Investigating the Effects of a Task-Specific Fatigue Protocol on Hand Tracking Performance Using a Wrist Robotic Device

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Abstract

The purpose of this work was to evaluate the effects of a dynamic submaximal fatigue protocol and forearm/hand anthropometrics on hand tracking performance. Participants traced a 2:3 Lissajous curve using a haptic wrist robotic device (WristBot). This same curve was traced before the fatigue (baseline), during the fatigue protocol, and after the fatigue protocol. Post fatigue trials were completed at 0, 1, 2, 4, 6, 8, and 10 minutes after the cessation of the fatigue protocol. Overall tracking performance and movement smoothness decreased immediately. Directional biases in the normal and longitudinal component of tracking error were present after the fatigue protocol. Proximal forearm circumference and forearm length had a negative correlation with movement smoothness. Hand tracking performance decreased due to the submaximal fatigue protocol. Those with a larger proximal forearm circumference and longer forearm length had better movement smoothness performance which can be applied to the workplace where hand and wrist are predominately used.

Keywords: Anthropometrics, Fatigue, Robotics, Performance

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Chapter 1: Introduction

1.01 Background

Humans interact with their surroundings by use of their upper extremities, especially the hand and forearm. From manual labor to daily activities, humans use their hands to utilize tools, operate machines and interact with others. The forearm is comprised of many muscles that work synergistically as well as antagonistically to control movements across the wrist and elbow joints. In the workplace, forearm muscle and force demands can vary, from low level force requirements such as typing on a keyboard to high level force efforts such as assembling cars on an assembly line. Despite the capability for a large range of force production, over time even low levels of muscle activity and effort can lead to localized muscle fatigue.

Workplace injuries result in thousands of loss-time claims in Ontario alone. This accounts for millions of dollars in healthcare costs annually, placing an increased burden on the Canadian economy (WSIB, 2019). Work related musculoskeletal disorders (MSD) to the hand and wrist joint are prevalent in manual labour jobs with repetitive, sub-maximal requirements. 11.8% of construction workers report a hand/wrist MSD compared to only 4.1% of office workers (Holmström & Engholm, 2003). Overuse injuries to the forearm, particularly the wrist extensor muscles are common and can affect an individual's capability for hand and wrist performance. Lateral epicondylitis (LE) is a common condition characterized by pain at the lateral epicondyle and is aggravated by contraction of the extensor carpi radialis muscle. LE affects 5-15% of the working population (Shiri et al., 2006) and wrist extension forces in those with LE are lower compared to a healthy population by 15-17% (Alizadehkhaiyat et al., 2009). Grip strength is also

16-19% lower in those with LE (Alizadehkhaiyat et al., 2009). Further investigation into wrist strength as well as wrist flexor and extensor muscle recruitment characteristics are needed to mitigate fatigue and injury to the wrist and elbow during occupational tasks.

While movement of the hand to grasp objects may be a simple task for most people, there are complex neural and biomechanical factors that must be overcome for task success. Despite the redundant design in forearm musculature, the flexors and extensors have very different roles when it comes to wrist movement and grip force production. Previous research has shown the wrist extensors contribute more to joint rotational stiffness (Holmes et al., 2015). Increased joint rotational stiffness leads to increased wrist joint stiffness and resistance to sudden perturbations (Holmes, 2015). In addition, wrist extensor muscle activity is high during gripping, regardless of the task. Wrist extensor muscle activity remains active while a person grips and performs wrist flexion or extension (Mogk & Keir, 2003a), indicating their primary involvement in wrist stability. On the other hand, the wrist flexors are task-dependent; flexor muscle activity is more active than wrist extensor activity only in wrist flexion positions (Mogk & Keir 2003a). This suggests the wrist flexors are primarily involved in flexion force production. Despite previous research supporting the wrist extensors role as wrist stabilizers, both Forman et al. (2020) and Kumar et al. (2020) saw no significant differences in wrist strength between the wrist flexor and extensor groups when performing maximal voluntary contractions (MVC). This leads us to investigate the use of the hand and wrist with a more holistic outlook.

Though the external effects of muscle fatigue are comprehensible, the underlying mechanisms in which fatigue manifests are more complex. Both peripheral and central mechanisms can be investigated to explain changes in human movement post-fatigue. To translate how fatigue can affect human performance, two types of fatigue have been proposed: performance fatigue and perceived fatigue (Enoka & Duchateau, 2016). Performance fatigue encompasses the decline in quantifiable measures for both contractile and neural properties, including decrements in force output, muscle fibre calcium level, neuromuscular propagation, and muscle activation patterns. A decline in any of the aforementioned measures can negatively impact movement accuracy leading to performance decrement and/or injury (Parijat & Lockhart, 2008). Research on fatigue performance for the distal upper extremity is limited. Recent work investigating the effects of submaximal isometric fatigue on hand tracking performance showed an increase in tracking error immediately after the cessation of the fatigue task (Forman et al., 2020). A similar study investigating the effects of submaximal dynamic fatigue on hand tracking performance also showed a decrease in tracking performance after completing a fatigue task (Kumar et al., 2020). The movement smoothness metric (jerk ratio) showed no return to baseline until 10 minutes post-fatigue task. This was novel as movement smoothness returned to baseline almost immediately during an isometric fatigue study (Forman et al., 2020). Kumar et al., (2020) showed no difference in performance metrics whether the flexors or extensors were fatigued. While strides have been made in understanding the roles of the wrist flexors and extensors in movement control and fatigue, there are still questions that remain unanswered related to individual characteristics that may play a role in neuromuscular control of the hand.

1.02 Research Gap

While previous literature has investigated the effects of fatigue on the wrist flexors or extensors (in isolation), in relation to hand tracking performance (Forman et al., 2020; Kumar et al., 2020), little research exists on the differential responses of these groups in tandem. One limitation to the previous work is that due to the high extensor muscle activity in most hand movements, the extensors were likely also fatigued during fatigue protocols that targeted the wrist flexors. In addition to wrist flexion and extension, the wrist can perform radial and ulnar deviation. Previous research in our lab has investigated both wrist flexion/extension and ulnar/radial deviation fatigue in isolation. Our first study investigated the effects of an isometric fatigue protocol on a complex dynamic tracking task (with separate experimental sessions for wrist flexor or extensor fatigue). Next, a single degree of freedom dynamic fatigue protocol was investigated using the same dynamic tracking task. The next logical progression is to investigate a task specific, multiple degrees of freedom fatigue protocol on a complex tracking task. There is little research on the effects of fatigue on tracking performance when considering fatigue protocols that target the entire forearm muscle complex.

1.02 Research Questions

1. How does a task specific, submaximal, dynamic forearm muscle fatigue protocol affect hand tracking accuracy?
2. How do distal upper extremity anthropometrics affect wrist flexion/extension torque and grip force production?
3. Will distal upper extremity anthropometrics affect tracking performance?

Chapter 2: Review of Literature

The hand and forearm are essential when interacting with our surroundings, especially in the workplace. Task frequency, duration, and intensity are important risk factors to consider when evaluating hand intensive tasks. Various combinations of these risk factors can lead to overuse of the hand and forearm, resulting in compensation from different muscles. It is not entirely clear why people performing the same workplace tasks develop injuries at different rates. Muscle fatigue is a complex process that can impair performance. It is possible that anthropometric characteristics and muscle fatigue may result in variances in joint kinematics which over time can lead to pain, and eventually MSDs. Although anthropometrics and force production have been studied, few studies have tried to correlate anthropometrics and hand tracking performance post fatigue. Quantifying fatigue and hand performance will further our knowledge on predispositions to fatigue at the forearm.

2.01 Injuries

Hand/wrist injuries result in ~20% of all visits to the emergency department in Europe (Van Eerd et al., 2016). MSDs are characterized as disorders that cause pain to muscles, tendons, joints and nerves (Van Eerd et al., 2016). Injuries of the upper extremity occur often due to our reliance on pushing, pulling, and gripping to perform jobs, play sports, and other activities of daily living. Factors that affect injury risk include posture, task duration, and force output requirements. It is important to consider interactions between the aforementioned to assess task injury risk (Moore et al., 1991). Though it is difficult to prevent acute injuries to the upper extremity, chronic injuries such as tendinosis, joint pain, and others occur over time and thus have a better chance of prevention if discovered early (Rettig, 1998). When a repetitive task requires disproportionate demands from muscles, it may lead to a change in muscle loading and joint kinematics. This may lead to increase muscular demand and therefore muscle damage and injury are more likely to occur (Kumar, 2001).

MSDs can cause short-term and long-term decrements in strength due to their painful nature and prolonged disuse can lead to muscle atrophy. Wrist flexion and extension strength of patients diagnosed with carpal tunnel syndrome (CTS) have shown to be lower than those without CTS (Ağırman et al., 2017; Reichard et al., 2010). Those with unilateral CTS showed similar flexion and extension force in the unaffected arm compared to a healthy control group (Reichard et al., 2010). This decrease in force due to injury may affect how people perform tasks that involve grip or other forearm actions. Though participants with CTS have been shown to have lower strength than participants without CTS, it is unclear how different strength profiles would affect strength values. Therefore, further investigation into different strength profiles of a healthy population may help us understand injury predisposition.

Epicondylitis is one of the most prevalent musculoskeletal injuries of the upper extremity (Erdem & Neyisci, 2019). Epicondylitis is an injury to the outer or inner aspect of the elbow caused by repeated use of the forearm, causing breakdown of the tendons of the wrist extensor and flexor muscles resulting in debilitating pain. A study comparing flexor and extensor strength of males diagnosed with LE and a healthy group showed no difference between strength profiles of both groups, but a higher wrist flexor average torque in the affected group (Unyó et al., 2013). These findings differ from Alizadehkhaiyat et al. (2007) as they saw a decrease in flexor and extensor strength in patients with LE. This study had participants perform isometric flexion and extension, whereas Unyó et al. (2013) had their participants perform isokinetic flexion and extension. Wrist extensor activation in LE patients compared to a healthy population differ as decreased extensor carpi radialis (ECR) activity was compensated by higher extensor carpi ulnaris (ECU) activity (Rojas-Martínez et al. 2007). Due to a higher prevalence to fatigue in those suffering from LE, other muscles must be used to compensate leading changes in movement patterns.

Both carpal tunnel and epicondylitis are chronic overuse injuries that cause pain and can have a troublesome recovery. With constant use of the extensor muscles specifically, fatigue occurs and may play a large factor in the overall health of the distal upper extremity. The effects of fatigue on injury occurrence have been widely researched, but predispositions to fatigue in the forearm still need to be investigated.

2.02 Anatomy

2.2.1 Joints

The forearm is comprised of two bones, the radius and the ulna. The distal ulnar/radial joint lies between the radial/ulnar heads and the metacarpals of the hand. The interaction between the ulnar head, radial head, and capitate bones dictates forearm rotation. The radius of curvature of the radius sigmoid notch is slightly larger (15 millimetres m vs 10 millimetres) than the curvature of the ulnar head. This allows for rotation and translation of the forearm (Chidgey, 1995). The triangular fibrocartilage complex (TFCC) is a complex of ligaments that provide stability to this joint when rotating or gripping (Figure 1) (LaStayo & Lee, 2006). The TFC contains ECU subsheath, ulnolate ligament, ulnotriquetral ligament and ulnar collateral ligaments (Palmer & Werner, 1981).

The proximal ulnar/radial joint allows for rotation of the forearm resulting in pronation and supination. The radial head interacts with the ulnar notch, resulting in 215 degrees of rotation. In addition to rotation, there is slight translation due to the shape of the radial head and notch. During pronation, the radial head translates anteriorly with pronation and posteriorly with supination (Weiss & Hastings, 1992).

The middle ulnar radial joint is constructed of interosseous membrane. The central band is oriented at a 21degree angle to the longitudinal axis of the ulna and originates from the proximal third of the radius and inserts on the distal quarter of the ulna. This membrane functions to allow smooth rotation of the forearm by stabilizing both bones, and it allows for force transfer from the radius to the ulna (LaStayo & Lee, 2006).

