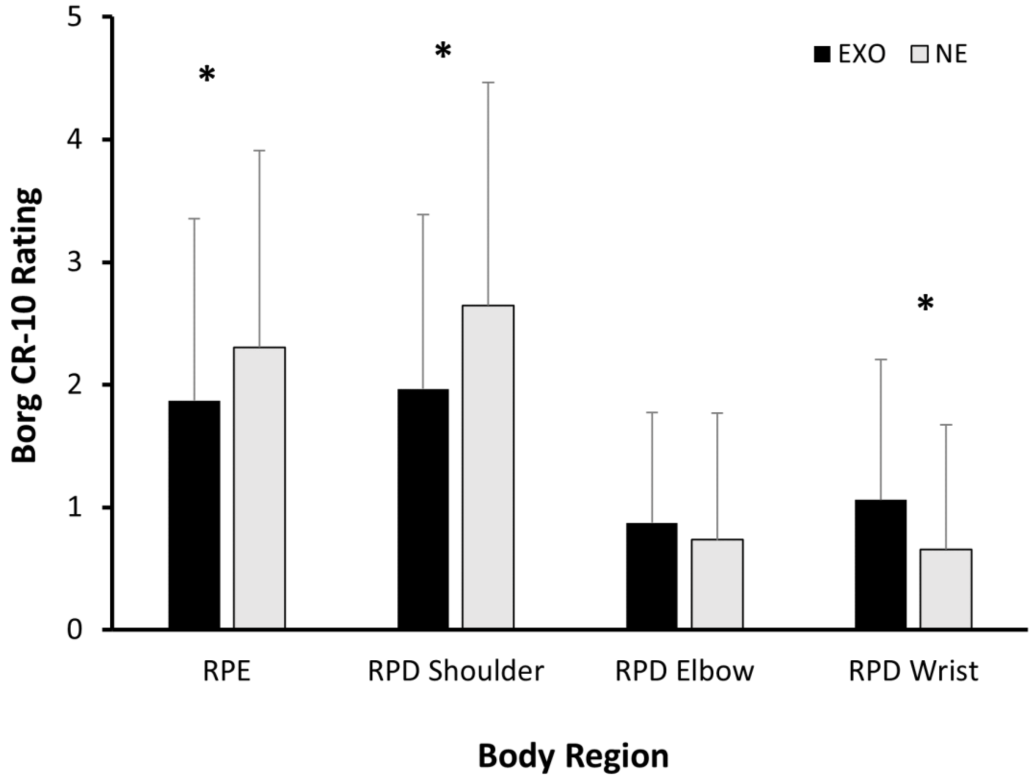

Figure 16. Mean RPE, shoulder RPD, elbow RPD, and wrist RPD for the EXO condition (black bars) and no exoskeleton (NE, grey bars) are shown. Error bars represent standard deviations, and **asterisks*** indicate a significant difference between groups (p<0.05).

The EXO group was significantly lower than the NE group for the RPE and Shoulder RPD scores. The EXO RPE was 0.43 points lower, and the EXO shoulder RPD was 0.67 points lower. For the wrist, however, the NE group had significantly lower scores by 0.4 points (**Table 9**).

4.1.3 Main Effect of Hand

Table 10. Summary of mean and standard deviations (SD) for the shoulder, wrist, and elbow RPD for the main effect of handedness.

	Shoulder		Elbow		Wrist	
Hand	Mean	SD	Mean	SD	Mean	SD
Left	2.44	1.72	0.86	1.03	0.94	1.11
Right	2.15	1.59	0.75	0.90	0.79	1.10

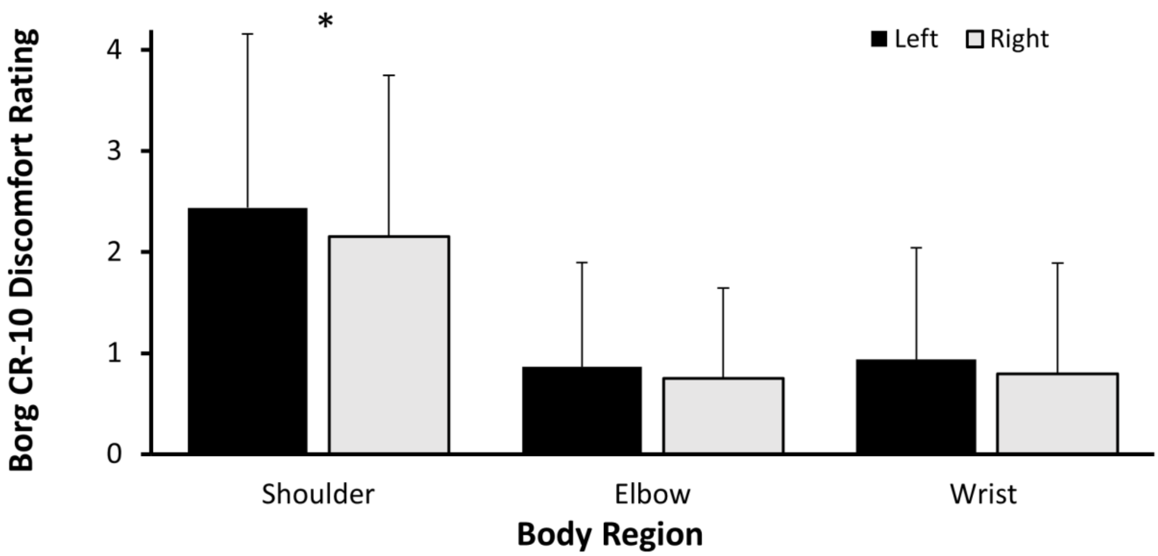

Figure 17. Mean shoulder RPD, elbow RPD, and wrist RPD for the left hand (black bars) and right hand (grey bars) are shown. Error bars represent standard deviations, and **asterisks*** indicate a significant difference between hands.

The right-side Borg CR-10 rating was significantly lower for the shoulder compared to the left side (**Figure 17**). Ratings for the elbow and wrist were relatively low for both sides, with values of approximately 1 out of a maximum score of 10 (**Table 10**). A rating of 1 out of 10 is described as “just noticeable” (**Figure 11**). The elbow and wrist had slightly lower but not statistically significant scores in the right elbow and wrist. The left shoulder RPD scores also had a lower right discomfort score, with the right shoulder having 0.29 points lower rating of discomfort compared to the left (**Table 10**). This indicates that left side was perceived to have higher discomfort throughout the task compared to the right side.

4.1.4 Interactions

No significant interactions for exoskeleton*hand, exoskeleton*time, or hand*time were present for the ratings of perceived exertion and discomfort (**Figure 18**, **Figure 19**, **Figure 20**, **Figure 21**).

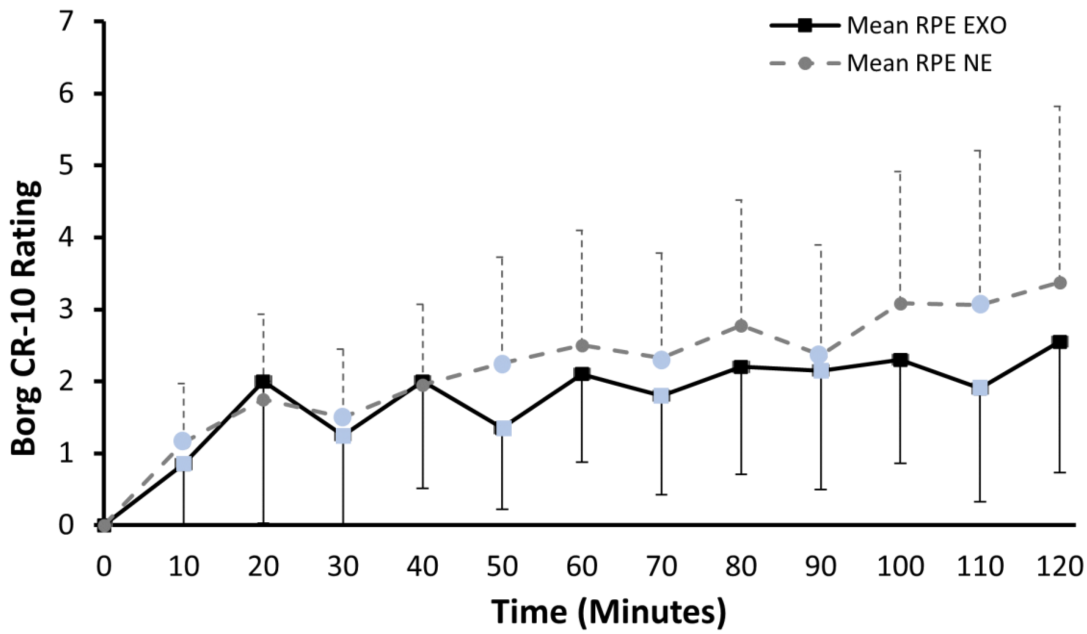

Figure 18. Mean RPE over the 2-hour protocol for the EXO and NE groups. EXO group has square markers with a solid black line, and NE group has circle markers with a dotted grey line. Error bars indicate standard deviations for each group (EXO is solid black, NE is dotted grey). Light blue markers (square and circle) indicate measurements taken after the ultrasound hold task (10 minutes into the 20-minute cycle) and the remaining markers indicate the measure was taken after completing the hit task, at the end of the 20-minute cycle.

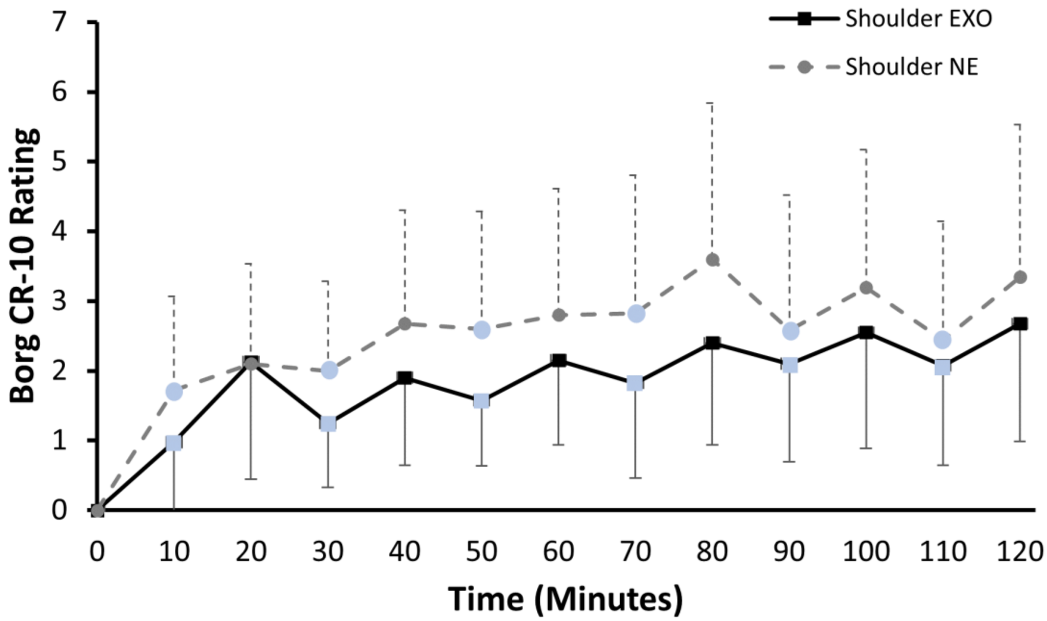

Figure 19. Mean shoulder RPD over the 2-hour protocol for the EXO and NE groups. EXO group has square markers with a solid black line, and NE group has circle markers with a dotted grey line. Error bars indicate standard deviations for each group (EXO is solid black, NE is dotted grey). Light blue markers (square and circle) indicate measurements taken after the ultrasound hold task (10 minutes into the 20-minute cycle) and the remaining markers indicate the measure was taken after completing the hit task, at the end of the 20-minute cycle.