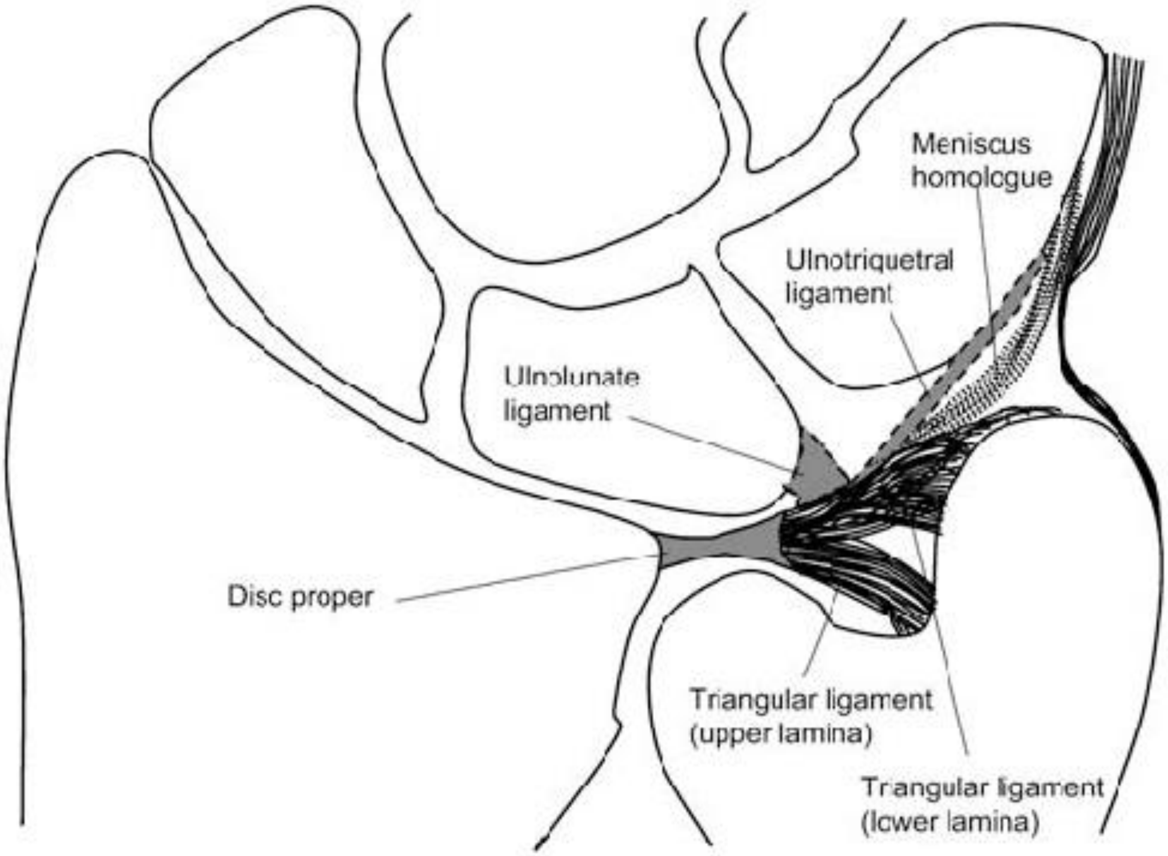

Figure 1. Schematic of the ligaments that form the TFCC. Adapted from Yoshioka et al., (2003).

2.2.2 Muscles

The forearm contains various muscles organized to perform the basic movements of the forearm. The muscles of the forearm are divided into three compartments: mobile wad, dorsal, and volar (Figure 2) (Boles et al., 2000). The mobile wad contains the extensor carpi radialis (ECR) and brevis (ECRB) which extend and abduct the hand. It also contains the brachioradialis which aids in forearm flexion. The dorsal compartment contains the extensor digitorum (ED), the extensor carpi ulnaris (ECU) and the extensor digiti minimi which extend the hand and phalanges. Looking deeper into this compartment lies the muscle responsible for supination, the supinator and other accessory muscles responsible for extending the phalanges.

The volar compartment is also separated into deep and superficial groups. The deep group contains the muscles that flex the phalanges and the pronator quadratus which pronates the forearm. The superficial group contains the flexor carpi radialis (FCR), flexor carpi ulnaris (FCU), and flexor digitorum superficialis (FDS). The FCR performs radial deviation of the hand while the FCR performs ulnar deviation. The FDS flexes the phalanges (Boles et al., 2000).

There are differences in moment generating capabilities between wrist flexors and extensors. Collectively, average moment arm length in the wrist flexors is 23% longer than average moment arm length of the wrist extensors (Gonzalez et al., 1997). In addition, physiological cross sectional area (PCSA) of the wrist flexors is approximately 2 times greater than the wrist extensors (Gonzalez et al., 1997). Muscle lines of action differ between wrist flexors and extensors. Direction of FCU and FCR vectors point towards wrist flexion whereas, direction of ECR and ECU are biased towards radial and ulnar deviation (Figure 3) (Bawa et al., 2000).

Figure 2. Muscle compartments of the forearm. Adapted from Boles et al. (2000).

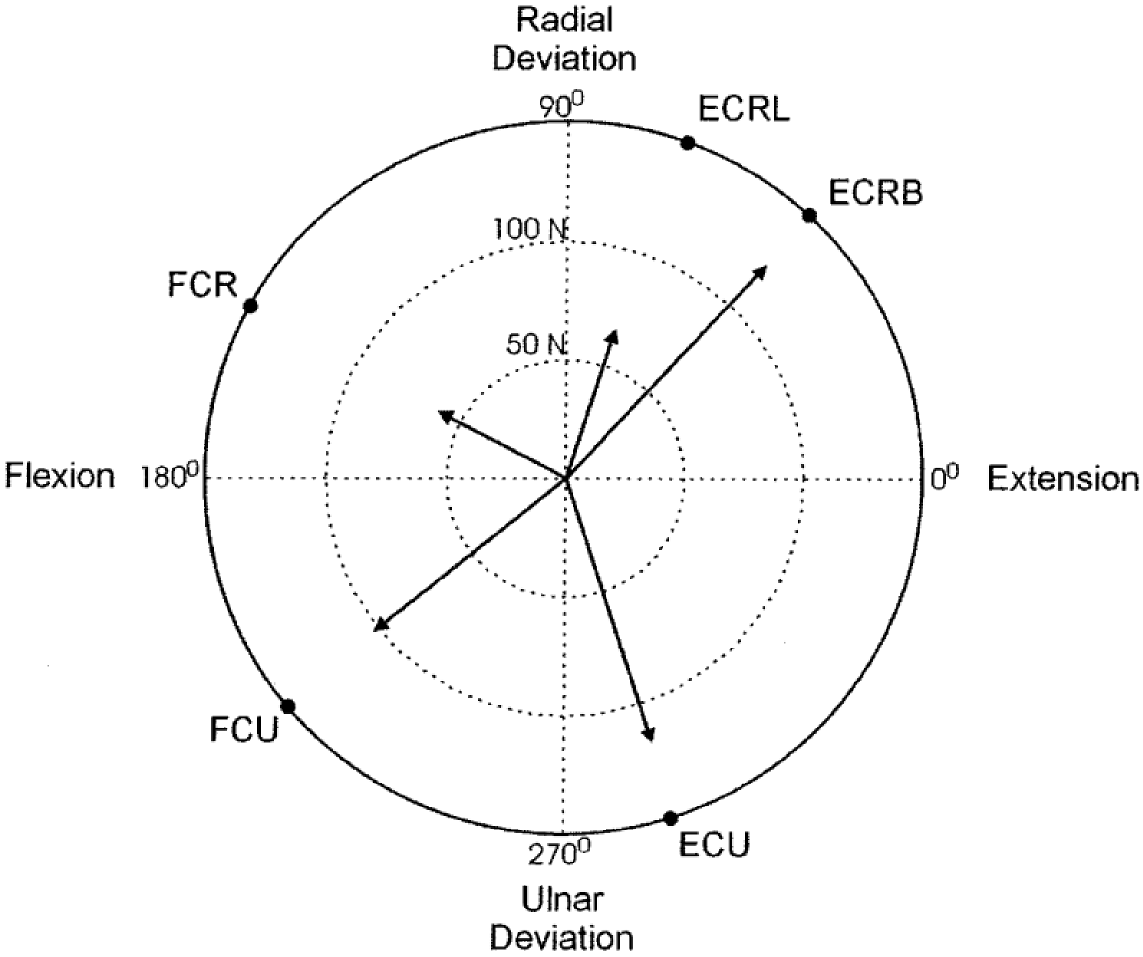

Figure 3. Direction of muscle and magnitude of forces in 5 forearm muscles (Adopted from Bawa 2000).

2.03 Anthropometrics

2.3.1 Forearm

Forearm and hand anthropometrics have been used to relate physical measurements to grip force production and overall strength. Early research has looked at various landmarks on the distal upper extremity such as forearm length, forearm girth, wrist circumference, hand length, hand circumference, hand length and finger length (Anakwe et al., 2007; Çakıt et al., 2015; Eidson et al., 2017; Li et al., 2010; Sirajudeen et al., 2012). Using multivariable linear regression analysis studies have shown different anthropometric measurements best correlating or predicting maximal grip strength. Due to the variability in anthropometrics taken by researchers, different forearm anthropometric measurements have been shown to correlate best with maximal grip strength. Hand circumference has been shown to be a better predictor of maximal grip strength than forearm circumference (r^2= 0.349) (Hemberal et al., 2014). Regression analysis has shown that maximal grip strength can be predicted using solely hand circumference (Li et al., 2010). Anthropometrics may be used to correlate athletic performance to feasible forearm and hand measurements. It has been shown that grip athletes have greater handgrip strength, greater palm width, finger length than non-athletes (Fallahi & Jadidian, 2011). Forearm girth has shown to correlate (r^2= 0.484) with handball throwing performance in university aged players (Mathavan, 2012). Therefore, measuring forearm anthropometrics could have practical implications to athletic performance.

The conclusions of these anthropometric studies are dependent on the anthropometric values taken. Hand circumference have been shown to correlate best with grip strength but results from other studies show forearm circumference being the greatest indicator. Collectively, hand and forearm anthropometrics are fairly accurate predictors of wrist strength. Research that encompasses more forearm and hand anthropometrics is needed to elucidate which anthropometric measurements best predict grip strength. Despite the plethora of research on maximal grip strength and anthropometrics, there is still little data on how forearm anthropometrics influence gripping endurance. Nicolay & Walker (2005) concluded that anthropometrics and fatigue may not be related due to fatigue being influenced by multiple factors such as fibre type, biochemistry, and individual motivation. Therefore, it is necessary to utilize anthropometrics to predict maximal grip forces and determine if these values can have any effect on fatigue performance.

2.3.2 Sex

Hand grip strength is also affected by sex. Males tend to produce greater grip force than females in both dominant and non-dominant hands (Forthomme et al., 2002; Klum et al., 2012; Nicolay & Walker, 2005). This may be due to the size of grip dynamometers as the optimal grip size for women is usually smaller than men. A grip diameter of 5.5 centimetres was shown to elicit optimal grip force for men (Ruiz-Ruiz et al., 2002). This discrepancy may be lessened when grip dynamometer handle sized is controlled. Won et al. 2009 investigated gender differences in a typing task which showed women used more force and had higher wrist extensor activity than men. This may be due to sex differences in tendon stiffness (Kubo et al., 2003). It has been shown that men have greater tendon stiffness than women which may partly explain the difference in force generation. (Kubo et al., 2003). Males also have a higher number of type I muscle fibres compared to females. Mean muscle fibre area has also been shown to be larger in males (6632 um^2) compared to females (3963 um^2) (Miller et al., 1993). In addition to different properties in males, forearm PSCA is significantly greater in males than females (Bishop et al., 1987). This may be the main reason for gender differences in handgrip force and wrist flexor and extensor production.

2.3.3 Age

Age has been shown to be a significant factor in handgrip strength. When a large range of age groups are studied, it is shown that those age 30-49 have higher grip strength than those that are younger (18-29) and older (50-65) (Anakwe et al., 2007; Klum et al., 2012). Conversely, Lopes et al. show no difference in age groups when looking at subjects 20-60 years old. These strength differences may be due to occupation as manual laborers more often are between the ages of 30-49 (Klum et al., 2011).

2.04 Strength

2.4.1 Hand Grip

Gripping is a fundamental movement that is vital to how we interact with the world. Applying force while gripping requires activity from both wrist flexor and wrist extensor musculature. The muscles on the dorsal and palmar sides of the forearm co-contract to maintain balance about the wrist joint. This co-contraction is important as musculature imbalance has been shown to cause injury (Gribble et al., 2003; Kumar, 2001). Normative data shows there are gender differences in maximal grip strength. (men: 540.8 ± 87.1; women: 329.4 ± 57.7 N) (Leyk et al., 2007). Muscle strength imbalances, specifically a weakness in wrist extensor strength, has been shown in those with tendinopathies such as epicondylitis (Alizadehkhaiyat et al., 2009). Though wrist flexors and extensors need to contract together to maintain joint stability, research has shown that the extensor muscles are more active than the flexors during isometric gripping at lower intensities (Hägg & Milerad, 1997; Mogk & Keir, 2003). This may be due to the extensor group having a smaller physiological cross-sectional area (Cutts et al., 1991). Therefore, to maintain muscular balance about the wrist joint, wrist extensors must work at a higher percentage of their maximum than the wrist flexors.

2.4.2 Effects of Posture on Grip force and Wrist Flexion/extension

Due to the complex arrangement of forearm musculature, different wrist postures have been shown to have an effect on grip force, wrist force and forearm muscle activity. Wrist flexor activity exceeds wrist extensor activity when the forearm is supinated (Mogk & Keir 2003a). On the contrary, extensor activity exceeds flexor activity when the forearm is pronated (Mogk & Keir 2003a). Changes in wrist extension and flexion torque have been shown when forearm posture is changed as well. When compared to a neutral wrist posture, wrist extensor force is greater in pronation and wrist flexion force is greater in supination (La Delfa et al., 2015). The ideal wrist position for maximizing grip force is at 0° (Neutral) to 30° of extension (Hallbeck, 1994; Hallbeck & McMullin, 1993). It was shown that 50% wrist flexion decreased mean maximal voluntary exertion (MVE) and grip endurance (Finneran & O'Sullivan, 2013). A decrease in grip force by 40-50% with the wrist in flexion has been previously shown by Mogk & Keir (2003a).