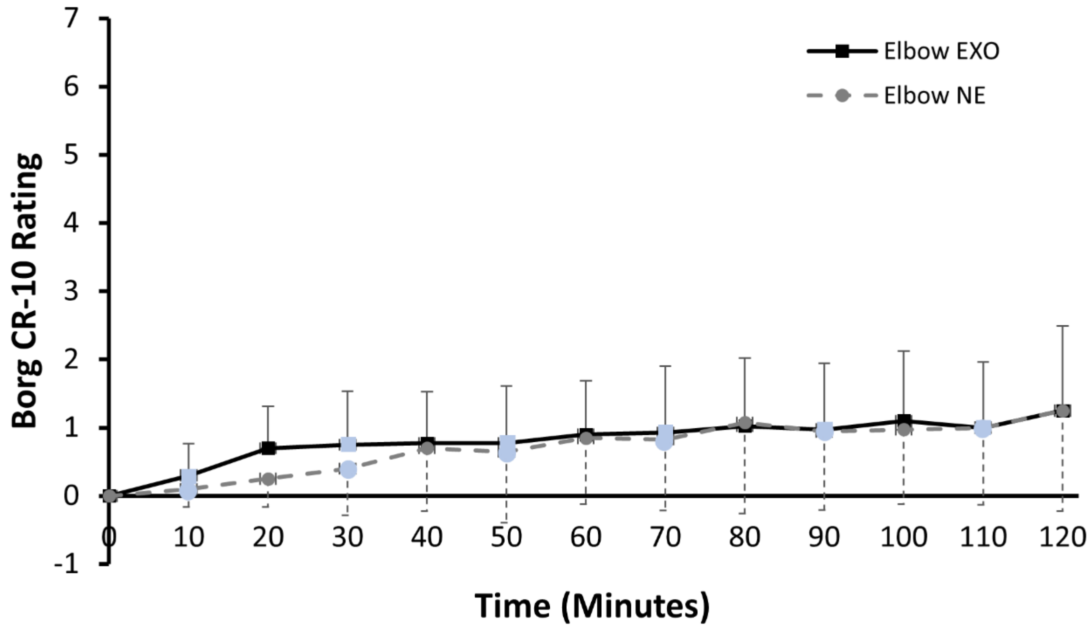

Figure 20. Mean elbow RPD over the 2-hour protocol for the EXO and NE groups. EXO group has square markers with a solid black line, and NE group has circle markers with a dotted grey line. Error bars indicate standard deviations for each group (EXO is solid black, NE is dotted grey). Light blue markers (square and circle) indicate measurements taken after the ultrasound hold task (10 minutes into the 20-minute cycle) and the remaining markers indicate the measure was taken after completing the hit task, at the end of the 20-minute cycle.

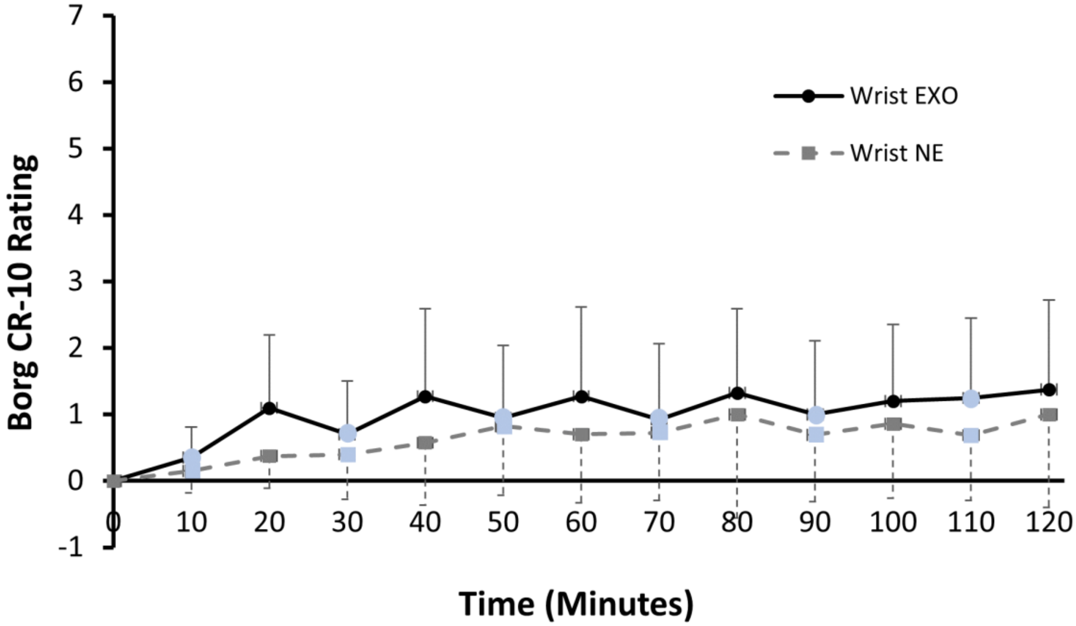

Figure 21. Mean wrist RPD over the 2-hour protocol for the EXO and NE groups. EXO group has square markers with a solid black line, and NE group has circle markers with a dotted grey line. Error bars indicate standard deviations for each group (EXO is solid black, NE is dotted grey). Light blue markers (square and circle) indicate measurements taken after the ultrasound hold task (10 minutes into the 20-minute cycle) and the remaining markers indicate the measure was taken after completing the hit task, at the end of the 20-minute cycle.

4.1.5 Exoskeleton by Hand Interaction

No significant exoskeleton by hand interactions occurred (**Figure 22**).

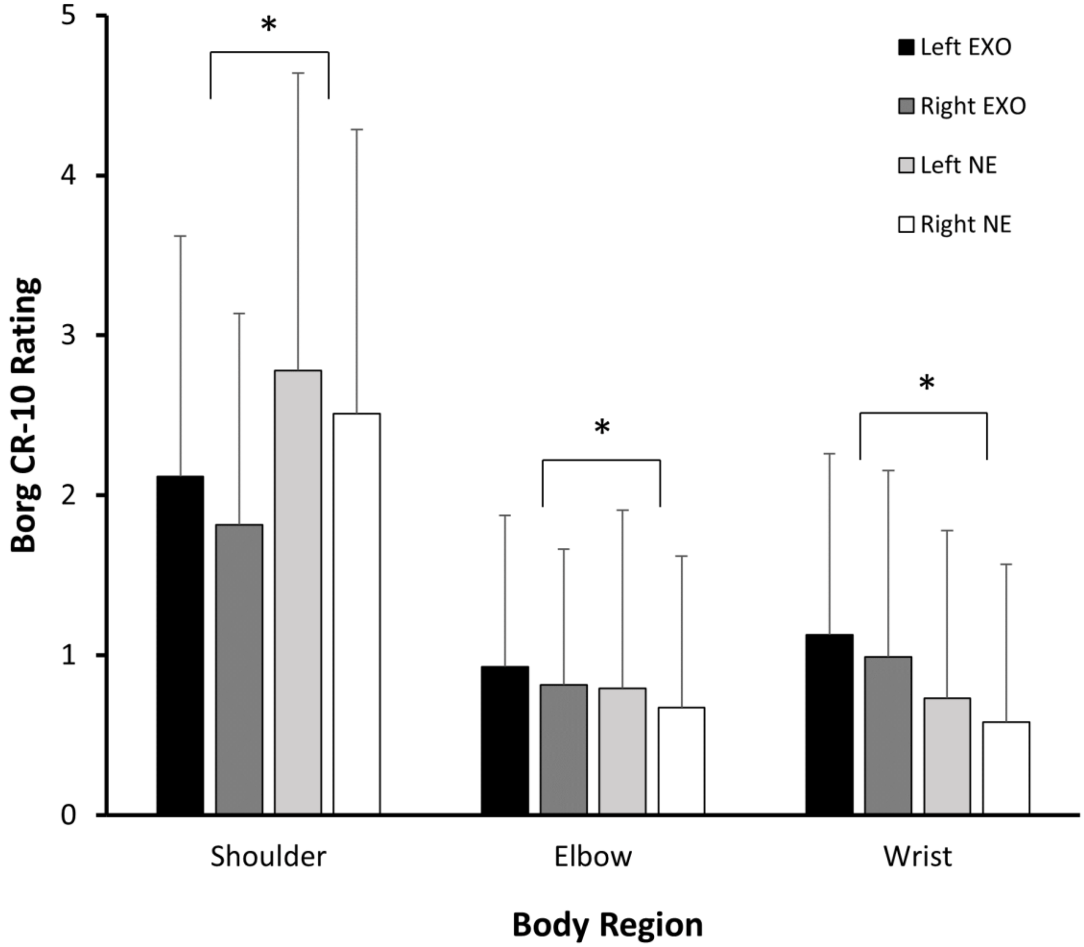

Figure 22. Mean RPD over the 2-hour protocol for the EXO and NE groups, separated by left and right hands. From left to right for each body region: left EXO bar is black, right EXO bar is dark grey, left NE bar is light grey, and right NE bar is white. No significant hand by exoskeleton interactions occurred. Significant main effects of exoskeleton is shown (EXO vs NE groups) using **asterisks***.

4.2 Force

In abduction, there was a significant main effect of hand and in external rotation, there was a significant main effect of exoskeleton (**Table 11**).

Table 11. Summary of p-values for main effects and interactions for the three-way ANOVA for dependent variables of rating of abduction and external rotation force. Significant effects (p<0.004) denoted with an **asterisk***.

Dependent Variable	Exo	Time	Hand	Exo* Time	Exo* Hand	Hand *Time	C*T*H
Abduction	0.223	0.9851	**<0.0001***	0.7994	0.0128	0.5853	0.6368
External Rotation	**<0.0001***	0.0125	0.3338	0.7905	0.0203	0.9626	0.9737

4.2.1. Main Effect of Hand

There was a main effect of hand on the abduction force, with the left hand having higher normalized force than the right (**Table 12, Figure 23**).

Table 12. Summary of mean and standard deviations (SD) for external rotation and abduction for the main effect of handedness.

	External Rotation		Abduction	
Hand	Mean	SD	Mean	SD
Left	90.43	20.43	98.12	12.36
Right	92.41	19.93	92.79	10.86

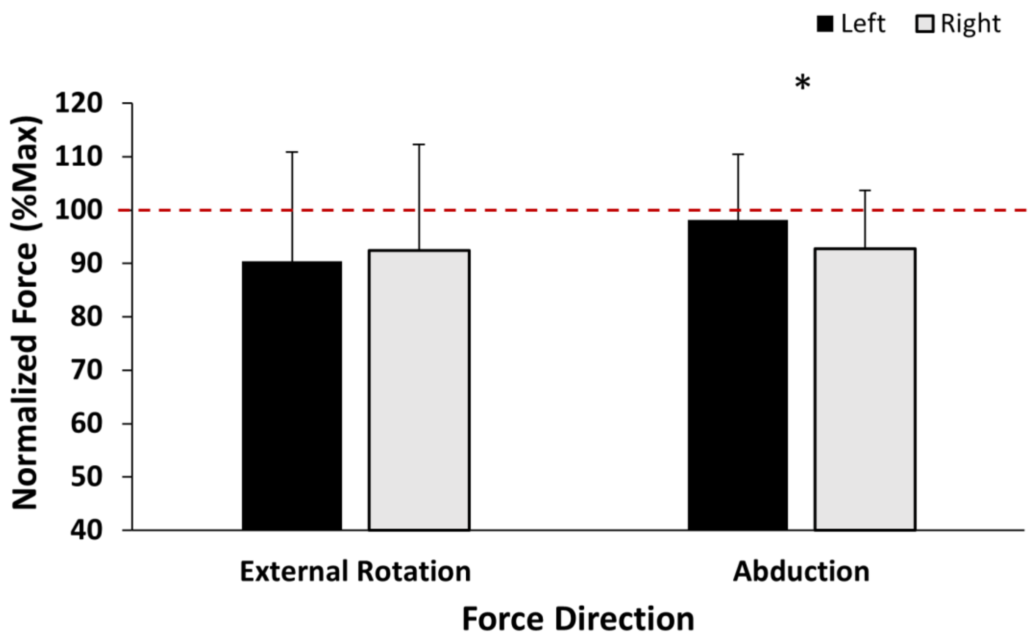

Figure 23. Mean normalized external rotation and abduction force for the left hand (black bars) and right hand (grey bars) are shown. Error bars represent standard deviations, and **asterisks*** indicate a significant difference between hands.

4.2.2 Main Effect of Exoskeleton

There was a significant main effect of exoskeleton on external rotation force, with the EXO group force being significantly lower than the NE group (**Table 13**, **Figure 24**). The maximum force results are in opposition to the trends in the infraspinatus MPF data (section 5.3).

Table 13. Summary of mean and standard deviation (SD) for external rotation and abduction for the main effect of exoskeleton.

	External Rotation		Abduction	
Exoskeleton	Mean	SD	Mean	SD
EXO	87.15	17.84	96.44	12.56
NE	95.71	21.47	94.46	11.19

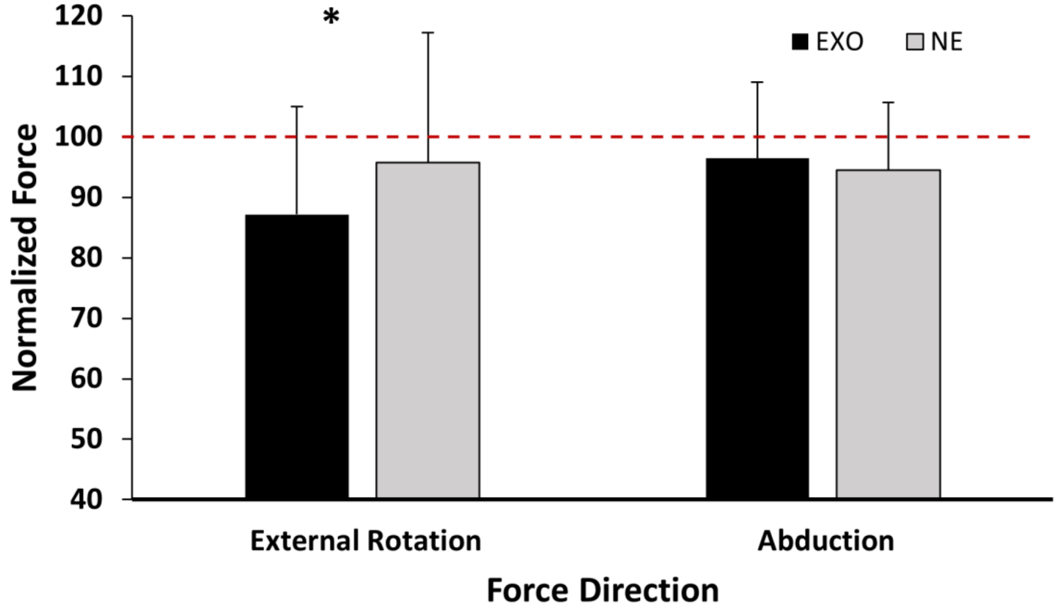

Figure 24. Mean normalized force for the EXO (black bars) and NE (grey bars) are shown. Error bars represent standard deviations, and **asterisks*** indicate a significant difference between hands.

4.3.2 Main Effect of Time

The main effect of time was not significant for the external rotation task. The trend in the data decreased at the 20-minute time point before returning to near-baseline values (**Figure 25**). The main effect of time on abduction force was not significant, and the trend in the data remained relatively flat from the 20 to 120-minute time points (**Figure 26**).

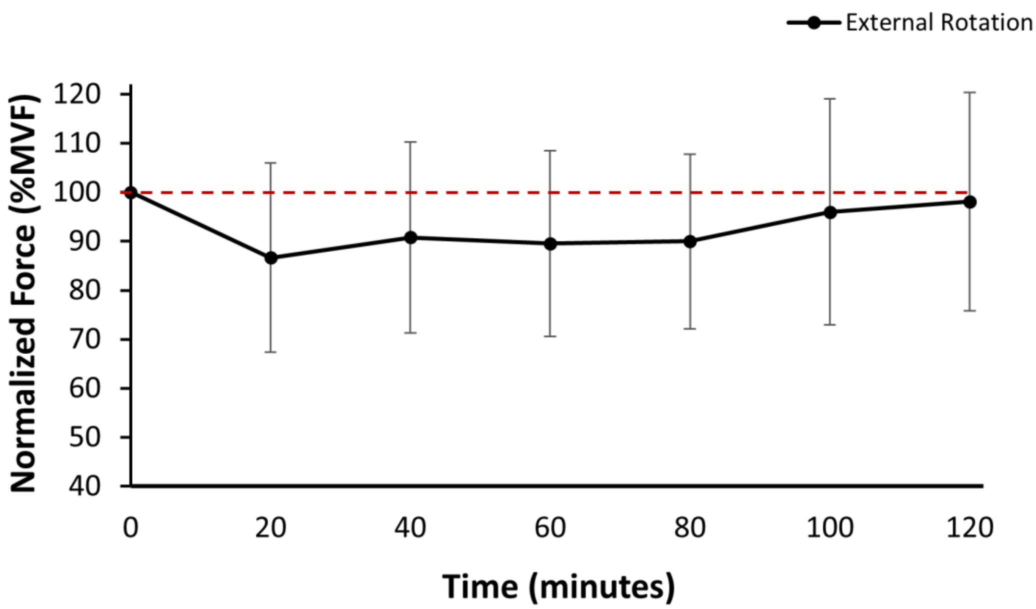

Figure 25. Mean normalized voluntary force in external rotation is shown, recorded every 20 minutes throughout the 2-hour protocol. Error bars indicate standard deviations.

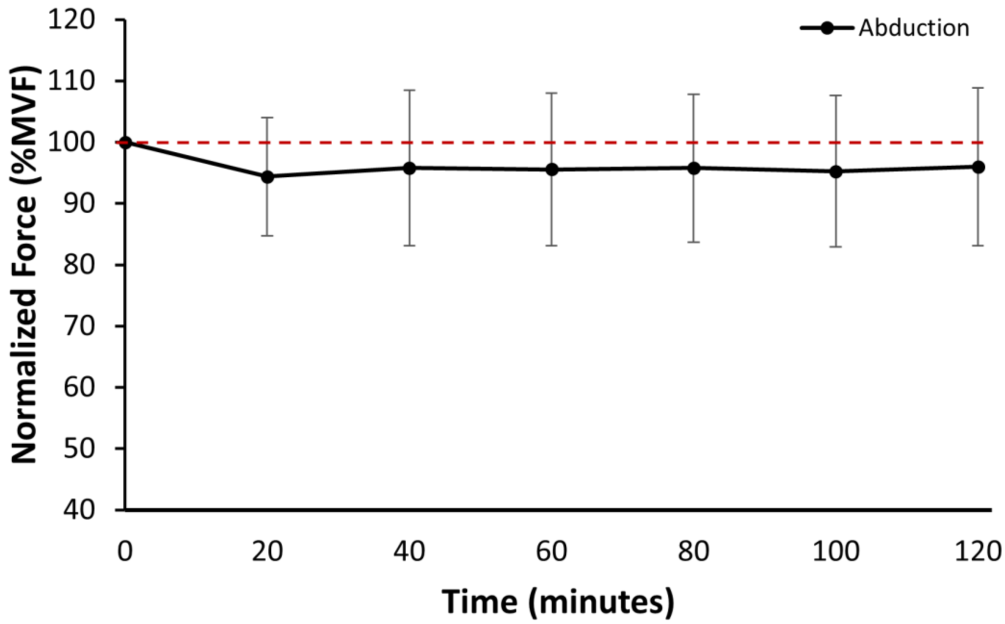

Figure 26. Mean normalized voluntary force in abduction, recorded every 20 minutes throughout the 2-hour protocol. Error bars indicate standard deviations.

4.3 Results Mean Power Frequency

Mean power frequency for the upper trapezius, supraspinatus, anterior deltoid, middle deltoid, and infraspinatus were tested using a 3-way ANOVA to determine if there were any significant main effects or interactions (**Table 14**). There were significant interactions between exoskeleton and hand for the upper trapezius, supraspinatus, middle deltoid, and infraspinatus. These interactions will be interpreted below. There were significant main effects of time for the upper trapezius, supraspinatus, and infraspinatus, and as there were no significant interactions with time, the main effects will be interpreted. All muscles had a significant main effect of exoskeleton, and this main effect will be interpreted for the anterior deltoid as there were no significant interactions for this muscle (**Table 14**).

Table 14. Summary of p-values for main effects and interactions of the three-way ANOVA for dependent variables mean power frequency (MPF). Significant effects ($p<0.0017$) denoted with an **asterisk***.

	Main Effects			Interactions		
Dependent Variable	Exo	Time	Hand	Exo* Time	Exo* Hand	Hand* Time
Upper Trapezius	**<0.0001***	**<0.0001***	0.2964	0.7683	0.0038	0.9262
Supraspinatus	**<0.0001***	**<0.0001***	**<0.0001***	0.4321	**<0.0001***	0.2081
Anterior Deltoid	**<0.0001***	0.7138	0.4008	0.2077	0.8115	0.9782
Middle Deltoid	**<0.0001***	0.8151	0.0846	0.3561	**<0.0001***	0.9934
Infraspinatus	**<0.0001***	**<0.0001***	**0.0007***	0.9635	0.0094	0.9855

4.3.1 Main Effect of Time

Main effects of time were significant for the upper trapezius, supraspinatus, and infraspinatus. Post-hoc Tukey HSD tests were run for these significant main effects to determine which time points had statistically significant differences. The effects are summarized in **Table 15**, **Table 16**, **Table 17**, and **Figure 27**, **Figure 28**, **Figure 29**, **Figure 30**, and **Figure 31** below.

Table 15. Summary of post-hoc tests completed for the main effect of time on **upper trapezius** normalized mean power frequency (nMPF). Mean, standard deviation (SD), degrees of freedom (DF), F ratio, p value, and Tukey HSD results are presented in the table. Levels of time not connected by the same letter are significantly different.

Time	Mean	SD	DF	F Ratio	P Value	Tukey HSD
10	101.57	7.59	11	4.1513	<0.0001	A
20	97.72	7.28				ABC
30	98.87	9.81				ABC
40	99.08	9.81				AB
50	98.21	10.11				ABC
60	97.08	8.90				ABC
70	97.17	7.57				ABC
80	94.55	7.06				C
90	97.06	7.51				ABC
100	95.39	8.13				BC
110	95.04	8.43				BC
120	95.02	9.00				BC

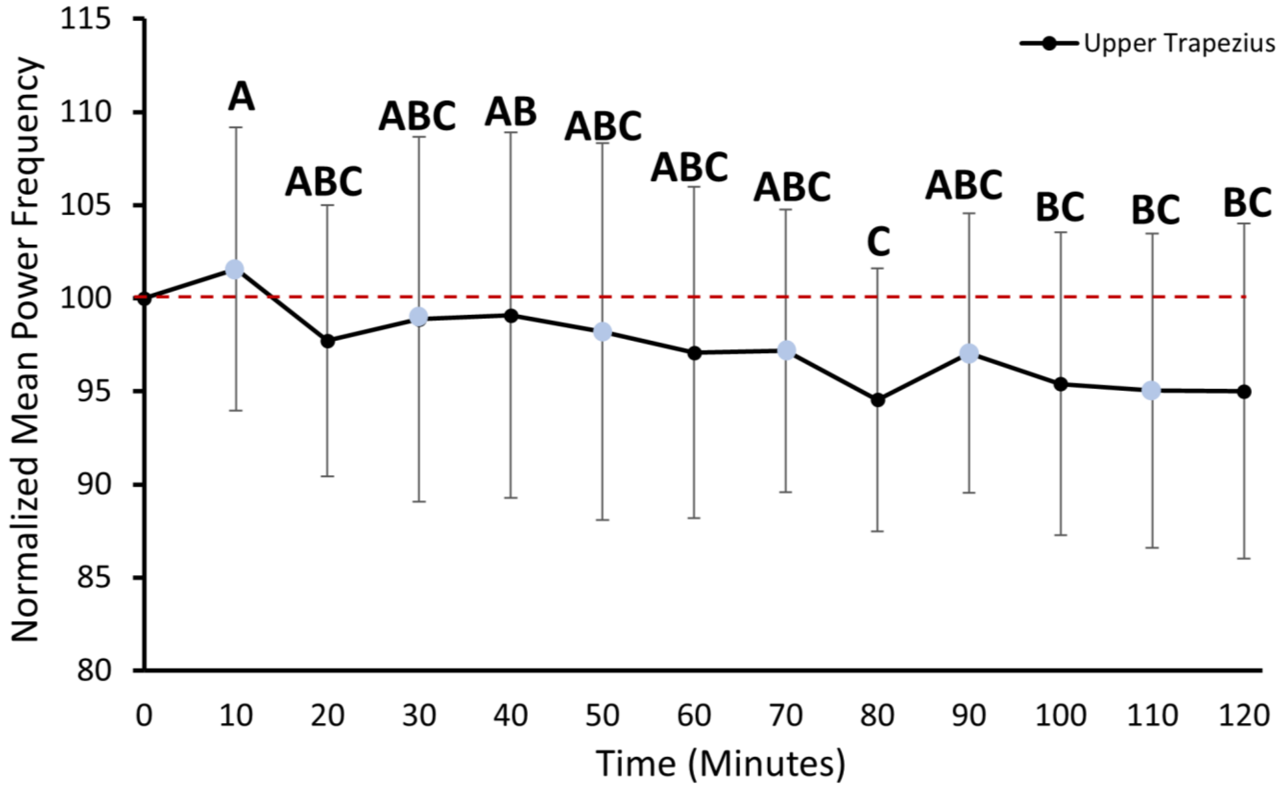

Figure 27. Mean normalized mean power frequency over the 2-hour protocol, measured every 10 minutes. Levels not connected by the same letter are significantly different. Every 10 minutes MPF was measured post ultrasound hold, indicated with light blue markers, and every 20 minutes MPF was measured post hit check task.

The main effect of time for the normalized MPF of upper trapezius is driven by the significant difference between the first time point (time = 10) being significantly higher than time points 80, 100, 110, and 120. Between time point 10 and 120, there was a 6.55 percent point drop (means = 101.57% and 95.02% respectively), and this difference did not become significant until the 80-minute mark.

Table 16. Summary of post-hoc tests completed for the main effect of time on **supraspinatus** normalized mean power frequency. Mean, standard deviation (SD), degrees of freedom (DF), F ratio, p value, and Tukey HSD results are presented in the table. Levels of time not connected by the same letter are significantly different.