2.05 Fatigue

Muscle fatigue is characterized as a progressive decline in force associated with muscle activity that is recoverable after a period of rest (Westerblad & Allen, 1991). In addition to force, contraction velocity and power are also negatively affected by fatigue. The complex process of muscle contraction can cause fatigue to originate at different parts of the motor pathway (Wan et al., 2017) . In addition to the peripheral changes that occur during fatigue, central changes can augment the decline in muscle performance (Gandevia, 2001). Central fatigue refers to disruptions in the signals that are necessary to elicit muscle activity. This disruption can happen anywhere along the central nervous system (CNS) (Gandevia, 2001). Peripheral fatigue refers to the reduction of force that is brought upon by changes in the processes that occur after the neuromechanical junction, including the sarcoplasmic reticulum and the myosin-actin complex (Fitts, 1994). Though calcium's role in muscle contraction has been well documented, decreases in calcium levels may only play a small role in the overall decrease in force production. Accumulation of metabolites such as inorganic phosphates and hydrogen ions can exacerbate the effects of decreased calcium on isometric force production (Hägg & Milerad, 1997; Mogk & Keir, 2003a)

2.5.1 Forearm Fatigue

In terms of forearm specific fatigue and endurance, low level fatigue of the extensors has been shown to still have an effect on muscle contraction mechanisms hours after fatigue protocol. Forearm fatigue is seen in the extensors more than the flexors during a submaximal gripping task even if the load is relatively low (Hägg & Milerad, 1997; Mogk & Keir, 2003a; Nicolay & Walker, 2005). This may be due to the extensors being primarily a wrist stabilizer. Physiological responses indicative of muscle fibre types show that forearm muscles are comprised of type II fast twitch muscle fibres (McIntosh et al., 1985; Mizuno et al., 1994). Since wrist extensor muscle activity is higher than wrist flexor activity in most wrist positions, the extensors experience fatigue quicker than wrist flexors. Though the wrist extensors are more fatigable than the wrist flexors, Forman et al. (2020) showed variability in time to exhaustion (25% MVC) between wrist flexors and extensors. 10 participants showed a slower time to exhaustion during isometric wrist extension whereas 4 participants showed a longer time to exhaustion during isometric wrist flexion. Following wrist extensor muscle fatigue, motor evoked potential (MEP) to EMG ratios were significantly larger; this may suggest that supraspinal excitability may have been increased. It has been shown that fatigue is harder to predict using anthropometrics than force due to the aforementioned confounding physiological and neurological factors (Nicolay & Walker, 2005).

2.5.2 Fatigue and Performance

Local muscle fatigue can have many implications for human movement. Performance fatigue considers objective measures such as the ability to produce force and the nervous system's ability to output signal (Enoka & Duchateau, 2016). Fatigue leads to decreased movement accuracy due to increased force variability (Missenard et al., 2008b). To perform movements accurately there is a level of co-contraction needed, especially for a multi-joint movement (Gribble et al., 2003). Fatigue may cause a decrease in force of the involved muscles which lead to kinetic imbalance throughout the movement. This imbalance over time can be problematic as movement is compromised as a compensatory mechanism leading to injury (Kumar, 2001). Fatigue has been shown to have negative implications to overhand sports performance as well. It has been shown in baseball and tennis players that experienced flexor fatigue lead to a decrease in accuracy and overall performance, that was attributed to the flexor's importance in hand and finger control (Wang et al., 2018). The baseball pitchers showed no significant change in speed, but accuracy was compromised when fatigued. They also showed higher FCR activity during the cocking and acceleration phase for baseball pitching and increased ECR during the cocking phase for tennis serving. Both increases in muscle activity may be to compensate for lack of muscle activity from synergists post fatigue. Thus, further investigation into muscle fatigue may improve performance in athletes that rely on hand accuracy (Forman et al., 2020; Kumar et al., 2020).

2.5.3 Forearm Muscle Activity

Though research on strength values of the wrist flexors and extensors are well documented, there is a lack of information on the neural activation of said muscles during and after fatigue. EMG can be used to objectively determine neural activation patterns in muscle even during muscle fatigue (Viitasalo & Komi, 1977). Early fatigue research suggested that static low-level contractions (<15% MVC) can be held indefinitely (Rohmert, 1960). Later work disproved this by showing increases in muscle activity and a decrease in the mean spectral frequency during one hour of isometric work (5-10% MVC) (Jørgensen et al., 1988). During localized muscle fatigue, there is an accumulation of metabolites due to repetitive muscle contraction. This accumulation leads to a decrease in action potential conduction velocity down a muscle fibre (De Luca, 1997).

Extensor muscle activity is important to investigate as it can affect overall grip force. Shimose et al., (2011) saw an increase in EMG activity of the ECU and ECR after exclusively training the forearm extensor muscles and a decrease in EMG of the FCU and FDS. Despite a less reliance on the wrist flexors, maximal grip force of the participants increased after an 8-week training program. This not only shows the relationship between EMG and force, but also the importance of extensor muscle activation in relation to grip force. Forman et al. (2020) found no significant difference between hand tracking performance post wrist flexor and extensor fatigue. One limitation their paper was that muscle activity was not measured during any of the fatigue trials. This should be noted because the extensors are still active during wrist flexion due to their wrist stabilizing properties (Mogk & Keir, 2003a). Measuring EMG of the wrist flexors and extensors would indicate if both muscle groups were fatigued during the flexor fatigue session leading to the decline in tracking performance.

When considering dynamic tasks, the flexor muscle group seems to be more task dependent than the extensor muscle group (Hägg & Milerad, 1997). When performing wrist flexion, flexor muscle activity was higher than extensor activity, but extensor activity was still present. When performing wrist extension, extensor muscle activity was higher than flexor muscle activity and flexor activity was minimal (Hägg & Milerad, 1997). When performing push and pull tasks, wrist muscle activation increased by 13% when the wrist deviated from a non-neutral position (Cudlip et al., 2018). This shows that the wrist extensors are being chronically activated regardless of wrist posture. During isometric gripping and wrist extension/flexion, average wrist extensor muscle activity has been shown to be 3.5 times higher than wrist flexor activity (Forman et al., 2019). Higher wrist extensor activity has also been shown in dynamic contractions as well (Forman, Forman, Avila-Mireles, et al., 2020). Since extensors are working at a higher percentage of their maximum force, they may be more susceptible to overuse than the wrist flexors. Grip force has been shown to decrease when only the wrist extensor muscles are fatigued, highlighting their importance in grip force production (Souza et al., 2017).

2.06 Wrist Robotics

Upper limb robotic assistive devices have been used to measure muscle activity under controlled environments (Casadio et al., 2009, Carpinella et al., 2009). More recently, EMG has been implemented in conjunction with robotic assistive devices to further understand muscle activity and co-contraction in early stroke patients (Qian et al., 2017). Forman et al. (2020) used an assistive robotic device to investigate the effects of forearm fatigue on hand tracking performance. They showed a decrease in figural error and tracking error immediately after a forearm fatigue protocol regardless if only the wrist flexors or only the wrist extensors were fatigued. This change in figural error and tracking error signifies increased deviation from the ideal tracking pattern. That is to say hand tracking performance became worse due to fatigue of the wrist flexors and extensors. Robotic assistive devices are beneficial in rehabilitation settings for participants as they can provide numerous repetitions, variability in movements, and movement assistance. They are also beneficial for the researcher/clinician as they can obtain quantitative and qualitative feedback on a subject/patient’s progress. In addition, researchers are able to decrease variability between subjects by normalizing the task or position of the limb when using the device. Robotic assistive devices also allow for control over force, stiffness, inertia/gravity and speed of movements. This versatility reiterates their importance in a research/clinical setting. Due to the kinematic data robotic assistive devices can measure, it can be a good indicator of wrist performance.

2.6.1 WristBot

The WristBot is a robotic assistive device built by the Italian Institute of Technology (Figure 4). The WristBot has the capability of moving with 3 degrees of freedom. This is accomplished by drivable motors that can be manipulated to only all the use to move in a specific plane. The 3 planes of movement are Flexion/Extension = ±70°; Radial/Ulnar Deviation = ± 35°; Pronation/Supination = ± 80° (Masia et al., 2009).The WristBot contains brushless motors that provide accurate haptic rendering and compensate for the weight and inertia of the device during movement (Marini et al., 2016). These motors allow for variable resistance, allowing customization between participants. WristBot has the capability to store kinematic data obtained from each participant. It can also be integrated with visual software that allows for the participant to track and follow patterns on a screen.

Figure 4. WristBot (Italian Institute of Technology)

Chapter 3: Study

3.01 Hypotheses

1) All tracking performance metrics will get worse immediately after the cessation of a submaximal task specific fatigue protocol. Kumar et al., 2020 saw decreases in tracking performance after a dynamic fatigue protocol that targeted the wrist flexors or extensors, individually. A combined wrist fatigue protocol should result in greater impairments.

2) There will be ulnar and radial directional differences between baseline tracking performance and the post task specific fatigue protocol. The fatigue protocol from previous studies fatigued only the wrist flexors and extensors, individually, different data collections. Our proposed fatigue protocol applies resistance to ulnar and radial movements as well as flexion and extension movements.

3) There will be a positive correlation between circumferential anthropometrics and grip force production. Forearm circumference and wrist circumference have a positive correlation with handgrip strength (Sirajudeen et al., 2012).

4) There will be a positive correlation between circumferential anthropometrics and post-fatigue tracking performance. As mentioned above, both forearm circumference and wrist circumference have been shown to have a positive correlation with handgrip strength (Sirajudeen et al., 2012). Those with higher grip strength may be less susceptible to the effects of muscle fatigue.

5) Forearm length and circumference will have a positive correlation to wrist flexor and extensor strength. Longer moment arms and larger PCSA increases moment generating capacity (Gonzalez et al., 1997; Lieber et al., 1992).

3.02 Methods

3.03 Participants

19 right-handed university-aged male participants (Age: 23.4 ± 1.8 years, Weight: 78.1 ± 8.2 kg, Height: 178.7 ± 6.3 cm) were recruited for this study. Male participants were recruited due to gender differences in fatigue (Kumar et al., 2020). Participants filled out the Edinburgh Handedness Questionnaire prior to starting the experimental protocol to determine handedness (Appendix A1). They also filled out a screening form to determine age, gender, and previous upper extremity injury history (Appendix A2). Participants were excluded from this study if they self-reported any upper limb disorder/injury within the last 12 months or if they currently had an upper extremity injury that would restrict wrist and arm mobility. No participants indicated a previous injury to the distal upper extremity within the past 12 months. This study was approved by the Brock University Research Ethics Board (File # 18-113).

Sample size was selected by conducting an *a priori* power analysis. This power analysis was completed using G*Power 3.1.9.6 (Universität Düsseldorf, Düsseldorf, Germany), and indicated that 10 participants will be sufficient to obtain adequate power (Cohen 1992) based on primary outcomes of robotic wrist tracking performance metrics. The effect size chosen ($f^2 = 0.5$) represented the lower range observed in the literature for the same dependent variables such as tracking error, figural error, and jerk ratio of 0.5-1.7 (Forman et al., 2020; Kumar et al., 2020; Squeri et al., 2010).

3.04 Experimental Setup

Upon entering the lab, participants were presented with an informed consent. They had the opportunity to ask any questions prior to signing the informed consent. Once they agreed and understood the contents of the form, they signed. In addition, participants were presented with an optional photography/video consent form in which they had the choice for their photo/video to be taken for research purposes (Appendix A3).

3.4.1 WristBot

The use of a haptic robotic device was utilized during the experimental protocol. Most people are unfamiliar with the haptic robot device; therefore, participants performed familiarization trials using the WristBot (Genoa, Italy) (Figure 5). This device moves with 3 degrees of freedom which allows the participant to move in wrist flexion/extension (±70°), radial/ulnar deviation (±35°), and pronation/supination (±80°) (Masia et al., 2009). WristBot contains 4 brushless motors that allow for resistance to be applied in any of the 3 movement directions and accounts for the weight and inertia of the handle. Participants traced a target cursor presented on a screen in front of them. The target cursor moved along a 2:3 Lissajous curve and the participants were required to move their hand (Figure 6) to track the object. Prior to experimental tracking, participants completed 13 practice trials of tracking. Analysis in our lab found no significant improvements to tracking error, figural error, and jerk ratio after 13 familiarization trials were completed.

Figure 5. WristBot Set up. System interface screen (right), WristBot device (middle)

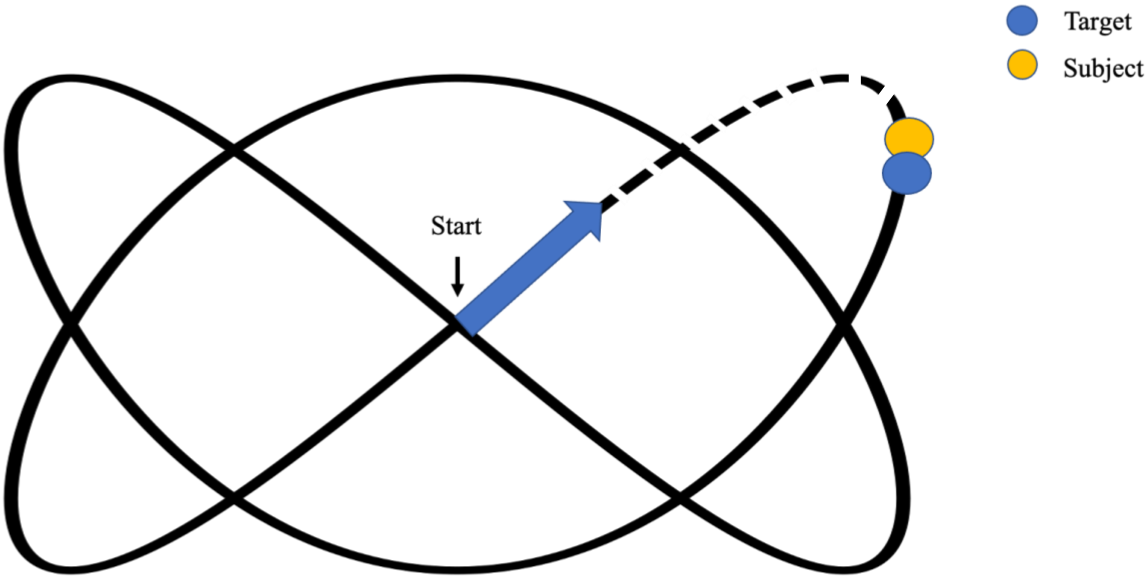

Figure 6. Example of 2:3 Lissajous Curve participants traced. Direction of tracking is indicated by the blue arrow. Dotted portion represents samples 1-567.