Time	Mean	SD	DF	F Ratio	P Value	Tukey HSD
10	100.12	5.35	11	3.68	<0.0001	AB
20	98.75	5.78				AB
30	100.02	6.16				AB
40	99.01	5.51				AB
50	101.74	11.90				A
60	97.73	6.42				B
70	98.48	7.62				AB
80	97.42	7.70				B
90	98.21	6.98				AB
100	96.52	5.67				B
110	97.59	6.59				B
120	96.96	8.28				B

For the supraspinatus, the main effect of time was driven by the decrease in nMPF that also occurred for the first time at 80 minutes. At 80 minutes, 100 minutes, and 120 minutes, the nMPF was statistically lower than the nMPF at 50 minutes (**Table 16**, **Figure 28**). The 80-minute time point was also statistically lower than the 10-minute time (**Table 16**, **Figure 28**).

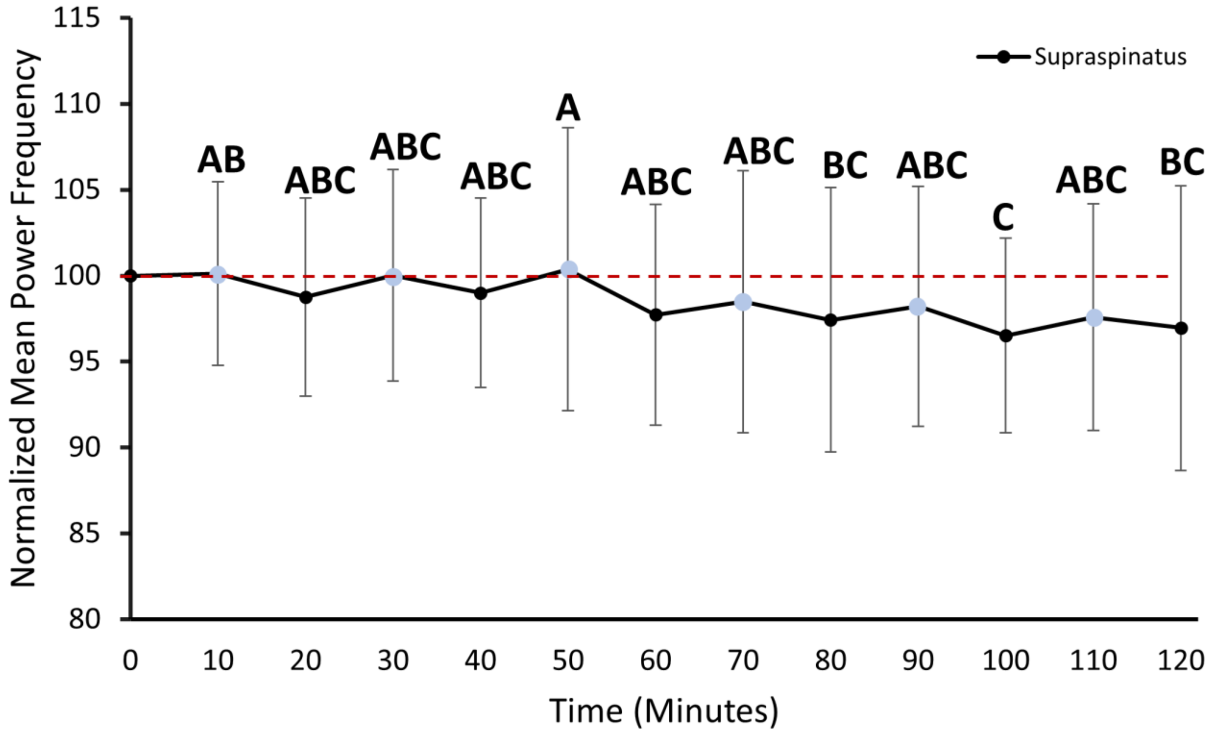

Figure 28. Mean normalized mean power frequency over the 2-hour protocol, measured every 10 minutes. Levels not connected by the same letter are significantly different. Every 10 minutes MPF was measured post ultrasound hold, and every 20 minutes MPF was measured post hit check task.

The ‘saw tooth’ pattern that was previously seen in the psychophysical data also existed in the supraspinatus nMPF data, as there was some recovery at the 10-minute intervals (light blue markers, **Figure 28**) indicated by the positive slope seen between 10 and 20 minutes. This is apparent in the data as the nMPF values at 80, 100, and 120 minutes were statistically lower than the nMPF at 50 minutes, but the values at 90 and 110 minutes were statistically similar to the nMPF at 50 minutes.

It appears the recovery after the US hold tasks is sufficient for the nMPF to remain at 100% up until the 60 and 70 minutes into the protocol where it starts to trend downwards from the red dotted line, indicating the 100% baseline value (**Figure 28**). Then, at 80, 100, and 120 minutes the nMPF becomes statistically lower than the previous time points.

Table 17. Summary of post-hoc tests completed for the main effect of time on **infraspinatus** normalized mean power frequency. Mean, standard deviation (SD), degrees of freedom (DF), F ratio, P value, and Tukey HSD results are presented in the table. Levels of time not connected by the same letter are significantly different.

Time	Mean	SD	DF	F Ratio	P Value	Tukey HSD
10	102.6038	9.824456	11	3.896	<0.0001	A
20	97.79533	8.467957				BC
30	100.786	7.604491				AB
40	97.88694	7.546262				BC
50	99.56985	9.803991				ABC
60	97.8867	8.972255				BC
70	99.11942	8.820268				ABC
80	97.65243	7.184033				BC
90	99.39933	8.19677				ABC
100	96.87942	6.467256				C
110	98.67651	8.741884				BC
120	97.41518	8.258106				C

For the infraspinatus, the ‘saw tooth’ recovery pattern identified in the psychophysical data emerges here as well and becomes statistically significant earlier than with the upper trapezius and supraspinatus. The 10-minute time point has a statistically higher nMPF than all subsequent 20-minute intervals (time = 20, 40, 60, 80, 100, 120). The 10-minute intervals (time = 10, 30, 50, 70, 90) are statistically the same until 110 minutes (**Table 17**, **Figure 29**).

Therefore, the main effect of time for the infraspinatus muscle is driven by the difference between the 10- and 20-minute intervals, and the decrease in nMPF from 100-120 minutes.

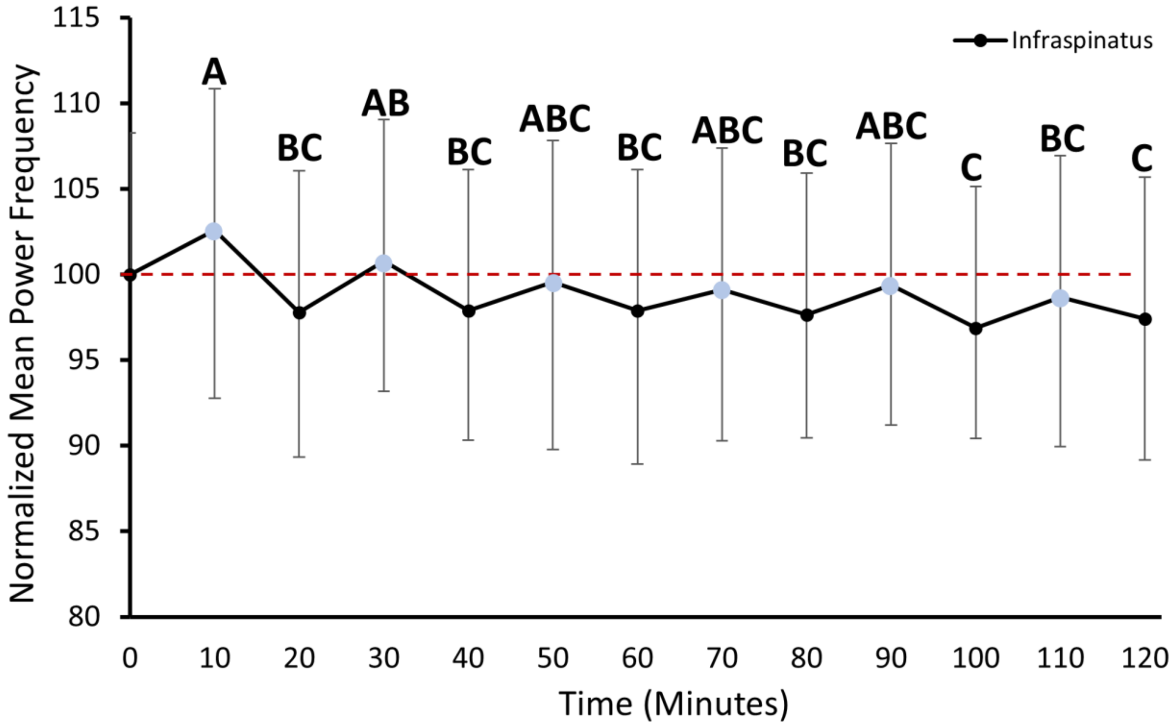

Figure 29. Mean normalized mean power frequency over the 2-hour protocol, measured every 10 minutes for infraspinatus. Levels not connected by the same letter are significantly different. Every 10 minutes MPF was measured post ultrasound hold, and every 20 minutes MPF was measured post hit check task.

The anterior deltoid nMPF was not significant for the main effect of time (**Table 14**). The values remain slightly above or on the red dotted line indicating 100% nMPF (**Figure 30**). This indicates that there was no change in the anterior deltoids nMPF, and therefore there were no signs of local muscle fatigue.

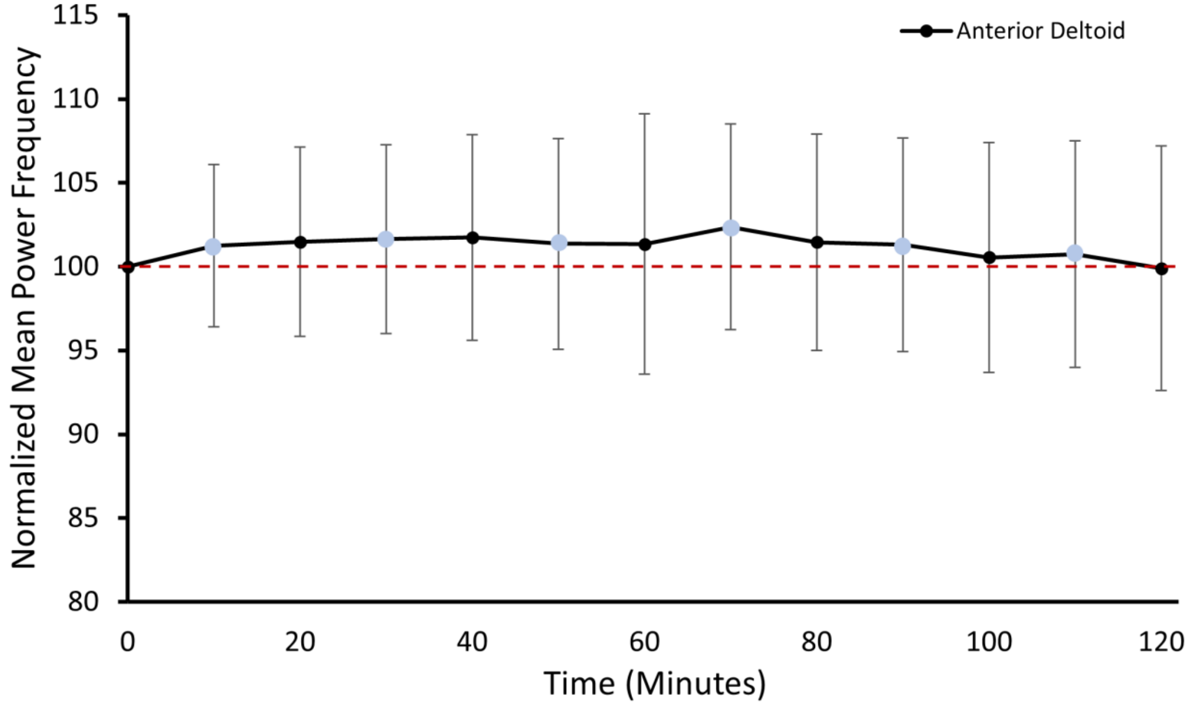

Figure 30. Mean normalized mean power frequency over the 2-hour protocol, measured every 10 minutes for the anterior deltoid. No significant differences were observed for this muscle. Every 10 minutes MPF was measured post ultrasound hold, and every 20 minutes MPF was measured post hit check task.

The middle deltoid nMPF had no significant effect of time (**Table 14**, **Figure 31**). Similar to the anterior deltoid, the values for the middle deltoid hovered above the 100% baseline measure of nMPF, meaning there were no indications of local muscle fatigue.

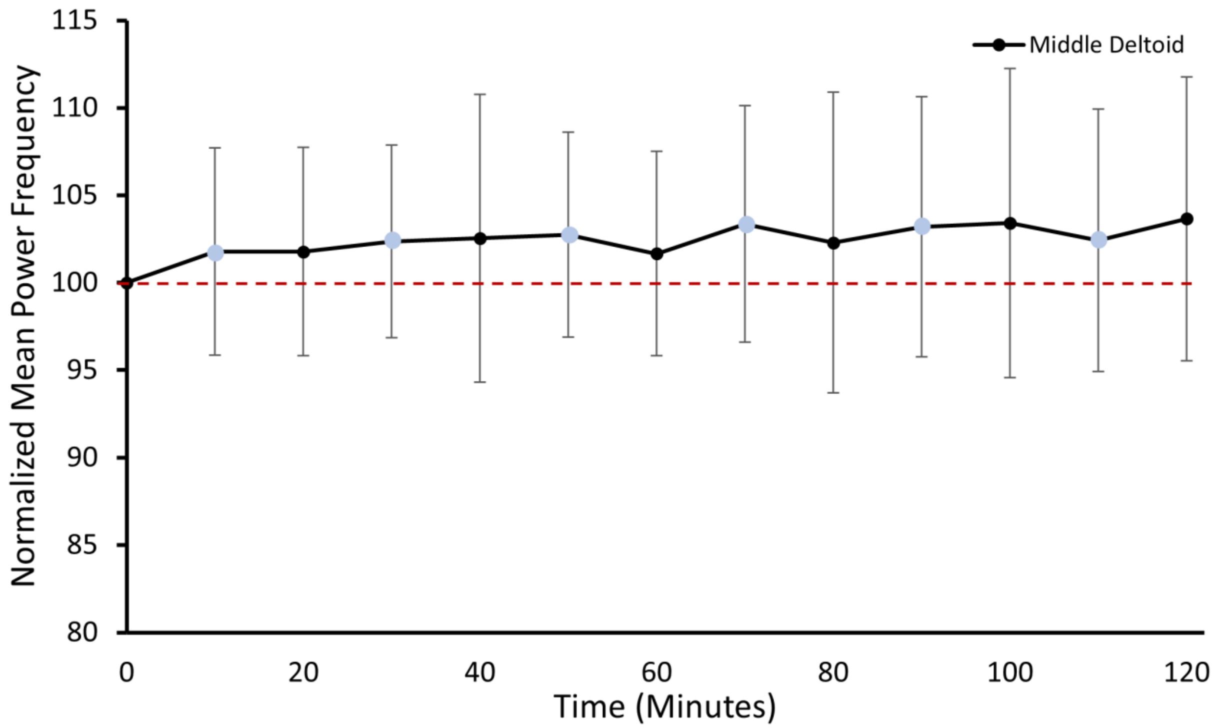

Figure 31. Mean normalized mean power frequency over the 2-hour protocol, measured every 10 minutes for the middle deltoid. No significant differences were observed for this muscle. Every 10 minutes MPF was measured post ultrasound hold, and every 20 minutes MPF was measured post hit check task.

4.3.2 Main Effect of Exoskeleton

Exoskeleton had a significant effect on all five muscles tested (**Table 14**). Summary statistics are presented in **Table 18**.

Table 18. Summary of mean and standard deviations (SD) for the MPF of the Upper Trapezius, Supraspinatus, Anterior Deltoid, Middle Deltoid, and Infraspinatus for the main effect of exoskeleton (EXO, NE).

	Upper Trapezius		Supraspinatus		Anterior Deltoid		Middle Deltoid		Infraspinatus	
Exo	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
EXO	101.00	9.25	101.74	7.69	102.82	5.12	104.18	7.96	100.68	9.49
NE	93.50	5.92	95.24	4.96	99.64	7.05	100.89	5.49	96.97	6.76

All muscles had a significantly lower MPF in the NE group compared to the EXO group ($p<0.05$, **Table 18**). The EXO group MPF remained closer to 100%, while the NE group decreased from 100% in each muscle.

For the anterior and middle deltoids, while there was a significant difference between the EXO and NE groups, the NE group remained at or above the red dotted line indicating 100% baseline (**Figure 32**). This indicates that these muscles did not experience significant fatigue in either group.

The upper trapezius, supraspinatus, and infraspinatus all had nMPF values at or above 100% baseline for the EXO group and had significant decreases in nMPF for the NE groups (**Figure 32**). The upper trapezius NE compared to EXO group decreased by 7.5% nMPF, the supraspinatus decreased by 6.5% nMPF, and infraspinatus decreased by 3.71% nMPF.

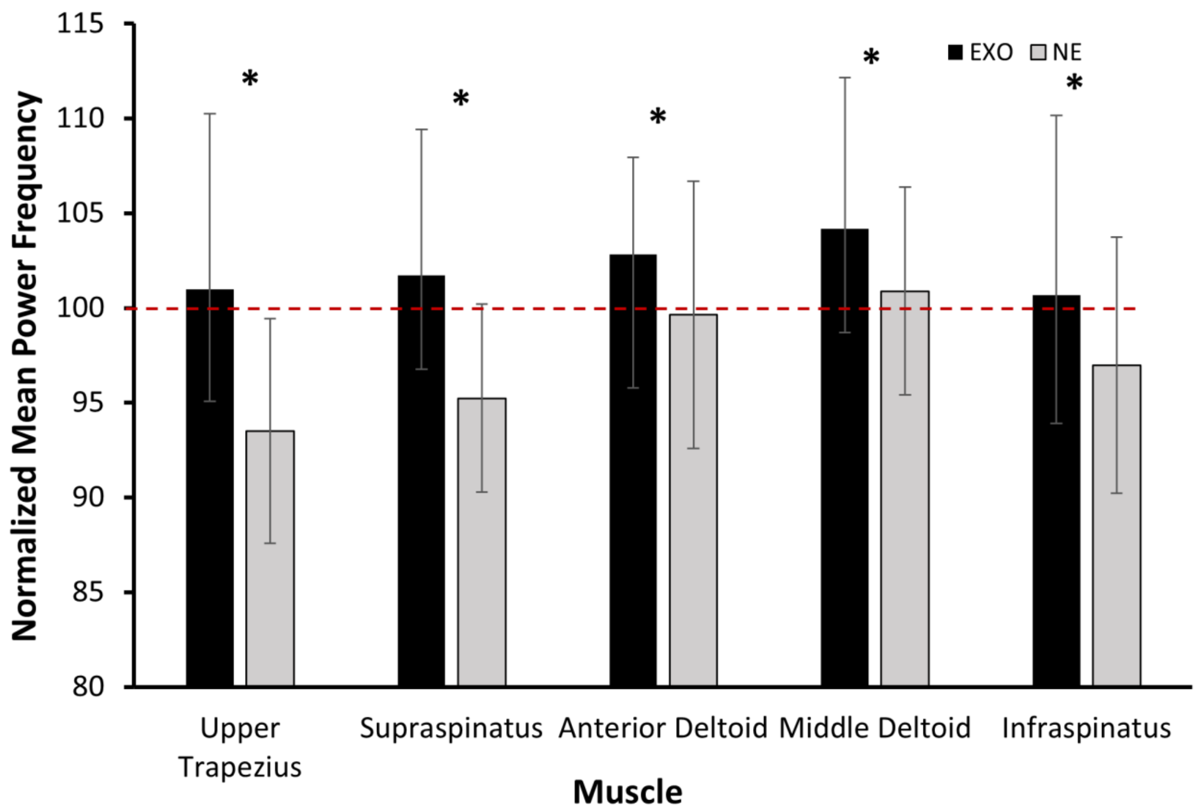

Figure 32. Mean normalized mean power frequency for the upper trapezius, supraspinatus, anterior deltoid, middle deltoid, and infraspinatus muscles are presented. Black bars indicate the EXO group, and grey bars indicate the NE group. Error bars represent standard deviations, and **asterisks** indicate a significant difference between groups ($p<0.05$).

4.3.3 Time by Exoskeleton Interaction

There were no significant interactions between time and exoskeleton (**Figure 33**, **Figure 34**, **Figure 35**, **Figure 36**, **Figure 37**).

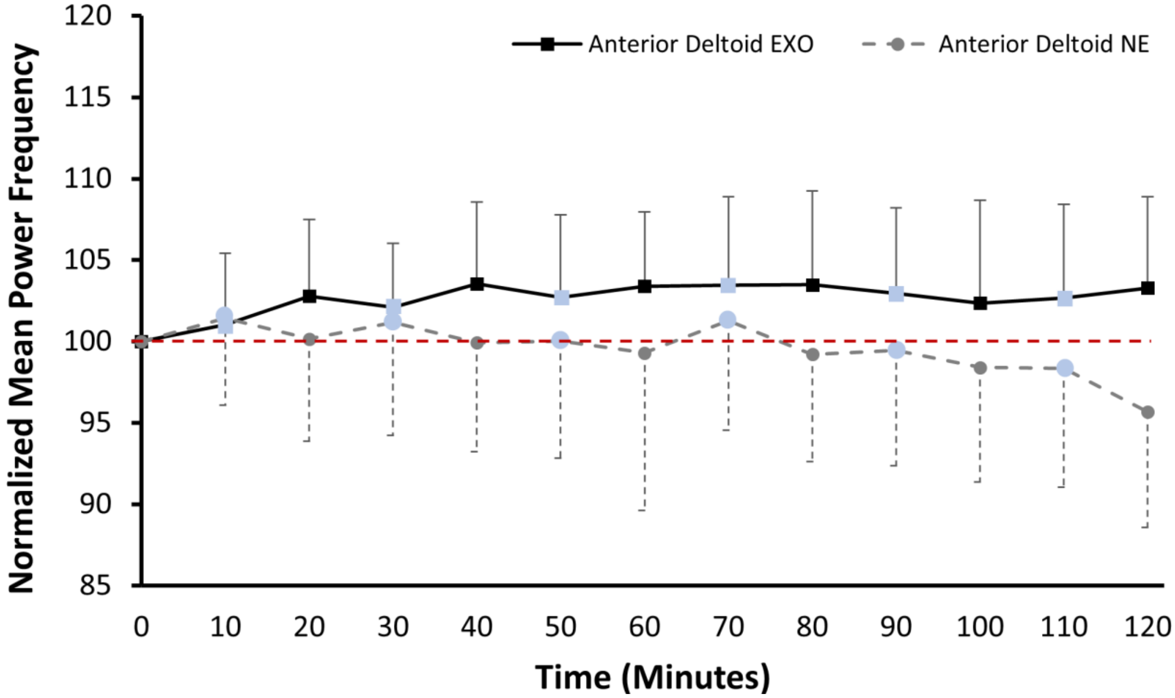

Figure 33. Interaction between exoskeleton and time for the mean normalized MPF over time for the anterior deltoid. No significant interaction between exoskeleton and time was observed for this muscle.

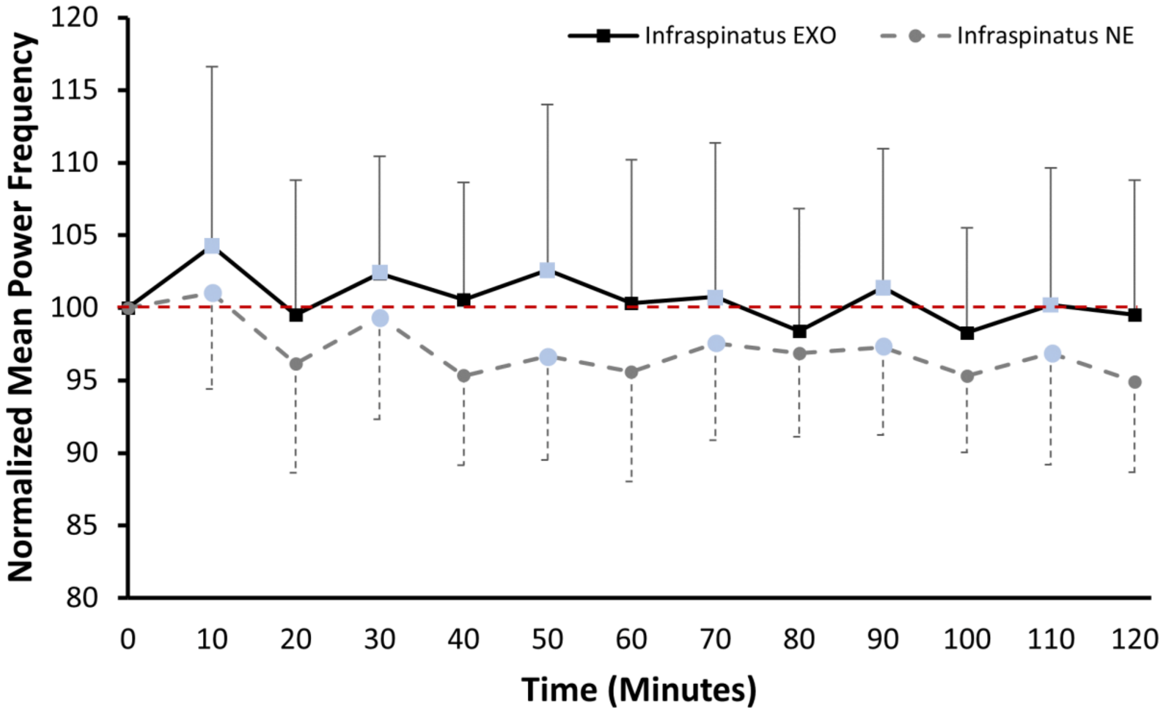

Figure 34. Interaction between exoskeleton and time for the mean normalized MPF over time for the infraspinatus. No significant interaction between exoskeleton and time was observed for this muscle.