3.4.2 Load Cell

Maximal wrist flexion and extension force was collected to determine maximal wrist strength and was used to normalize resistance force for the fatigue protocol. Participants were seated in front of a force transducer (Model: BG500, Mark-10 Corporation, New York, USA) mounted above the table (Figure 7). The pad of the force transducer aligned along the metacarpophalangeal joint on the palmar side of the hand during maximum flexion trials and along the proximal knuckles on the dorsal side of the hand during maximum extension trials. A mark was placed on the hand where the transducer pad contacted the hand. This ensured consistent placement during MVC measurements. Participants were instructed to exert as much force as possible for both flexion and extension. Each trial lasted 2 seconds, and 2 minutes of rest was given between exertions. Participants were instructed not to lift their forearm or flex their elbow or fingers and to isolate wrist action. Two baseline trials were completed to determine maximal flexion and extension force. The larger of the two trials was deemed the participants maximal flexion/extension value. If the two values differed by more than 10%, a subsequent trial was performed and if the subsequent trial was within 10%, the larger of the two values was taken. Torque was calculated by taking the force (N) multiplied by the moment arm measured in metres (m). Moment arm was measured as the shortest perpendicular distance from the point of rotation (wrist crease) to the applied force (centre of the transducer pad).

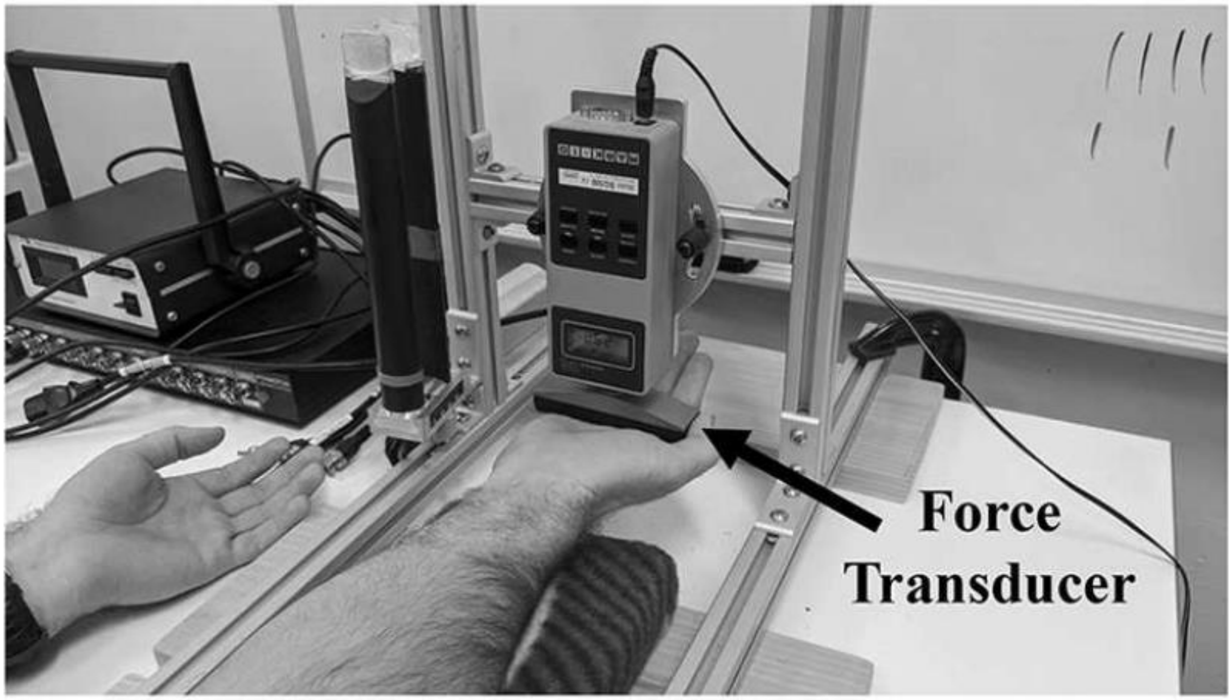

Figure 7. Load cell setup for maximal wrist flexion trials. (Photo from Forman et al., 2019)

3.4.3 Grip Dynamometer

To assess grip force participants performed 2 maximal grip trials using a Jamar Smart handgrip dynamometer (Performance Health, USA). Participants were instructed to hold the dynamometer handle at their side while standing. Handle diameter was set at 5.5 cm as this has been shown to produce optimal grip force in males (Ruiz-Ruiz et al., 2002). The largest value between the two trials determined maximal grip force. If the two values differ by more than 10%, a subsequent trial was performed, and if the subsequent trial was within 10%, the larger of the two values was taken.

3.4.4 Anthropometrics

Anthropometrics of the distal upper extremity were measured to evaluate correlations to wrist flexion/extension force and grip force. First, measurements of forearm circumference were taken at proximal and distal locations. Proximal forearm circumference was defined as the largest part of the proximal forearm. Distal forearm circumference was defined as circumference just proximal to the styloid process of the ulna. Forearm length was measured and defined as the length from the olecranon process to styloid process of ulna. Wrist circumference was defined as the circumference as the space just distal to styloid process of ulna. Hand length was measured and defined as the length from the tip of the third distal phalange to the styloid process of the ulna. All measurements were collected using a fabric measuring tape to the nearest millimeter.

3.05 Experimental Protocol

Following informed consent and screening, participants had anthropometric measurements of the forearm taken (See anthropometric section). Next, participants performed the MVC trials to determine wrist flexor and extensor torque. Participants then performed two hand grip trials (See handgrip section) to determine maximum grip force. After 2 minutes of rest, WristBot familiarization was performed by completing 13 trials of a Lissajous curve. Next, 5 unresisted trials were performed to obtain baseline tracking results. Participants then completed a forearm fatigue protocol using the WristBot (see below). Immediately after completion of the fatigue task, tracking trials commenced. 7 trials of the Lissajous curve were performed with a hand grip MVC taken at 2 minutes, 6 minutes, and 10 minutes post fatigue protocol (Figure 8).

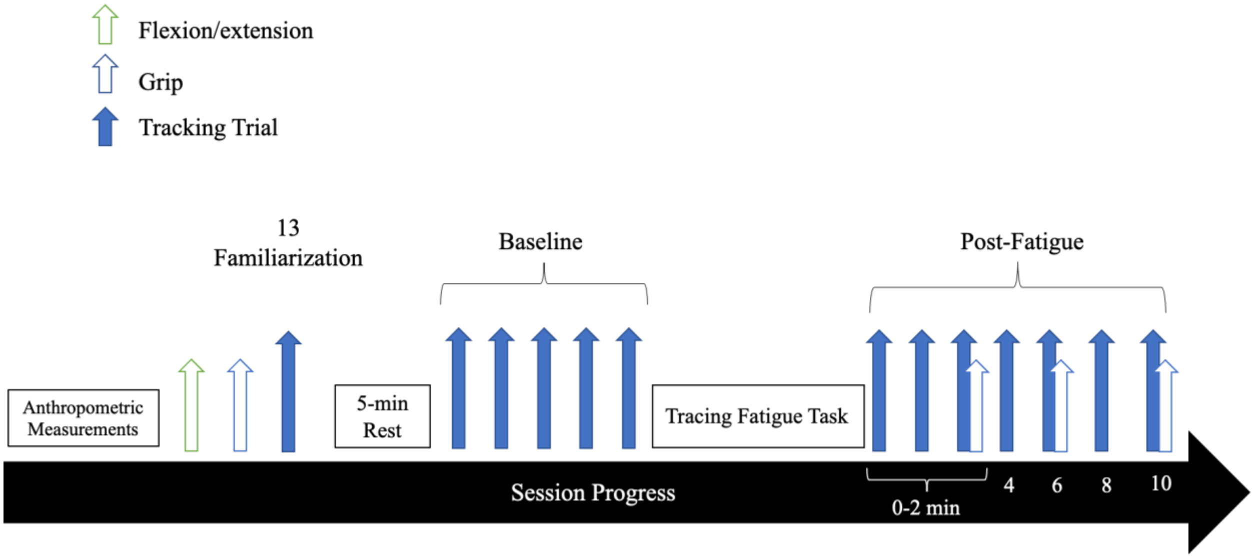

Figure 8. Timeline of experimental protocol. Blue arrows represent a tracking trial and white arrows represent an MVC.

3.5.1 Fatigue Protocol

To assess the effects of forearm muscle fatigue on hand tracking performance, a fatigue task was completed by each participant prior to tracking activity. Participants were seated in front of the WristBot looking at a computer monitor in front of them (Figure 5). Participants grasped the handle of the WristBot with their right hand. Participants were then instructed to accurately overlay a target circle which was programmed to move along a Lissajous curve (Figure 6). One lap of the curve was considered one trial. The target took approximately 11 seconds to complete one trace. The WristBot was programmed to apply resistive force at 40% of each participant's highest MVC whether that be during wrist flexion or extension. Participants were verbally encouraged to keep tracking until they felt they can no longer perform the task. Participants traced until exhaustion or up to 20 minutes, whichever occurred first. During the fatigue protocol, participants were asked to rate their perceived exertion on a 1-10 Borg scale (Appendix A4) every 2 minutes.

3.5.2 Tracking Task

Immediately after completing the forearm fatigue protocol participants started the tracking protocol. Like the fatigue protocol, participants were instructed to overlay the target circle as accurately as possible. The target moved along a Lissajous curve that was displayed on the monitor in front of the participant at eye-level (Figure 5). One trace of the Lissajous curve constituted one trial. The participant performed 7 tracking trials over a 10-minute period post-fatigue task. Within the first 2 minutes, 3 trials were completed. After the third trial a handgrip MVC was performed. From then on, every second tracking trial was followed by a handgrip MVC. 1-min of rest was given between tracking trials to determine fatigue recovery. No resistance to the tracking was applied by the robot (like the familiarization trials).

3.06 Data Analysis

3.6.1 Tracking Performance

A 6^{th} order Savitzky-Golay filter was used to smooth the robot positional data in the x and y-axis (Squeri et al., 2010). The Savitzky-Golay filter is a polynomial fitting filter that uses the method of linear least squares. This filter fits a polynomial to data segments in a predetermined window length. A 170-millisecond window was used as previously used by Squeri et al. (2010) and Forman et al. (2020). Due to the absence of a starting cue, initial tracking movement (samples 1-567) were not analyzed (Figure 6). This allowed for the participant to catch up to the target before analysis began. Two groups of tracking performance metrics were assessed: 1) tracking error and 2) movement smoothness. These metrics originated from Squeri et al., (2010) and have been used recently to quantify tracking performance (Forman et al., 2020; Kumar et al, 2020).

3.6.2 Tracking Error

Tracking error was calculated as the Euclidean distance ($|\vec{e}|$) between the subject's handle position to the target position. H represents the handle (Subject) position in the x and y direction. T represents the target's position in the x and y direction. Error from each tracking point is summed and divided by the total number of points (N) in a trial (Equation 1). This results in a tracking error mean value.

$$|\vec{e}| = \frac{\sum_{i=l}^{N} \sqrt{(H_x - T_x)^2 + (H_y - T_y)^2}}{N} \qquad (1)$$

Tracking Error was subdivided into 4 groups to determine if there was a direction bias. Upward (radial deviation) and downward (ulnar deviation) direction bias was investigated, as well as left (flexion) and right (extension) bias (Figure 9).

3.6.3 *Longitudinal Component of Tracking Error*

This was used to determine if the subject's position is behind or ahead of the target position at each data point. If the value is positive, the subject is ahead of the target relative to the target's trajectory. If the value is negative, the subject is behind the target.

$$\overrightarrow{u_l} = \frac{1}{\sqrt{\dot{T}_x^2 + \dot{T}_y^2}} \left[\dot{T}_x \;\; \dot{T}_y\right] = \left[ux_l \; uy_l\right] \qquad (2)$$

$$\delta_l = \vec{e} \cdot \overrightarrow{u_l} \qquad (3)$$

$\vec{u}_l$ represents the unit vector of the trajectory of the target (T) at each data point. δ_l represents the longitudinal component of tracking error (Equation 2). First, the direction of trajectory needs to be established to determine if the handle position differs from the target position. The first derivative of the target displacement is needed to determine the tangent vector to the target trajectory. This value is normalized to calculate the unit vector. The unit vector is multiplied by the tracking error of the respective trial (Equation 1) to obtain the direction (Equation 3).

3.6.4 *Normal Component of Tracking Error*

This component is similar to the longitudinal component, but instead of behind or ahead of the target, the normal component determines whether the handle is to the left or right of the target at each data point.

$$\vec{u}_n = \left[uy_n \; -ux_n\right] \qquad (4)$$

$$\delta_n = \vec{e} \cdot \overrightarrow{u_n} \qquad (5)$$

Again, the direction of trajectory of the target needs to be established to determine if handle position differs from target position (Equation 4). Therefore, equation 1 was used to determine the direction. U_n is orthogonal to u_l and then it is multiplied by the error vector to obtain the direction (Equation 5). If the resulting value is positive, the handle position is to the right of the target. In contrast, if the value is negative, the handle position is to the left of the target.

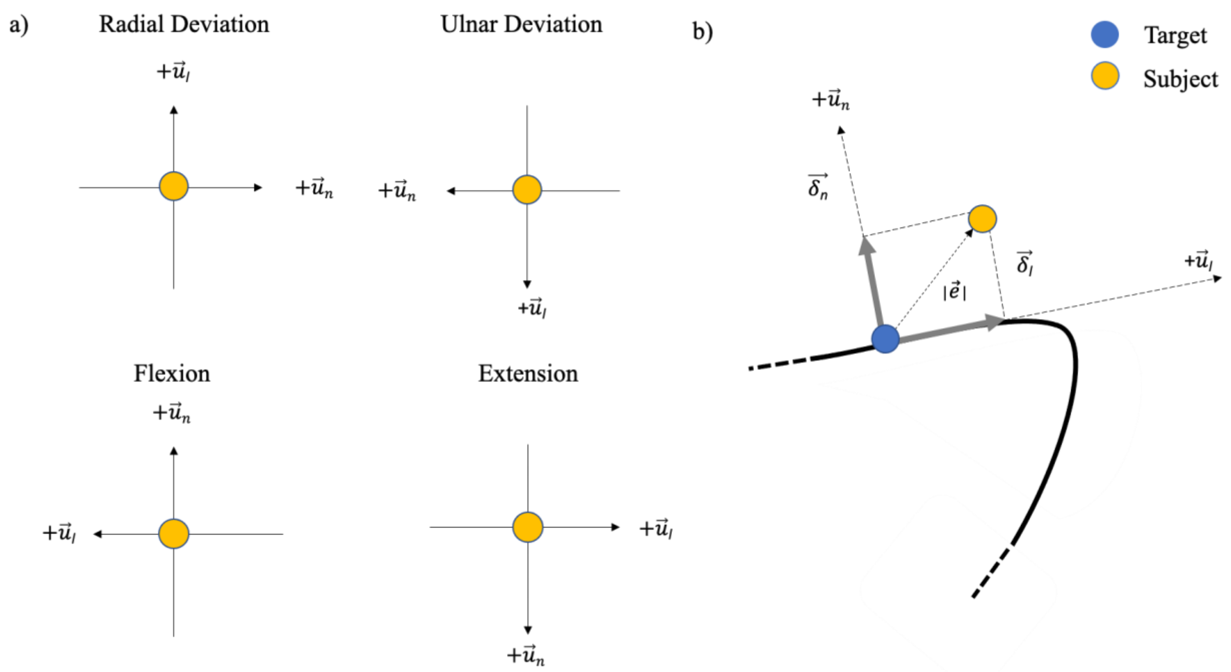

Figure 9. a) Directional tracking axes are shown. All components are with respect to the kinesiological action. b) Tracking axes are shown. +$\vec{u}_l$ represents the longitudinal axis with its respective component represented by δl. +$\vec{u}_n$ represents the normal axis with its respective component represented by δn. The Euclidean distance between the subject (yellow) and the target (blue) as denoted by $\overrightarrow{|e|}$. (Figure derived from Kumar et al., 2020).

3.6.5 Figural Error

This metric determines how accurately the participant moved their position along the ideal trajectory. This metric looks at tracking trajectory irrespective of speed, meaning it does not factor whether the subject is behind or ahead of the target.

$$
\begin{gathered}
dist_{A-B}\ (i) = \left\| A_i - B_j \right\| \quad i = 1, 2, \ldots n \\
dist_{B-A}\ (i) = \left\| A_i - B_j \right\| \quad j = 1, 2, \ldots m \\
FE_{AB} = \frac{\sum_{i=l}^{n} dist_{A-B}\ (i)\ +\ \sum_{j=l}^{m} dist_{B-A}\ (j)}{n+m}
\end{gathered}
\tag{6}
$$

“A” and “m” represents the time series and total number of samples of the target trajectory respectively. “B” and “n” represent the time series and total number of samples of the handle trajectory respectively (Equation 6). “$dist_{A-B}$” represents every data point of the handle compared to a single data point of the target. The distance between the minimum handle data point distance to the single target data point is then determined (min i). The same calculations are made using a single handle data point to every target data point ($dist_{B-A}$). This occurs for every target and handle data point in the trial. The difference from each point is then summed and divided by the total number of samples ($n + m$) (Equation 6).

3.6.6 Jerk Ratio

After applying the 6th order Savitzky-Golay filter, jerk was calculated. Jerk was found by taking the 3rd differential of both handle and target displacement data. Integrated squared jerk was defined by the following equation (Equation 7).

$$
ISJ = \int_0^d \left(\dddot{H}_x^2 + \dddot{H}_y^2 \right) \mathrm{dt} \tag{7}
$$

$$
JR = \frac{ISJ_H}{ISJ_T} \tag{8}
$$

Jerk ratio is a quantifiable measurement of movement smoothness. Jerk ratio is comprised of the integrated squared jerk of the handle (ISJ_H) divided by the integrated squared jerk of the target (ISJ_T) (Equation 8). Since jerk ratio compares the handle to the target, jerk ratio of 1 represents movement that is as smooth as possible. A jerk ratio greater than 1 signifies that handle movement was not as smooth as target movement.

3.07 Statistical Analysis

Statistical analyses were performed using SPSS software (SPSS, IBM Corporation, Armonk, NY, USA). A one-way repeated measures ANOVA (measurement time) was conducted for MVC data, all tracking error metrics, and jerk ratio to identify differences between the fatigue session as well as between baseline and following the dynamic fatigue protocol. The relationship between peak wrist extension and flexion torque and distal upper limb anthropometrics was assessed using Pearson correlation coefficients. This determined which measurements best correlate with maximal flexion and extension force.

A one-way repeated measures ANOVA with time as within-subject factor was conducted to analyze the effects of fatigue on tracking performance as well as fatigue recovery post task cessation. Significance was set to $p > 0.05$. Pearson's correlations were conducted to determine any significant ($p < 0.05$) correlations between flexion/extension force and lower arm anthropometrics. Correlations of percent change between baseline and the 0-minute mark, and lower arm anthropometrics were determined. Significant findings were further analyzed using Bonferroni post-hoc tests.

Chapter 4: Results

Table 1 highlights the group anthropometrics and force characteristics for the study demographics.

Table 1. Group Average for Anthropometrics and Force Characteristics

Characteristic	Average (SD)
Age	23.4 (1.8)
Weight (kg)	78.08 (8.21)
Height (cm)	178.66 (6.34)
Maximum Wrist Flexion (Nm)	14.84 (2.97)
Maximum Wrist Extension (Nm)	13.41 (2.09)
Maximum Grip (kg)	52.54 (6.56)
Hand Length (cm)	19.32 (0.99)
Forearm Length (cm)	27.05 (2.19)
Distal Forearm Circumference (cm)	21.61 (1.74)
Proximal Forearm Circumference (cm)	27.79 (2.45)
Wrist Circumference (cm)	17.42 (0.65)

4.01 Prescence of Fatigue

Figure 10 shows group average data for maximum grip force before and after the fatigue protocol. The group average for maximum grip was 52.5 ± 6.6 kg which is slightly higher than normative data for participants 18-24 years (47.0 ± 8.1 kg) (Wang et al., 2018). Grip force had a significant main effect of time ($P < 0.05$) for all time points post fatigue. There was a significant decrease in grip force which resulted in a 6.1 kg decrease 2 minutes (46.4 ± 7.4 kg) after the fatigue trial ($P < 0.001$). At 6-minutes post fatigue (47.9 ± 7.3 kg), there was a slight return to baseline, but maximum grip never returned completely to baseline, even at the end of the post testing protocol. All participants were able to perform the tracing task for the maximum time of 20 minutes.

There was a significant interaction between RPE score and time during the fatigue protocol. RPE scores were significantly higher at 10-minutes into the fatigue protocol (5.0 ± 1.7) compared to the 2-minute time point (2.6 ± 0.9). RPE scores were also significantly higher at the 20-minute mark (6.3 ± 1.8) compared to the 10-minute mark

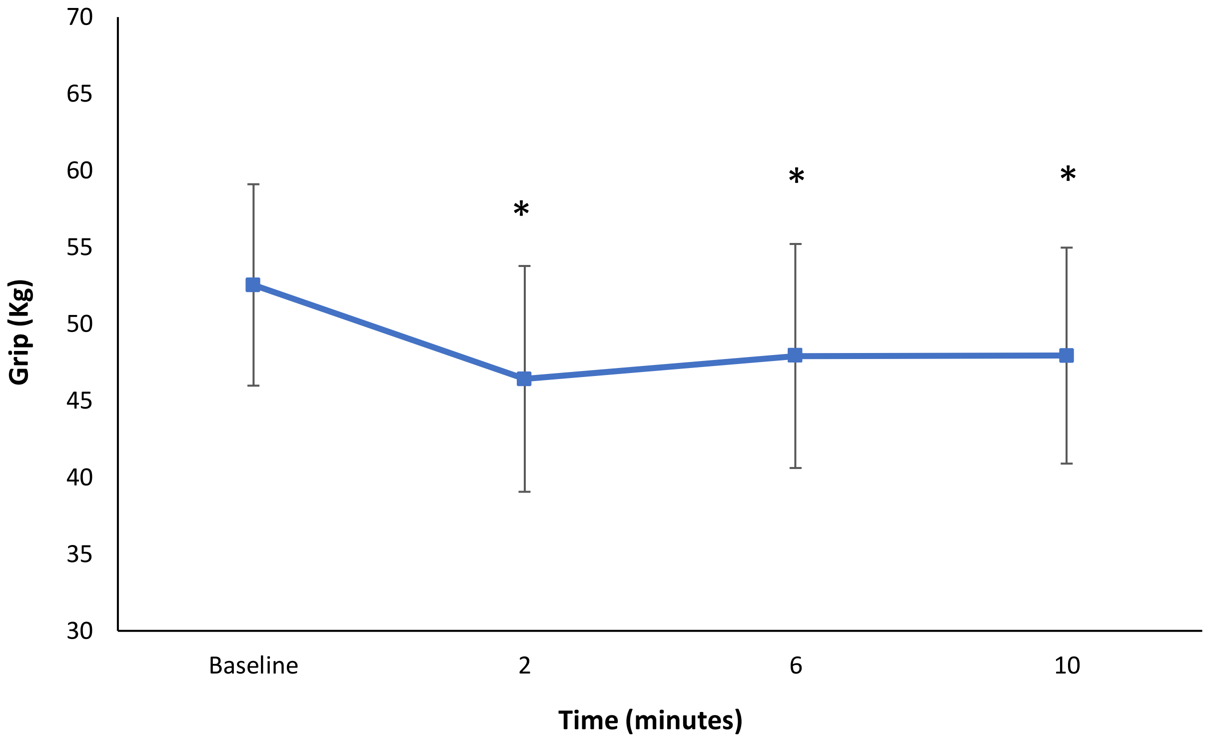

Figure 10. Maximum grip force (kg) before (time 0) and after (time 2, 6 and 10 minutes) the fatigue protocol. * indicates time point is significantly different than baseline p<0.05).

4.02 Tracking Performance

4.2.1 Tracking Error

Figure 11 shows group data for tracking error from baseline to 10 minutes post fatigue trial. There was a significant main effect of time for tracking error (F = 5.22, p = 0.00). Pairwise comparisons showed a significant difference between baseline (2.2° ± 0.5) and the 0-minute timepoint (2.8° ± 0.8). Tracking error returned to baseline steadily starting at the 1-minute mark but then remained elevated past baseline for the duration of the testing. Pairwise comparisons also showed a significant difference between the 0-minute mark and the 8-minute ($p = 0.013$) and 10-minute mark ($p = 0.019$) showing a return to baseline near the end of the session.