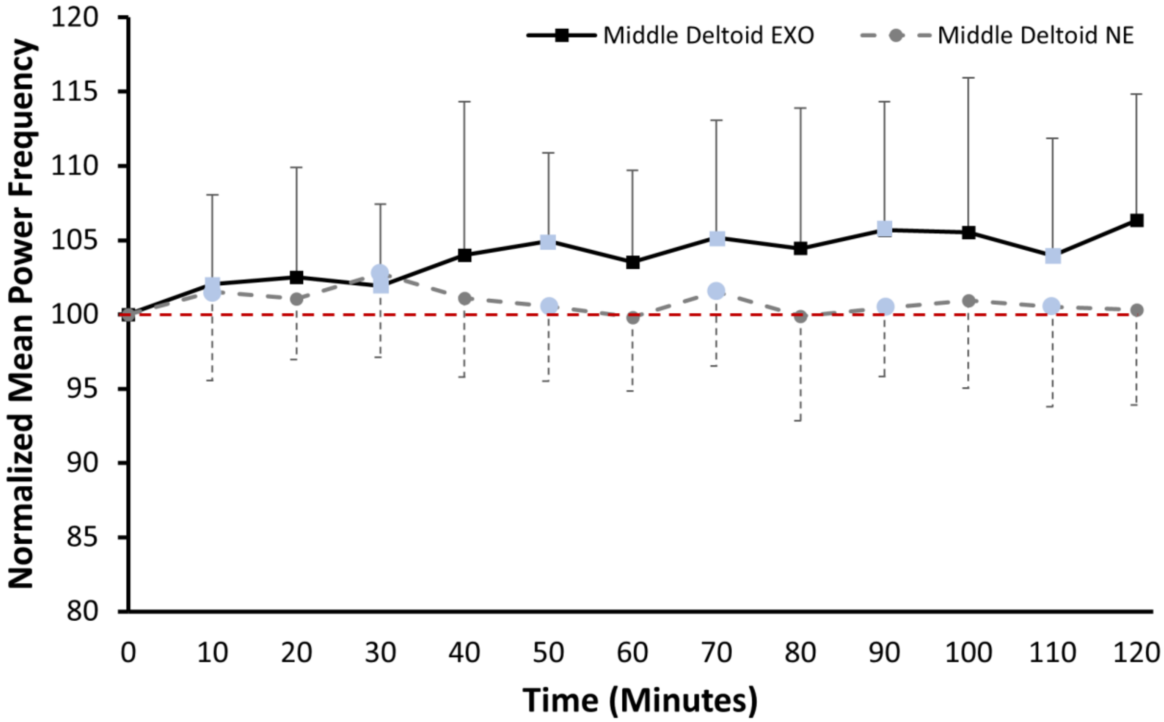

Figure 35. Interaction between exoskeleton and time for the mean normalized MPF over time for the middle deltoid. No significant interaction between exoskeleton and time was observed for this muscle.

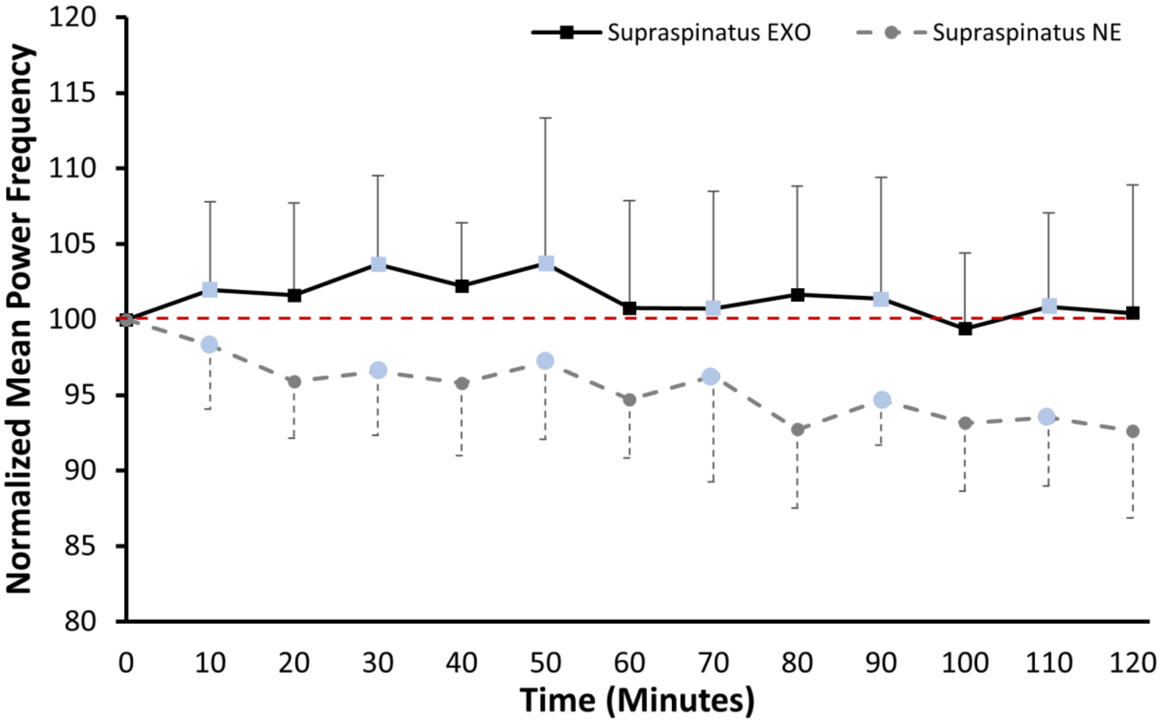

Figure 36. Interaction between exoskeleton and time for the mean normalized MPF over time for the supraspinatus. No significant interaction between exoskeleton and time was observed for this muscle.

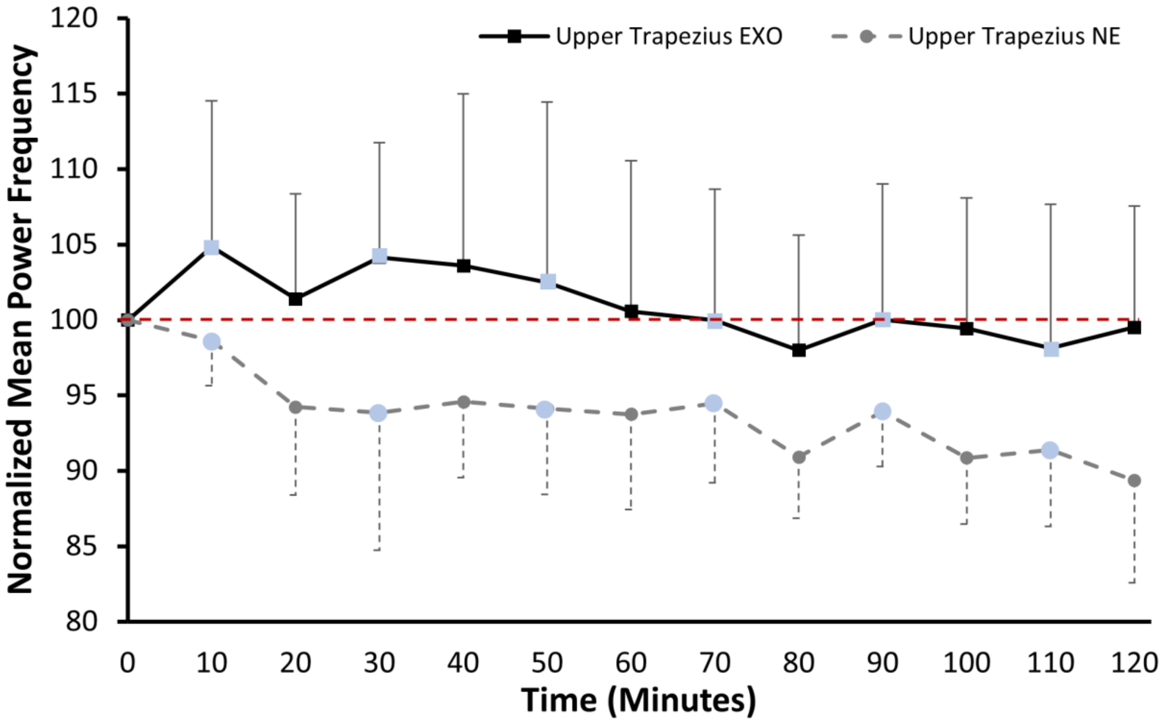

Figure 37. Interaction between exoskeleton and time for the mean normalized MPF over time for the upper trapezius. No significant interaction between exoskeleton and time was observed for this muscle.

4.3.5 Main Effect of Hand and Exoskeleton by Hand Interactions

Exoskeleton by hand interactions for the supraspinatus, and middle deltoid were significant (**Table 14**). Main effect of hand was significant for the infraspinatus (**Table 14**).

Table 19. Summary of post-hoc tests completed for the interaction between exoskeleton (EXO, NE) and hand (right, left) on **supraspinatus** normalized mean power frequency. Mean, standard deviation (SD), degrees of freedom (DF), F ratio, P value, and Tukey HSD results are presented in the table. Levels of time not connected by the same letter are significantly different.

Exoskeleton	Mean	SD	DF	F Ratio	P Value	Tukey HSD
Left EXO	104.33	9.11	1	27.95	<0.0001	A
Right EXO	99.12	4.67				B
Left NE	95.38	4.91				C
Right NE	95.09	5.03				C

Table 20. Summary of post-hoc tests completed for the interaction between exoskeleton (EXO, NE) and hand (right, left) on **middle deltoid** normalized mean power frequency. Mean, standard deviation (SD), degrees of freedom (DF), F ratio, P value, and Tukey HSD results are presented in the table. Levels of time not connected by the same letter are significantly different.

Exoskeleton	Mean	SD	DF	F Ratio	P Value	Tukey HSD
Left EXO	105.89	9.38	1	25.62	<0.0001	A
Right EXO	102.46	5.75				B
Left NE	100.10	5.34				C
Right NE	101.67	5.55				BC

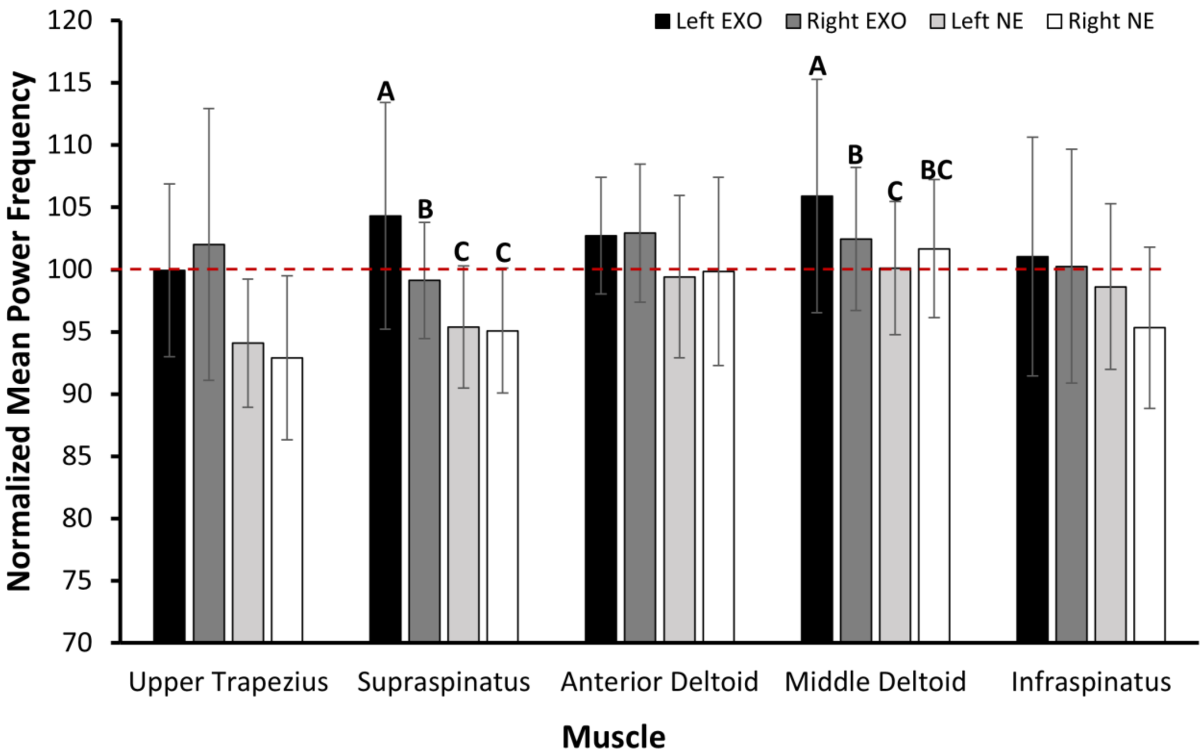

Figure 38. Mean normalized mean power frequency over the 2-hour protocol for the EXO and NE groups, separated by left and right hands. From left to right for each body region: left EXO bar (black), right EXO bar (dark grey), left NE bar (light grey), and right NE bar (white). Levels not connected by the same letter are significantly different as per the post-hoc Tukey HSD test (**Table 19**, **Table 20**).