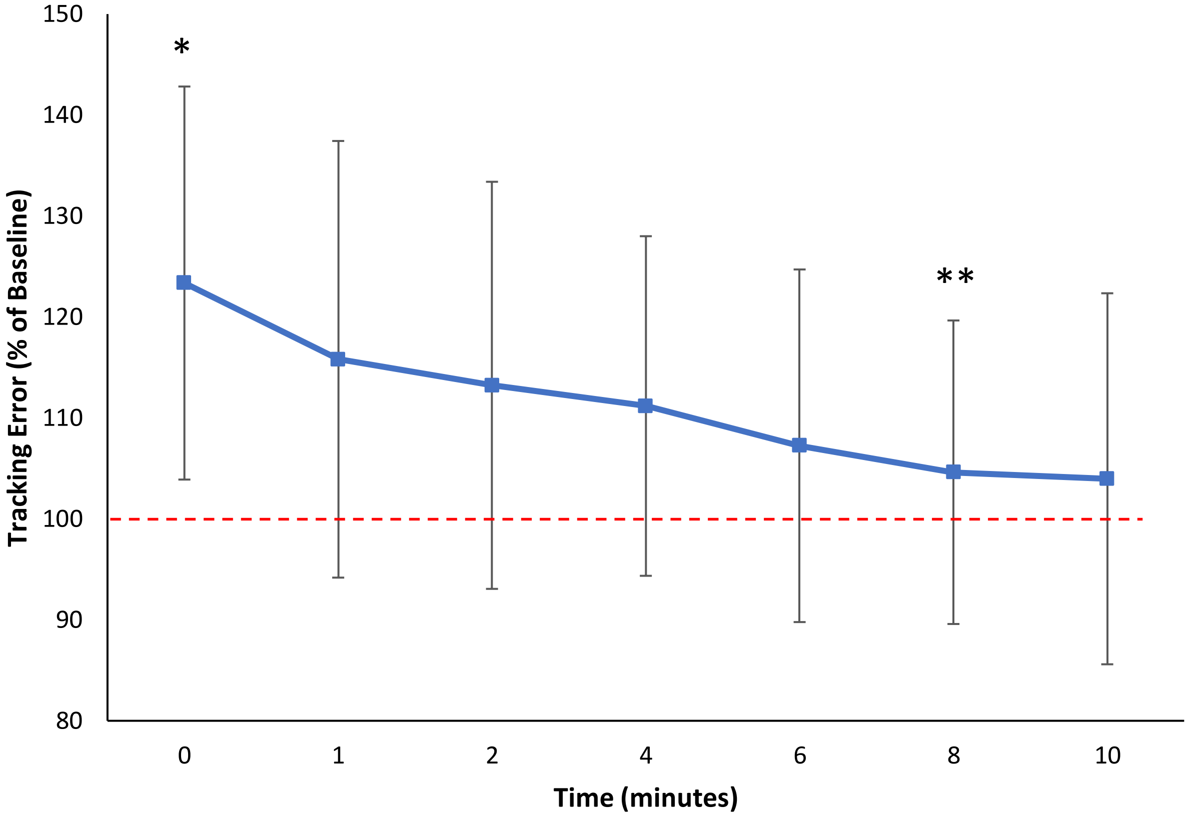

Figure 11. Average tracking error as a percentage of baseline over time. * indicates time point is significantly different than baseline p<0.05). ** indicates time point is significantly different than time 0 (pre), p<0.05).

4.2.2 Jerk Ratio

Figure 12 shows group data for jerk ratio from baseline to 10 minutes post fatigue trial. There was a significant main effect of time ($F = 3.62$, $p = 0.001$) for jerk ratio. Pairwise comparisons showed a significant difference between baseline (35.4± 10.9) and the 0-minute

(43.6 ± 11.7) time point (p= 0.038). Jerk ratio was significantly higher immediately after the end of the fatigue task than at baseline. There was also a significant (p = 0.027) difference between the 0-minute and the 8-minute mark (35.7 ± 8.0).

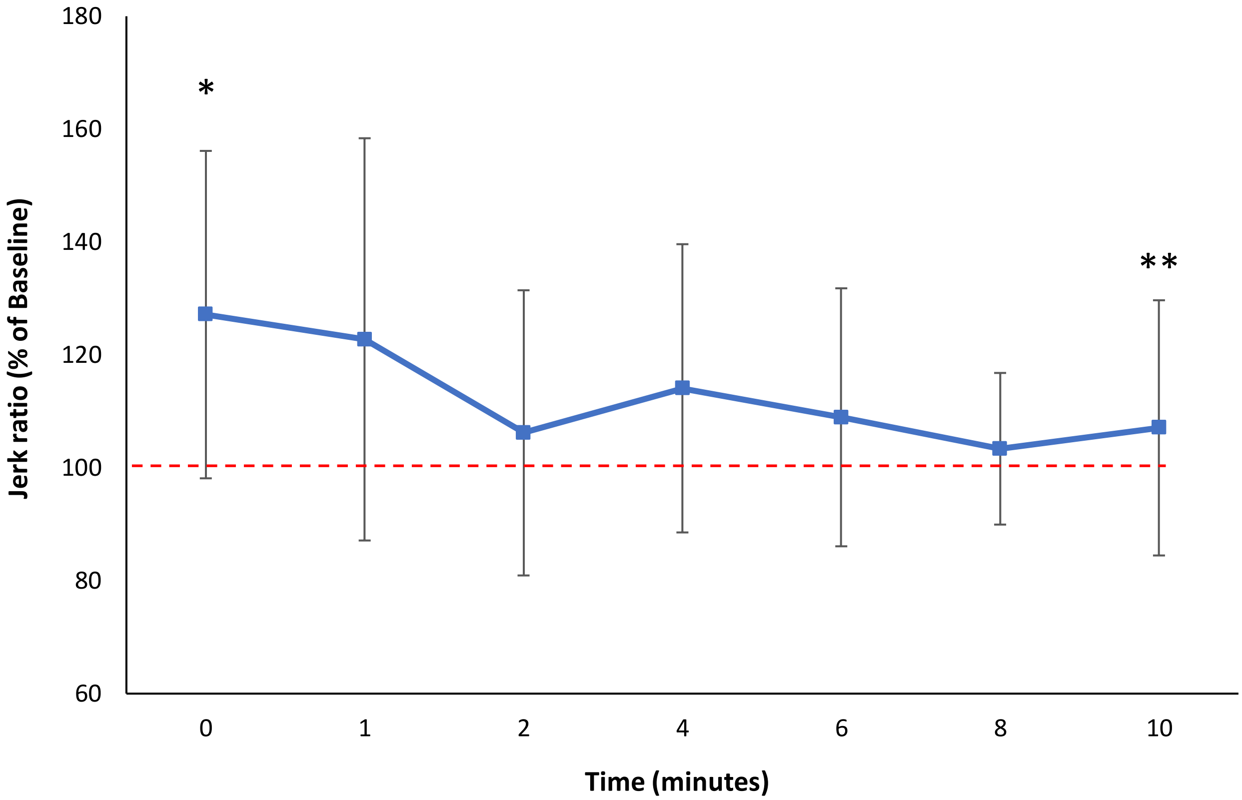

Figure 12. Average jerk ratio as a percentage of baseline over time. * indicates time point is significantly different than baseline, p<0.05). ** indicates time point is significantly different than time 0, p<0.05).

4.2.3 Figural Error

Figure 13 shows group data for figural error from baseline to 10 minutes post fatigue trial. There was a significant main effect of time for figural error (F= 4.26, p = 0.0001). Pairwise comparisons showed a significant difference between baseline (0.97° ± 0.21) and the 0-minute (1.17° ± 0.31) time point (p= 0.001). Participants had a higher amount of figural error immediately after completing the fatiguing protocol. There was also a significant difference between the 0-minute and 10-minute (0.95° ± 0.20) time point (p = 0.03).

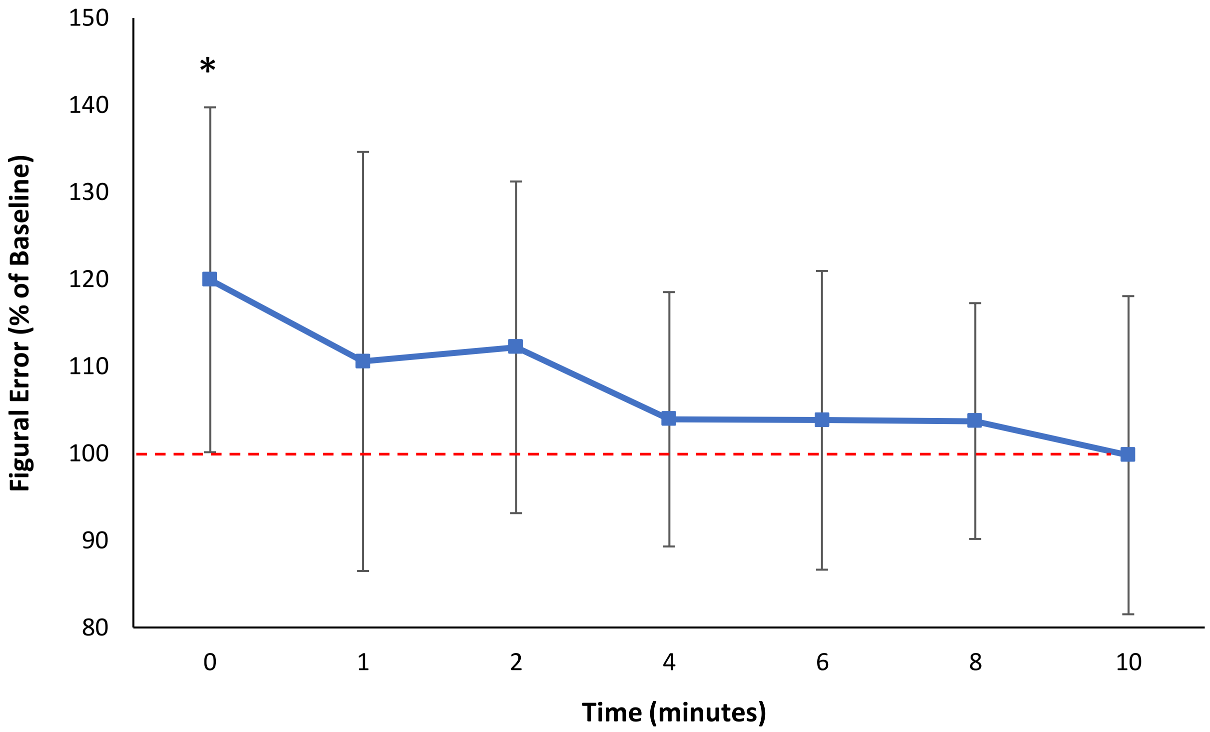

Figure 13. Group average of figural error as a percentage of baseline over time. * indicates time point is significantly different than baseline p<0.05).

4.2.4 Tracking Error (Longitudinal Component)

Figure 14 shows group data for tracking error (longitudinal component) from baseline to 10 minutes post fatigue trial. There was a significant main effect of time for tracking error (longitudinal) (F = 2.86, p = 0.008). Pairwise comparisons showed no significant (P > 0.05) differences between any time points.

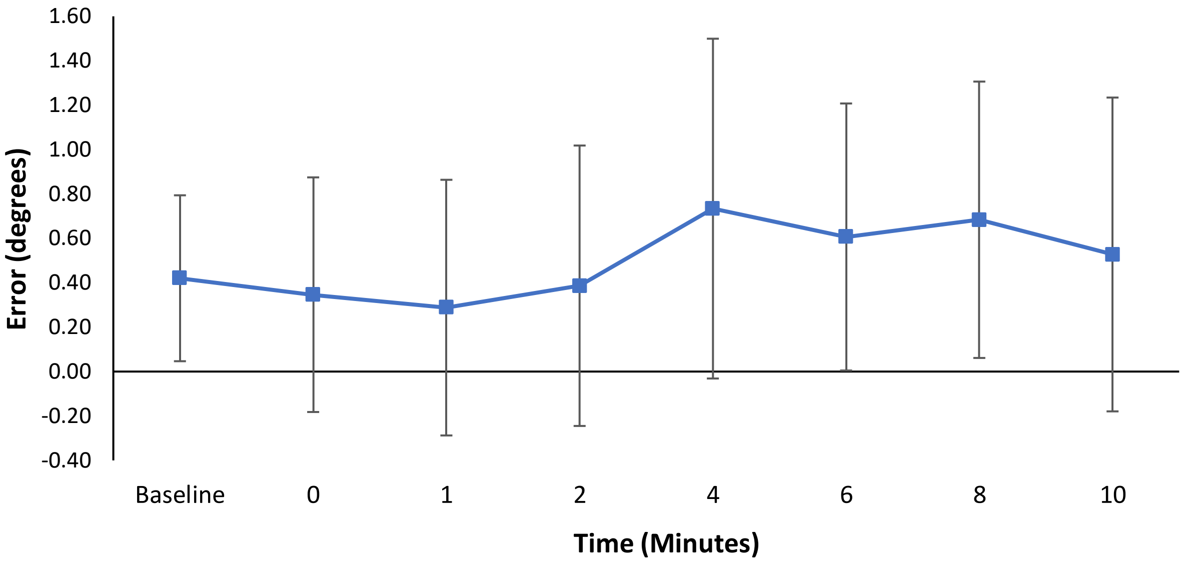

Figure 14. Group average of the longitudinal component of tracking error. Error is shown in degrees (º) from baseline to the end of the fatigue recovery period.

4.2.5 Tracking Error (Normal Component)

Figure 15 shows group data for tracking error (normal component) from baseline to 10 minutes post fatigue trial. There was a significant main effect of time for tracking error (normal) (F = 2.23, p = 0.003). Pairwise comparisons show a significant difference between two time points and the trial immediate after the fatiguing task (0-minute). The 4-minute trial (p = 0.04) and the 10-minute (p = 0.02) trial were both significantly different than the trial immediately post-fatigue task.