The supraspinatus two NE groups were significantly lower than the EXO groups with no difference between the left and right sides (**Figure 38**). The right EXO group was significantly lower than the left EXO, however both EXO groups hovered at or above the 100% baseline measure (means = 99.12, 104.33), indicating they did not experience fatigue compared to baseline.

The middle deltoid also had a significant interaction, with the left EXO higher than the right EXO group, and the left NE group lower than the right NE. In this case, all groups were above the 100% baseline measure indicating these groups did not experience fatigue compared to the baseline measure. The left infraspinatus was higher than the right (means 99.8%, 97.8%), indicating the right hand experienced a greater amount of fatigue compared to the left.

5.0 Discussion

The discussion starts with a summary of key findings, followed by a discussion of the hypotheses, the differential effects on the right and left sides, psychophysical measures, localized muscle fatigue, and force results.

5.1 Key findings

The task resulted in the supraspinatus, infraspinatus, and upper trapezius showing significant signs of localized muscle fatigue (measured by a decrease in MPF) over the 2-hour protocol, while the deltoids did not, which is linked to injury mechanisms in the shoulder. Wearing the exoskeleton decreased these markers of fatigue in the upper trapezius, supraspinatus, and infraspinatus muscles, with markers remaining at levels close to baseline measures. Wearing the exoskeleton also decreased perceived exertion and discomfort scores in the shoulder, indicating a decrease in perceived fatigue in the targeted body region for this device.

Additional findings included the exoskeleton increasing perceived discomfort at the wrist and resulting in a larger maximum voluntary strength deficit in external rotation. This decrease in voluntary strength was driven by a decrease in force output early in the protocol which returned to baseline measures by the completion of the 2-hour task.

5.1 Hypotheses

5.1.1 Hypothesis 1

Hypothesis one stated that the mean power frequency percent change would be lower in the anterior deltoid, middle deltoid, upper trapezius, supraspinatus, and infraspinatus when wearing the exoskeleton compared to no exoskeleton. This hypothesis was accepted. Main effect of exoskeleton on nMPF was significantly lower in all five muscles.

5.1.2 Hypothesis 2

Hypothesis two stated that ratings of perceived exertion would be lower when wearing the exoskeleton compared to no exoskeleton. This hypothesis was accepted.

5.1.3 Hypothesis 3

Hypothesis three stated that ratings of perceived shoulder, elbow, and wrist discomfort would be lower when wearing the exoskeleton compared to no exoskeleton. This hypothesis was partially accepted. Shoulder discomfort was lower when wearing the exoskeleton, elbow discomfort was not affected, and wrist discomfort was higher when wearing the exoskeleton.

5.1.4 Hypothesis 4

Hypothesis four stated that strength percent change would be lower in both elevation and external rotation when wearing the exoskeleton compared to no exoskeleton. This hypothesis was rejected. There was no change in abduction force when wearing the exoskeleton, and there was a reduction in force in the exoskeleton group in external rotation.

5.1.5 Hypothesis 5

Hypothesis five stated that this task would cause fatigue over time in the 5 muscles examined. This hypothesis was partially accepted. This task caused a significant decrease over time in nMPF of the upper trapezius, supraspinatus, and infraspinatus. There were no significant decreases in nMPF of the anterior or middle deltoid.

5.1.6 Hypothesis 6

Hypothesis six stated that there would be no systemic change in strategy over the 2-hour protocol (as measured by hand by time interaction). This hypothesis was accepted. There were no significant hand by time interactions, indicating there was no significant systematic change in strategy throughout the task protocol.

5.1.7 Hypothesis 7

Hypothesis seven stated that the use of the exoskeleton would not change the strategy over time. This hypothesis was accepted, as there were no significant 3-way interactions between exoskeleton, hand, and time.

5.2 Differences in Hand

There was no interaction of hand over time (**Table 4**, **Table 11**, **Table 14**), indicating there was no systemic change in strategy over the course of the 2-hour protocol.

There were a few significant main effects of hand in the shoulder RPD (**Table 4**), abduction force (**Table 11**), and MPF of the middle deltoid, supraspinatus, and infraspinatus (**Table 14**). The difference between the left and right shoulder was small but significant, with the left higher than the right (means = 2.44, 2.15, $p<0.002$). The difference between hands for the supraspinatus and the middle deltoid existed in the groups at or above baseline (**Table 19**, **Table 20**, **Figure 38**), indicating the fatigue markers had not decreased from baseline in these groups.

In the infraspinatus MPF, there was a small but statistically significant difference with the left higher than the right (means 99.8%, 97.8%, $p<0.001$), indicating the right arm experienced greater fatigue. This could be due to the hammering motion completed primarily by the right (dominant) arm during the HIT task, as this required the arm to externally rotate, and would be more demanding on the infraspinatus. The left arm positioned the chisel on the weld location, requiring primarily elevation of the arm.

5.3 RPE and RPD Main Effects of Exoskeleton and Time

5.3.1 Rating of Exertion and Shoulder Discomfort

The shoulder discomfort and rating of perceived exertion followed similar patterns and magnitudes (**Figure 12**, **Figure 13**), which could indicate that the whole-body exertion rating was driven by the demand on the shoulders during this task. Since this was an upper extremity focused task, this was expected. The main effect of time and exoskeleton was significant for the shoulder ($p<0.0001$), indicating the RPD increased over time and was significantly lowered by the exoskeleton. Generally, ratings of exertion and discomfort in the shoulder/upper limb regions have been previously reported to decrease with the use of PUEE's. Discomfort was lowered when wearing the exoskeleton in short duration tasks involving simple arm elevation, tracing, drilling, and screwing task types (Alabdulkarim & Nussbaum, 2019; Kim & Nussbaum, 2019; Debrosses et al., 2021; Van Engelhoven et al., 2019; Grazi et al., 2020; Huysamen et al., 2018), and during longer duration tasks of 30 minutes to 1 hour in length (Tetteh et al., 2022; Weston et al., 2022). Field assessments in automotive assembly (Smets 2019), plastering (de Vries & de Looze, 2021) and in an operating room (Liu et al., 2018) reported lower pain and discomfort scores in the shoulder, agreeing with the decrease in shoulder discomfort and RPE in this study.

While the difference in RPD in this study may be small ~1 point on a 10-point scale, (**Table 6**, **Figure 13**), it may be relevant to decrease risk of injury in the workplace. A previous longitudinal study measured peak and cumulative discomfort ratings using the Borg 10-point scale, in the workplace over a 3-year period. They found that peak discomfort ratings greater than 2 increased individuals' risk of reporting musculoskeletal pain (regular or prolonged) by a relative risk (RR) of 1.90 in the shoulder. There was evidence that working at a discomfort level of less than 2 also increased risk of developing future musculoskeletal pain in the shoulder at a lesser relative risk (RR 1.61) (Hamberg-van Reenen et al., 2008). This supports interventions that would decrease the workers discomfort ratings even if the decrease is small.

5.3.2 Distal Upper Extremity

During this task, the wrist and elbow both had low ratings of discomfort throughout the task for both the EXO and NE group (**Figure 20**, **Figure 21**), both hovering at a rating of 1.3 or less throughout the 2-hour protocol. However, even with these low ratings, there was a significant main effect of time and exoskeleton (**Table 4**) on the wrist.

The significant main effect of time indicated that while this was a more demanding task on the shoulder, the elbow and wrist experienced an increase in discomfort over the 2-hour task protocol as well. Exoskeleton usage had no effect on elbow discomfort, which is apparent in **Figure 20** as the EXO and NE groups data points overlap. For the elbow, there was a 1.05-point increase from 10 to 120 minutes, and for the wrist there was a 0.96-point increase. Of note, the wrist had significantly lower scores in the NE group compared to the EXO group. This is an important finding as it could flag potential negative effects of the exoskeleton on body regions it was not primarily designed to offload.

In previous literature, exoskeleton use has generally decreased ratings of discomfort (McFarland & Fischer, 2019). Most commonly ratings of discomfort have been measured in the shoulder and upper arm (McFarland & Fischer, 2019), but there are fewer that have investigated the effects of the exoskeleton on downstream regions of the upper extremity. A simple task completed in lab had lower forearm discomfort (Kim et al., 2019), and a longer, one hour duration task resulted in lower wrist and hand discomfort (Weston et al., 2022) when wearing an exoskeleton. These two studies consisted of simple tasks that allowed the forearm and wrist to maintain a neutral posture. Another field study involving surgeons reported lower, but not significant, decreases in wrist pain when wearing the exoskeleton (Liu et al., 2018). A study testing multiple exoskeletons reported mixed results, with one exoskeleton of similar design to the Levitate having no impact on wrist discomfort, and an exoskeleton that directly supports the tool, offloading the wrist, decreasing wrist discomfort (Alabdulkarim & Nussbaum, 2019). As many of the studies were simple task types completed in lab, and one involved surgical procedures at below shoulder elevations, more tasks representative of the workplace are needed to determine the long term effects on the wrist.

5.4 Mean Power Frequency

In the muscles measured during this study, there were significant main effects of exoskeleton on all five muscles ($p<0.0001$), significant main effects of time for the upper trapezius, supraspinatus, and infraspinatus ($p<0.0001$), and interactions between exoskeleton and hand for the upper trapezius, supraspinatus, middle deltoid, and infraspinatus ($p<0.01$). These effects will be discussed in this section. Of note, in some muscles such as the anterior and middle deltoids (**Figure 30**, **Figure 31**, **Figure 33**, **Figure 35**) nMPF values exceeded 100% baseline consistently throughout the trial, with a slight increase over time. Additionally, in the NE condition, all muscles had nMPF values >100% baseline (Figure 32). As the task was 2 hours in length, and RPE increased over time (**Figure 12**), there may have been an increase in skin temperature of the participants as the task progressed. Increases in skin temperature have been shown to result in increased MPF of the sEMG signal (Winkel & Jørgenson, 1991), which could account for the observed increases in nMPF over time.

5.4.1 Anterior and Middle Deltoids

Few previous PUEE studies have analyzed EMG in the frequency domain as a measure of fatigue (Tetteh et al., 2022; Schmalz et al., 2019; Rashedi et al., 2014), likely due to the relatively short duration of tasks completed in lab. While time domain EMG has been used to predict future fatigue states (ACGIH, 2016; Jonsson, 1982), mean or median power frequency is used as the gold standard method to directly physiological processes that occur as fatigue develops (Al-Mulla et al., 2012). Previous PUEE studies using mean or median power frequency as a measure of fatigue have used tasks that are 5-30 minutes long (Tetteh et al., 2022; Schmalz et al., 2019; Rashedi et al., 2014), which may not be representative of tasks commonly completed in the workplace for hours at a time.

Additionally, the studies that included frequency domain analyses of EMG have primarily measured fatigue of the deltoid, which may not translate well to overall risk of injury in the shoulder. These studies have shown mixed effects of the exoskeleton. A study reported no effect of exoskeleton on fatigue in a low demand task (Tetteh et al., 2022). Other studies reported a decrease in progression of fatigue in the deltoids, biceps brachii, and serratus anterior, but an increase in fatigue in the latissimus dorsi during a 5-minute static hold task (Schmalz et al., 2019), and a reduction in MPF when wearing the exoskeleton on the right anterior and middle deltoids (Rashedi et al., 2014).

In this thesis, a 2-hour task emulating a welding inspection task completed in industry was used to measure the fatigue state over time deltoids along with the shoulder stabilizers. A decrease in MPF over time is indicative of increased local muscle fatigue (Cifrek et al., 2009; Bigland-Ritchie & Woods, 1984; De Luca, 1997). Over the 2-hour duration of this task, the anterior and middle deltoids remained at or above the 100% baseline measure (**Figure 30**, **Figure 31**), indicating that the muscles did not fatigue as a result of this protocol.

5.4.2 Supraspinatus

The rotator cuff plays a critical role in stabilizing the humerus relative to the scapula during overhead work. When elevating the arm, the deltoids have an upward pull on the humerus, and the supraspinatus has a slight downward and compressive force applied to the humerus to maintain the humeral head in the center of the glenoid (Greenfield, Donatelli, & Brody, 2004). When the supraspinatus fatigues, the humerus translates upwards, decreasing the subacromial space (Chopp et al., 2010).

While fatigue of the rotator cuff is linked to injury mechanisms in the shoulder during overhead work (Chopp et al., 2010; Dickerson et al., 2023), it has not been measured during any previous PUEE studies (De Bock, 2022). Measuring the muscle activity and fatigue from the shoulder stabilizers, particularly the supraspinatus, is a critical missing piece to improve our understanding of how the PUEE may affect risk of injury in workers using these devices.

In the 2-hour protocol during this study, the deltoids did not show significant signs of fatigue (**Figure 30**, **Figure 31**), while the supraspinatus had a significant decrease in MPF over time (**Table 16**). However, when using the exoskeleton, the MPF was significantly higher in the EXO group compared to the NE group (**Figure 32**), with the EXO group close to the 100% baseline measure (**Figure 36**). This demonstrates that after the 2-hour protocol there was significantly less fatigue accumulation in the supraspinatus of the EXO group.

Additionally, this significant decrease in MPF over time for the supraspinatus may indicate that over a longer period of time fatigue would continue to accumulate to a greater degree in the NE group. In this study a 2-hour protocol was performed, however, in the workplace shifts continue for 8 hours. Workers typically receive a break every few hours, but this may not be enough to recover fully if significant fatigue has accumulated, meaning the effects of fatigue will compound over the shift, the work week, or longer term. Hamberg-van Reenen et al. showed this trend in their baseline measurement of RPD in over 1000 participants. They measured ratings of discomfort in the upper extremity 3 times before lunch and 3 times after lunch (**Figure 39**, Hamberg-van Reenan et al., 2008). The same pattern is present in both individuals who reported discomfort (dashed lines) and those who did not (solid lines), but it was accentuated in the former. On average, after the lunch break, participants' discomfort decreased but not to baseline. Therefore, after their break, they were not able to fully recover, started at a higher point, and continued to increase in discomfort until the end of their shift (afternoon 3, **Figure 39**). A similar pattern could be expected in the supraspinatus fatigue accumulation throughout the shift.

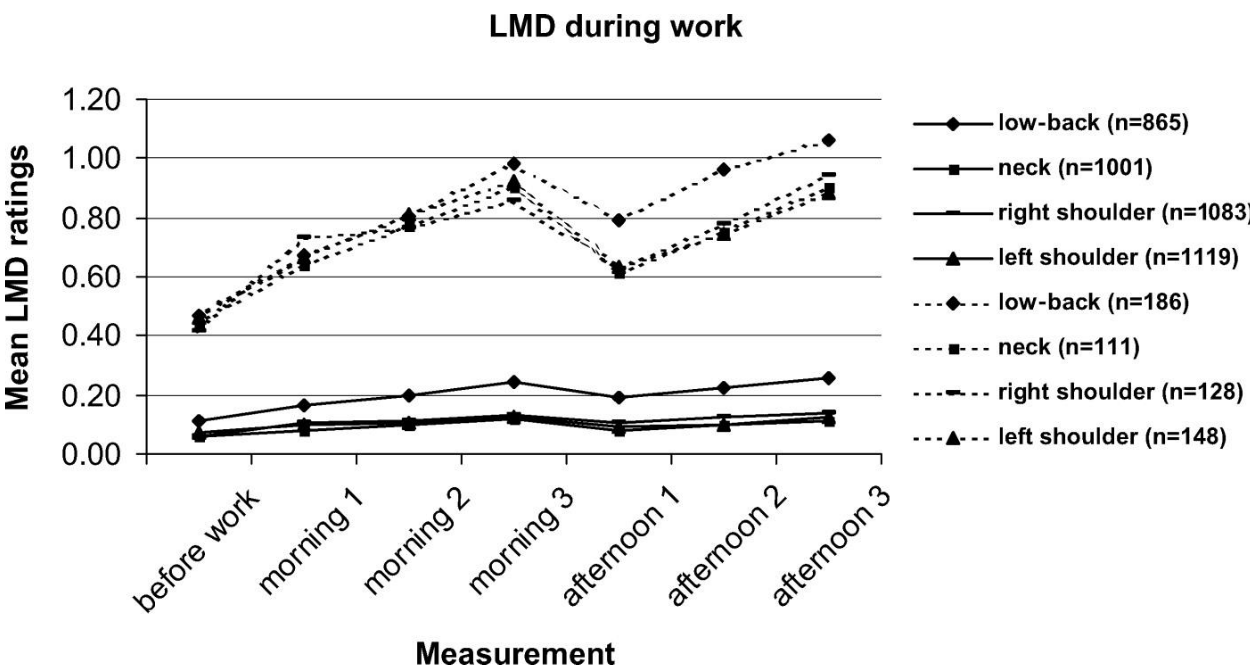

Figure 39. Mean localized musculoskeletal discomfort (LMD) in the low-back, neck and shoulder regions over the course of the working day. Solid lines represent the whole study sample; dashed lines represent the group of workers who reported LMD ratings higher than zero at least once in the day. Image from Figure 1 Hamberg-van Reenen et al. (2008).

It is important to note that in this case there was not a significant exoskeleton by time interaction, only a significant main effect of time and main effect of exoskeleton. Further testing should be done to confirm that the effect of the exoskeleton over a full shift is beneficial.

5.4.3 Infraspinatus

Infraspinatus plays an important role in stabilizing the shoulder alongside the 3 other rotator cuff muscles. Over the 2-hour protocol, there was a significant main effect of time for the infraspinatus, and post-hoc testing revealed a significant decrease in MPF at 20 minutes (**Table 17**, **Figure 29**), indicating early signs of fatigue in this muscle. Supraspinatus and upper trapezius did not show a significant decrease in MPF until 60 and 80 minutes, respectively (**Table 15**, **Table 16**). The fatigue in the infraspinatus may have occurred due to the external rotation of the arm that was required during the HIT task, completed before collecting the 20-minute reference task measures. The exoskeleton reduced these effects of fatigue in the infraspinatus. There was a significant main effect of hand (**Table 14**).

The overall reduction in fatigue by the exoskeleton in this study generally agrees with previous research. While there are few studies that have measured infraspinatus muscle activity (De Bock et al., 2022; Kim & Nussbaum, 2019; Van-Engelhoven et al., 2019; De Bock et al., 2023), none of which have measured fatigue directly with MPF, the results generally indicate a reduction in muscle activation. Short duration tasks involving overhead drilling (Kim & Nussbaum, 2019) and tracing (Van-Engelhoven et al., 2019) have decreased percent activation of the infraspinatus. A study that completed a 4-minute fatigue protocol before donning the PUEE and completing a drilling task PUEE reported an increase in infraspinatus muscle activity with the exoskeleton during the raising of the drill, and no differences when holding the drill overhead or lowering (De Bock et al., 2023). While evidence is mixed, these findings generally agree with the positive effect of the exoskeleton in this study.

5.4.4 Upper Trapezius

The upper trapezius assists in stabilizing the glenohumeral joint alongside the rotator cuff muscles. It functions as a scapular stabilizer, assisting in arm abduction in overhead postures (Kinsella & Carl, 2013). This muscle would be highly involved in facilitating the overhead postures required during this overhead weld task, and the significant decrease in MPF over time (**Table 15**, **Figure 27**), shows that there was fatigue accumulation over the 2-hour protocol.

Decreasing the load in the upper trapezius muscle may also reduce risk of injury and pain reporting. Trapezius muscle strain typically results from overuse of the muscle (Kinsella & Carl, 2013), and an ergonomic intervention that lowered upper trapezius muscle activity resulted in a reduction in sick days from musculoskeletal pain in assembly workers after a one-year follow-up (Aaras, 1994). In the welding task performed in this study, the wearing the exoskeleton resulted in a significant reduction in MPF (means = 93.5%, 101.0%, $p<0.001$), and therefore muscle fatigue. While not significant, the exoskeleton*time interaction graph shows that the NE group MPF trended downward from the start to the end of the 120-minute task, while the EXO group trend was more flat (**Figure 37**). These results support that the exoskeleton had a positive effect on reducing fatigue of the upper trapezius during this overhead welding task.

This agrees with findings from previous PUEE exoskeleton research. No previous studies have measured the upper trapezius in the frequency domain, however there are studies that measured muscle activity (De Bock et al., 2022). Most studies showed a reduction in muscle activity when using the exoskeleton (Debrosses, Schwartz, & Theurel, 2021; Grazi et al., 2020, deVries et al., 2019; Jorgensen, Hakansson, & Desai, 2022; de Vries and de Looze, 2021). One in-field study found no statistical difference in upper trapezius activity, however there was an insignificant reduction in muscle activity with the exoskeleton (Gilette & Stephenson, 2019). The inability to reach significance could in part be due to the small sample size (n = 6, Gilette & Stephenson, 2019). The results of this thesis agree with the direction in which the EMG data has trended in previous work.

5.5 Force

5.5.1 External rotation

The decrease in force in the EXO group external rotation (**Table 13**, **Figure 24**) does not align with the infraspinatus muscle fatigue results, which indicate the NE group was more fatigued than the EXO group (**Table 18**) and may suggest that the participants were experiencing central fatigue that modulated the amount of force output during the earlier force collections of the voluntary maximal force trials. This is further supported by the trend seen in the main effect of time on external rotation decreasing at 20 minutes before returning to baseline levels at the end of the protocol (**Figure 25**).

Maximal voluntary efforts require a physical output that is modulated by the cognitive centers of the brain (Behrens et al., 2023), which are more likely to be affected during long duration tasks (Bigland-Ritchie & Woods, 1984, Edwards, 1981). If the perceived difficulty of the task increases, the brain may decrease the voluntary force output to avoid further fatiguing the muscles and maintain energy levels to complete the task (Behrens et al., 2023). Previous studies have explored the potential for cognitive fatigue due to back exoskeletons (Zhu et al., 2021; Stirling et al., 2020; Bequette et al., 2020), and noted increased measures of frustration, perceived physical and mental workload, and effort when wearing an active back exoskeleton in non-expert users (Bequette et al., 2020), as well as increased brain activity when wearing an exoskeleton (Li et al., 2018). One potential mechanism for increased cognitive load being additional haptic feedback from the exoskeleton (Stirling et al., 2020). This potential increased cognitive workload paired with early signs of fatigue in the infraspinatus may help explain the decrease in force in the EXO group compared to the NE group during the external rotation force task. Future work should investigate perceived cognitive fatigue along with comparing expert and non-expert users of exoskeletons to advise workplace implementation recommendations.

6.0 Conclusion

This thesis produces novelty in exoskeleton research, specifically the characterization of fatigue of the rotator cuff muscles during a simulated 2-hour workplace emulative task. The overhead weld inspection task caused increased markers of fatigue in stabilizing shoulder musculature (supraspinatus, infraspinatus, and upper trapezius) while the deltoids did not show signs of fatigue after 2 hours of overhead work. The combination of a fatigued rotator cuff paired with non-fatigued deltoids has negative implications for occupational shoulder injury precipitation, particularly for superior humeral head translation and resulting subacromial impingement. Wearing the exoskeleton reduced the effects of fatigue in the supraspinatus, infraspinatus, and upper trapezius over the 2-hour protocol, and could potentially maintain these positive effects over a longer period.

Wearing the exoskeleton decreased shoulder discomfort, however wrist discomfort increased slightly with the exoskeleton, while remaining generally low. This should be considered and monitored over a longer period when implementing exoskeletons in the workplace. Additionally, external rotation force was lower with the exoskeleton than without, driven by a decrease in force output at the start of the collection period that returned to baseline values by the end of the 2-hour protocol. This may be due to the participants' non-expert status both with the exoskeleton and the workplace task increasing cognitive fatigue. This needs to be explored further in future research as cognitive fatigue was not directly measured in this thesis and may be affected differently in a workplace setting compared to the lab environment.

Overall, the passive upper extremity exoskeleton tested in this thesis reduced fatigue of the rotator cuff muscles. This had not been previously explored during a longer duration task representative of the workplace.

7.0 Practical Considerations for Exoskeleton Usage in the Workplace

This thesis was completed to investigate the impact of a passive upper extremity exoskeleton during an overhead work task where exoskeletons have been previously implemented in industry due to challenges with removing the overhead work component. Exoskeletons are commonly considered personal protective equipment (PPE). Based on the hierarchy of controls (NIOSH, 2015), PPE should only be implemented after other hazard control measures that eliminate or substitute the overhead work component of the task have been investigated, and it is determined they are not viable options.

Exoskeletons alone will not remove the hazard caused by overhead work; however, they may reduce it. This thesis has shown that there is potential for the exoskeleton to reduce the effects of fatigue in the shoulder when completing prolonged overhead work. Reducing or delaying the effects of fatigue will decrease the overhead work hazard that is caused by fatigue of the stabilizing shoulder muscles, however there is still inherent risk in the task due to the overhead posture required. The ideal solution would remove the overhead work component from the work completely.

Additionally, this thesis builds on the existing body of PUEE literature by characterizing the fatigue response of the stabilizing shoulder muscles (supraspinatus, infraspinatus). While these muscles are more directly linked to injury mechanisms than the deltoids, they are less frequently measured. However, the task was only 2 hours long, and while it provides insights into the trends the stabilizing muscles experienced, the definition of fatigue was not reached in this time. Future work should continue to explore the effects of PUEE's on fatigue of the shoulder stabilizing muscles, as well as the direct impact of exoskeletons on injuries in the workplace over a longer period of time – such as a full shift, week, months, or years. This will provide a better understanding of the potential for injury reduction of passive upper extremity exoskeletons.

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