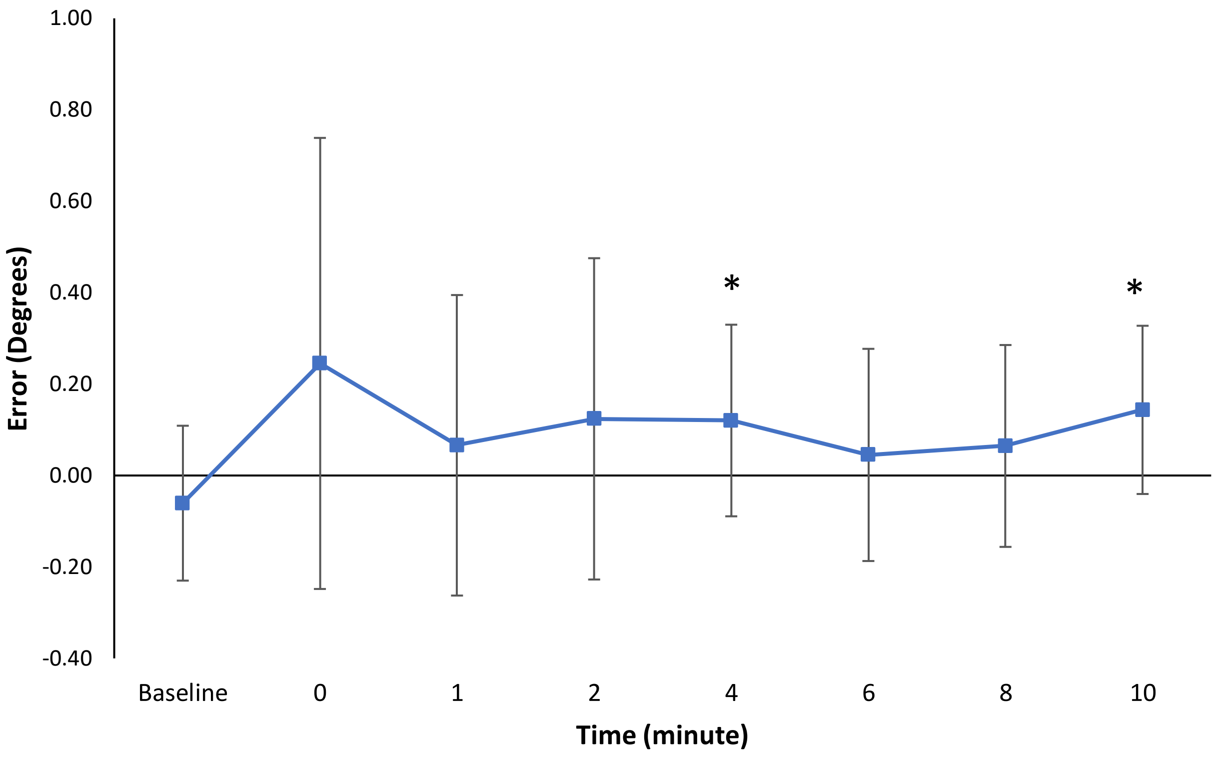

Figure 15. Group average of the normal component of tracking error. Error is shown in degrees (º) from baseline to the end of the fatigue recovery period. * indicates time point is significantly different than baseline p<0.05).

4.03 Anthropometrics

Only wrist circumference and flexion torque were found to have a significant correlation (p = 0.037, r = 0.482). There were no other significant correlations between wrist flexion/extension torque and hand/arm anthropometrics (Table 2).

Proximal forearm circumference (p = 0.022) and forearm length (p = 0.026) had a significant correlation with jerk ratio (Table 3). There was a moderate negative correlation (r = -0.521) between proximal forearm circumference and jerk ratio. There was also a moderate negative correlation (r = -0.509) between forearm length and jerk ratio. There were no significant correlations between percent change from baseline to the 0-minute mark for tracking error or figural error.

Table 2. Wrist Flexion/Extension Torque Correlations

		Wrist Circumference	Forearm Proximal	Hand Length	Forearm Distal	Forearm Length
Maximum Grip	Pearson Correlation	-.104	-.244	.319	.066	.262
	Sig. (2-tailed)	.670	.313	.183	.788	.279
	N	19	19	19	19	19
Flexion Torque	Pearson Correlation	.482*	.067	.307	.364	-.158
	Sig. (2-tailed)	.037	.785	.201	.125	.517
	N	19	19	19	19	19
Extension Torque	Pearson Correlation	.329	.070	.419	.175	.219
	Sig. (2-tailed)	.169	.775	.074	.474	.368
	N	19	19	19	19	19

* Correlation is significant at the 0.05 level (2-tailed).

Table 3. Jerk Ratio Correlations

		Wrist Circumference	Forearm Circumference (Proximal)	Hand Length	Forearm Circumference (Distal)	Forearm Length
Percent Change	Pearson Correlation	-.156	-.521*	-.362	.350	-.509*
	Sig. (2-tailed)	.522	.022	.128	.142	.026
	N	19	19	19	19	19

* Correlation is significant at the 0.05 level (2-tailed).

Chapter 5: Discussion

This study investigated the effects of submaximal fatigue, on hand tracking performance, using a task specific fatigue protocol. 20 minutes of resisted (40% maximal torque) tracking of a 2:3 Lissajous curve was shown to decrease grip force by 15%, 2 minutes after the end of the fatiguing task. Tracking metrics showed a decrease in performance immediately after the cessation of the task specific fatigue protocol. Similar to our previous isometric fatigue study (Forman, et al., 2020), there was an initial significant decline in performance, then a steady return to baseline starting at the 1-minute mark for tracking error, figural error and jerk ratio. We also demonstrate the normal component of tracking error changed from a left bias to a right bias during the fatigue trials. A novel finding of this study was the correlation between forearm anthropometrics and jerk ratio performance. This protocol may have more real-life application than previous work, as most activities of daily living and workplace tasks occur at a submaximal force level and involve all planes of motion of the wrist.

5.01 Tracking performance

Our first hypothesis was true as tracking error, figural error, and jerk ratio performance were impaired after the completion of the task specific fatigue protocol. Here, we refer to the task as ‘task specific’, because both the task used to fatigue and used to measure performance were the same. The task specific fatigue protocol resulted in a 23% increase in tracking error, a 27% increase in figural error, and a 20% increase in jerk ratio immediately following the cessation of the fatigue protocol. The novelty of this study was the task specific fatigue protocol. The principle of task dependency of muscle fatigue states that the dominant mechanism to muscle fatigue is specific to the processes that are stressed (Cairns et al., 2005). Although this submaximal dynamic fatigue protocol impaired tracking error, the decrease in tracking error was not as prominent as the decline observed in our previous maximal isometric fatigue protocol (Forman, et al., 2020). Differences in intensity have been shown to elicit differences in the physiological and biochemical properties of contractile protein. Higher frequency contractions result in a larger acidosis of calcium. Although calcium concentration levels decline in both low and high intensities, calcium sensitivity was reduced when acidosis occurred, resulting in less force production (Chin & Allen, 1998). We can conclude tracking error, figural error and jerk ratio recovered from fatigue as there was a significant difference between these metrics at baseline and the 0-min timepoint, but no significant difference between baseline and any other timepoint.

Our second hypothesis was true as we saw differences in normal component of tracking error. Group data for baseline tracking showed participants on average were to the left of the target during unfatigued baseline trials. After the fatiguing task, participants were consistently to the right of the target or bias towards the inside of the trace. Similar trends have been shown where participants consistently underestimated the amount of force needed to perform forearm flexion after eccentric muscle fatigue (Jaric et al., 1999; Saxton et al., 1995). This finding differed from our isometric fatigue study and dynamic fatigue study where participants were equally bias towards both the left and right side of the target. This finding may be due to impaired proprioception of the wrist. Fatigue has been shown to impair Golgi tendon organ activity and decrease central activity reducing proprioception which may have negative implications to performance (Allen & Proske, 2006; Hutton & Nelson, 1986; Zabihhosseinian et al., 2015). In addition, mechanically sensitive group III and IV afferents have shown to increase discharge rate when fatigued, further complicating joint position sense (Windhorst, 2007).

Carpenter et al., (1998) showed a 73% increase in shoulder movement when targeting 90 degrees of internal and external rotation post fatigue. Since the fatiguing task involved motion in all four planes of wrist motion, forearm muscle contractions were both eccentric and concentric. Eccentric contractions have been shown to elicit neuromuscular dysfunction including joint position impairments and increase tremors (Saxton et al., 1995). With a 20% decline in post exercise wrist and hand fatigue levels, wrist proprioception has been shown to decrease for at least 5 minutes post exercise (Karagiannopoulos et al., 2020). Therefore, fatigue of the forearm muscles may have affected proprioception leading to a false sense of joint position. This may explain why the participants had a change in pre and post fatigue tracking error in the normal direction. Participants were also bias towards staying ahead of the target throughout the trace as noted by the positive longitudinal component of tracking error (Figure 14). Movement velocity decreases during fatigue so to compensate for the reduction in force, participants overcompensated to allot more movement time to performing the intended task and thus maintaining task performance (Jaric et al., 1997)

Differences in tracking performance may also be due to movement variability. Participants may have changed movement strategies to compensate for the sensation of fatigue at the 0-minute mark which may explain the reduction in tracking error starting at the 1-minute mark. High subject variability post-fatigue has been well documented showing that subjects compensate for the effects of fatigue in various ways, such as reducing range of motion (Fuller et al., 2009; Sparto et al., 1997). Previous work from our lab has demonstrated that 13 familiarization trials of this novel tracking task were sufficient to elicit no further improvements to tracking error, figural error, and jerk ratio (Cousins et al. 2021). In addition, during the fatigue protocol subjects performed approximately 100 laps of the same trace. Thus, we are confident that the changes observed in tracking performance post fatigue, are likely not familiarization related. There are a plethora of strategies one can use to complete a task especially when multiple joints are involved. In our case, the task involved a single joint, but multiple degrees of freedom and the robotic device provided no restrictions to movement. Additional motor control strategies may have been utilized at the onset of fatigue that could have transferred over to the post fatigue trials. Previous research has shown that after the onset of fatigue, kinematics are altered to perform movements that contribute to the goal of the task (Cowley et al., 2014; Qin et al., 2014). Gates & Dingwell, (2008) showed subjects either performed quick short or slow long sawing movements to maintain a timing goal. Despite the variability of sawing biomechanics, task goals were still maintained. In the present study, participants were able to trace the figure similar to baseline 1 minute after the end of the fatigue task which suggests they were able to perform the goals of the task. Altering the handle speed and position to stay in line with the target trace (end goal) would result in good tracking error and figural error performance but would increase jerk ratio. Therefore, to maintain the end goal of producing an ideal trace in the presence of muscle fatigue, participants may have altered their wrist joint kinematics resulting in good tracking performance, at the expense of movement smoothness. It is still unclear how individuals determine ideal movement strategies to complete a certain task. The forearm muscles are complex, with lines of action controlling multiple degrees of freedom and redundancy. Further research into the muscle recruitment hierarchy is needed to determine how one compensates for the diminished force output when specific muscles are fatigued to maintain task performance.

5.02 Peripheral vs. central fatigue mechanisms

Performance fatiguability encompasses both the effects of fatigue on contractile properties and effects on muscle activation (Enoka & Duchateau, 2016). High level contractions sustained for a short period of time may cause fatigue impairments related to the contractile property of muscle. Processes at or distal to the neuromuscular junction, calcium release and uptake from the sarcoplasmic reticulum, metabolites and force production can all be affected by fatigue. In the present study, there was only an average of 15% decrease in force, which means it is unlikely that the decrease in force was due to less calcium being released from the sarcoplasmic reticulum (Nocella et al., 2011). Initial force decline may be due to a decrease in force in each individual cross bridge. In addition tension on the muscle fibre due to eccentric contractions disrupt sarcomere function causing impairment to muscle contraction (Proske & Allen, 2005). Muscle contractile impairments may play a role in the fatigue shown in the present study, but deficits to muscle activation may be more responsible for the deficits in performance.

Central fatigue refers to the effect of fatigue on any process involving the central nervous system (CNS) such as reduced motor drive and reduced excitability of the motor unit (Bigland-Ritchie & Woods, 1984). Repeated contractions result in constant firing of motoneurons which in turn leads to a decrease in excitability input, lower excitatory drive from supraspinal areas such as the motor cortex, and an increase in group III/IV afferent neuron firing (Darques & Jammes, 1997; Taylor et al., 2016). Low level contractions have shown to elicit decreases in voluntary activation and lengthening of the silent period signifying an inhibition withing the motor cortex (Smith et al., 2007; Søgaard et al., 2006). This eventually leads to muscle force generating capacity being less than the force demands resulting in performance decrements or even task failure. The fatigue protocol of this study consisted of repeated isotonic contractions of the wrist flexors/extensors and radial/ulnar deviators at 40% maximal torque. The constant submaximal force demand of the task may have led to increased demand from the central nervous system to maintain task performance. Dynamic fatigue protocols have been shown to elicit more neuromuscular fatigue compared to isometric fatigue protocols (Boccia et al., 2015; R. I. Kumar et al., 2020). Results of the present study showed a significant decrease in isometric grip force production that did not return to baseline after 10 minutes of recovery (Figure 10). In addition, though it wasn't statistically significant, figural error and jerk ratio remained above baseline (unfatigued) levels for at least 4 minutes after the cessation of the fatigue protocol. This prolonged impairment of performance suggests central fatigue factors are mainly responsible. Although central fatigue is more difficult to measure during prolonged low level contractions compared to maximal contractions, a steady increase in perceived effort paired with a decline in maximum voluntary force suggest central impairments (Smith et al., 2007; Søgaard et al., 2006). In the present study, RPE changed significantly from the 2-minute (2.6 ± 0.9) timepoint to the 20-minute timepoint (6.3 ± 1.8) despite the force demands remaining the same. This discrepancy may be due to signals from group Ia and II muscle afferents as subjects get less feedback from muscle spindles giving the illusion that they require more force to sustain the demand. Participants RPE score may have also increased due to increased pain felt at the hand and wrist. Increased metabolites can be sensed by a subtype of fatigue-sensitive group III/IV muscle afferents called metabo-nociceptors (Taylor et al., 2016). This results in an increased sensation of pain when there is inadequate blood flow to the muscle.

5.03 Anthropometrics

Our third hypothesis stating forearm anthropometrics would have a positive correlation with grip force was not true. We saw no significant correlations with any hand/forearm anthropometrics and maximum grip. This was surprising as forearm circumference has been shown to be a good predictor of handgrip strength (Anakwe et al., 2007). Forearm length and handgrip strength showed moderate correlation in young adult males (Koley & Singh, 2009). The mean values for the same anthropometrics were similar between this present study and Koley & Singh (2009). Distal forearm circumference, forearm length, and hand length in the Koley and Singh (2009) were 27.02 cm, 28 cm, and 19.38 cm, respectively. In the present study, distal forearm circumference, forearm length, and hand length were 27.79 cm, 27.05 cm, and 19.32 cm, respectively. Compared to other hand grip correlation studies the sample size of this study was relatively small as both studies by Anawke et al. (2007) and Koley & Singh (2009) recruited over 150 males for their study. Our sample size was also very similar, with little variability across the sample.

Our fourth hypothesis of circumferential anthropometrics correlating to better tracking performance was only true for proximal forearm circumference and the jerk ratio performance metric. Proximal forearm circumference had a moderate negative correlation with jerk ratio (r = – 0.521). This suggests that the larger the proximal forearm circumference, the smoother the movement while tracking after fatigue of the forearm muscles. Muscle mass accounts for about 71% of total forearm volume in untrained individuals, therefore forearm circumference may be a good predictor of forearm strength (Maughan et al., 1986). A study looking at anthropometrics in light manual workers (gardening, cleaning) and non-manual workers (clerks, secretaries, book keepers) saw a significant difference in forearm circumference in the light manual group (Saremi & Rostamzadeh, 2019). Since jerk ratio is a quantifiable measurement of movement smoothness, this finding may be applicable to the workplace. Forearm length also had a moderate negative correlation (r = - 0.509) with jerk ratio.

The lack of correlations between forearm anthropometrics and fatigue resistance is in line with previous literature. Hand and arm anthropometrics showed no correlation with grip endurance (Nicolay & Walker 2005). Anthropometrics in general may not be the best indicator for endurance or fatigue resistance. These indirect measurements have no physiological correlation to CNS processes such as motor unit recruitment or neural drive. Fatigue and endurance are heavily influenced by biochemical processes in the muscle cell (Nicolay & Walker 2005). Sustained isometric 50% MVC of the biceps and soleus during elbow flexion and plantar flexion respectively showed a higher increase of EMG amplitude for the biceps compared to the soleus showing differences in fatigability of muscle (Kimura et al., 2004). On the other hand, single force outputs such as maximum grip or maximum wrist flexion/extension or more influenced by biomechanics. Moment arm length, physiological cross-sectional area are key indicators of biomechanical strength advantage (Gonzalez et al., 1997). These factors can be indirectly measured; thus anthropometrics correlate better with single force output measurements.

Our fifth hypothesis was partly true as the only hand/arm anthropometric measurement to significantly correlate with wrist flexion or extension torque was wrist circumference with wrist flexion torque (r = 0.482). Chimera et al., 2021 showed a similar correlation with wrist circumference and wrist flexion torque although they saw correlations with proximal forearm circumference and wrist flexion/extension torque. Differences may lie in training status, as mentioned previously, there are differences in the amount of forearm muscle mass when measuring proximal forearm circumference in untrained and trained individuals (Maughan et al., 1986). Forearm length may not have correlated with wrist flexion/extension torque due to the architecture of the forearm muscles.

5.04 Limitations

Electromyography was not collected in this study, so there was no evaluation of forearm muscle activity during the tracking tasks. It is unclear whether a specific muscle or group of muscles compensated for the effects of fatigue. Muscle activity in conjunction with kinematics would help further explore differences in movement variability and give further insight into individual movement strategies.

Sex/age differences is another limitation of this study since it only included young adult males. Previous studies have shown fatigue differences in males and females. Age has also been shown to be a factor in handgrip strength. Therefore, these findings cannot be generalized to the entire population.

Another limitation of this study was the level of fatigue for each individual participant. Although every participant had the same relative resistance and same duration it was unclear whether the magnitude of fatigue was the same for every participant. The RPE scores significantly changed throughout the fatigue protocol but RPE is subjective as it is solely based on the response of the participant. In addition, a decrease in grip force was the sole physiological indicator of fatigue. Although a decrease in force accompanied by an increase in RPE suggests central fatigue mechanisms were present, no direct measurements of corticospinal activity or motor unit activity were measured.

5.05 Future Work

Future work should incorporate EMG to record muscle activity from all the major forearm muscles. This will help understand the organizational hierarchy of muscles used in the forearm while fatigued. Although forearm circumference was shown to correlate with better jerk ratio (movement smoothness), it is still unclear whether the extensor strength or flexor extensor strength is more influential to tracking performance. Investigations into flexor/extensor strength ratios may help us better understand the role of each muscle group, especially when it pertains to co-contraction and joint stability. Performing this study with an occupational population in which hand accuracy is imperative to success would help translate the results of this study and previous tracking studies done in our lab into practice. It would also help understand any predispositions to hand tracking success if compared to a non-occupational population.

5.06 Conclusion

A submaximal task specific fatigue protocol impaired hand tracking accuracy of young male adults. Directional biases were shown when the task demands included fatigue of the four primary directions of wrist movement. Forearm circumference and length were shown to correlate with better movement smoothness during hand tracking. This work could be useful for those who are responsible for job allocation in the workplaces where accuracy is imperative to job performance.

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Appendix: Participant Forms

A1: Edinburgh Handedness Questionnaire

Edinburgh Handedness Inventory

Surname__________________________Given Name______________________________

Date of Birth_____________________________Sex_____________________________________

Please indicate your preferences in the use of hands in the following activities by *putting + in the appropriate column*. Where the preference is so strong that you would never try to use the other hand unless absolutely forces to, *put ++*. If any case you are really indifferent put + in both columns.

Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task.

	Left	Right
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking Match (match)		
10. Opening box (lid)		
i. Which foot do you prefer to kick with?		
ii. Which eye do you use when using only one?		

L.Q.	Leave the spaces blank	DECLE

A2: Participant Screening/Participation Form

Date of Birth ______________________________

Date _____________________________________

Questions:

1. **Male or Female? (circle)**

2. **Age: ____________**

3. **Previous upper extremity injury?   Yes   /   No   (circle)**

   If Yes, please identify (list) any injuries that you have had in the past 12 months and when it occurred (e.g. sprained wrist, 2 months ago):

   Some examples may include, but are not limited to: muscle strain/sprain, ligament strain/strain, bone/joint pain, neurological impairments, etc.

   ____

   ____

   ____

A3: Consent to use video/photographs

CONSENT TO USE PHOTOGRAPHS IN TEACHING, PRESENTATIONS, and/or PUBLICATIONS

Title of Project: Investigating the Neuromechanical Effects of fatigue in Different Forearm Strength Ratios using a Wrist Robotic Device

Principal Investigators:
Dr. Michael Holmes
Assistant Professor
Department of Kinesiology
Brock University

Sometimes a certain photograph clearly demonstrates a particular feature or detail that would be helpful in teaching or when presenting the study results at a scientific conference or in a publication.

I agree to allow photographs in which I appear to be used in teaching, scientific presentations and/or publications with the understanding that I will not be identified by name. I am aware that I may withdraw this consent at any time without penalty, and the photograph will be confidentially deleted.

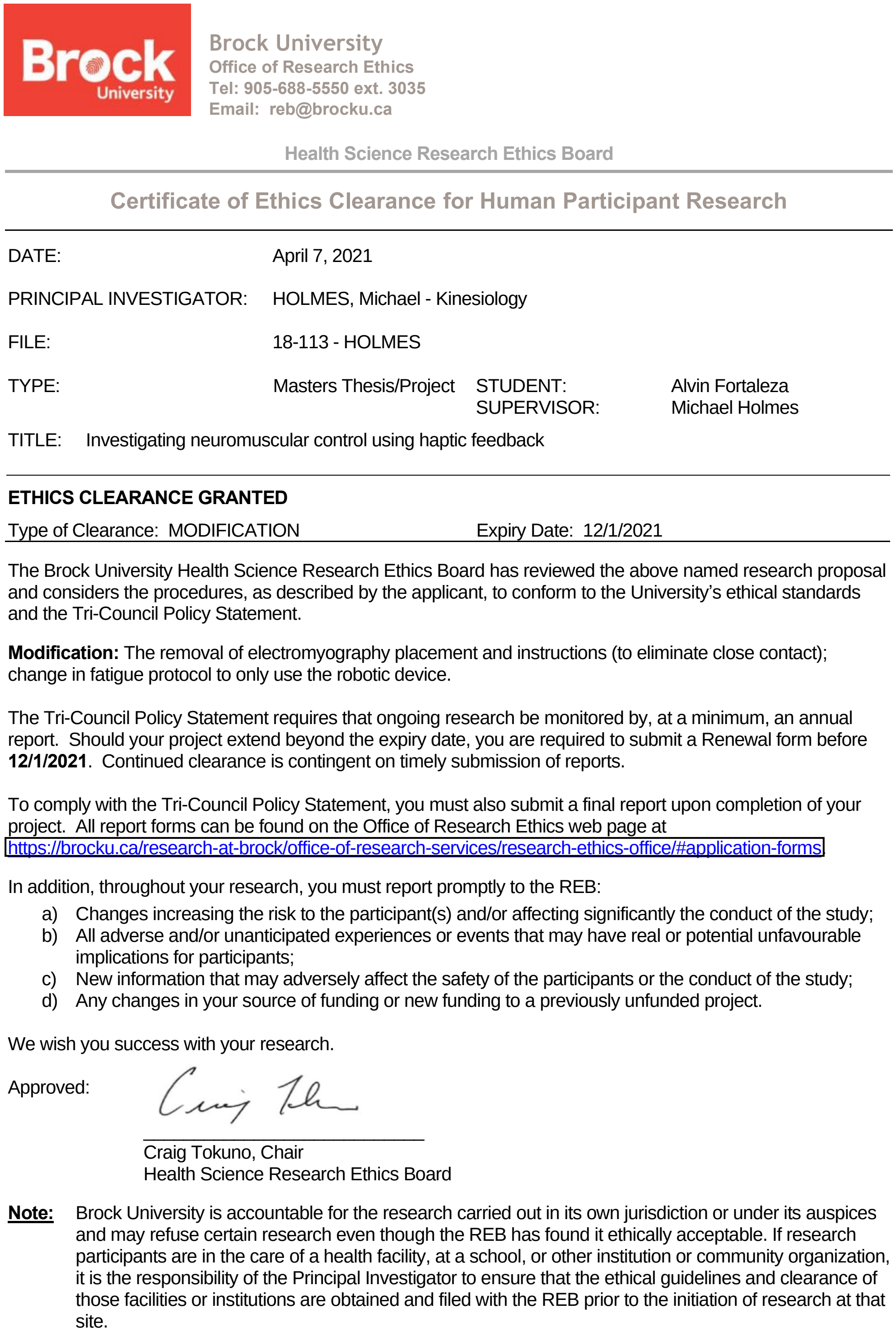
I was informed that if I have any comments or concerns resulting from my participation in this study, I may contact the Research Ethics Office at (905) 688-5550 Ext. 3035, reb@brocku.ca.

___________________________	________________________________
Printed Name of Participant	Signature of Participant
__________________________	________________________________
Dated at Brock University	Witnessed

A4: RPE Scale

Rating	Descriptor
0	Rest
1	Very, Very Easy
2	Easy
3	Moderate
4	Somewhat Hard
5	Hard
6	*
7	Very Hard
8	*
9	*
10	Maximal

A5: Certificate of Ethics Clearance



Brock University
Office of Research Ethics
Tel: 905-688-5550 ext. 3035
Email: reb@brocku.ca

Health Science Research Ethics Board

Certificate of Ethics Clearance for Human Participant Research

DATE:	April 7, 2021		
PRINCIPAL INVESTIGATOR:	HOLMES, Michael - Kinesiology		
FILE:	18-113 - HOLMES		
TYPE:	Masters Thesis/Project	STUDENT: SUPERVISOR:	Alvin Fortaleza Michael Holmes

TITLE: Investigating neuromuscular control using haptic feedback

ETHICS CLEARANCE GRANTED

Type of Clearance: MODIFICATION

Expiry Date: 12/1/2021

The Brock University Health Science Research Ethics Board has reviewed the above named research proposal and considers the procedures, as described by the applicant, to conform to the University's ethical standards and the Tri-Council Policy Statement.

Modification: The removal of electromyography placement and instructions (to eliminate close contact); change in fatigue protocol to only use the robotic device.

The Tri-Council Policy Statement requires that ongoing research be monitored by, at a minimum, an annual report. Should your project extend beyond the expiry date, you are required to submit a Renewal form before **12/1/2021**. Continued clearance is contingent on timely submission of reports.

To comply with the Tri-Council Policy Statement, you must also submit a final report upon completion of your project. All report forms can be found on the Office of Research Ethics web page at https://brocku.ca/research-at-brock/office-of-research-services/research-ethics-office/#application-forms.

In addition, throughout your research, you must report promptly to the REB:
a) Changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;
b) All adverse and/or unanticipated experiences or events that may have real or potential unfavourable implications for participants;
c) New information that may adversely affect the safety of the participants or the conduct of the study;
d) Any changes in your source of funding or new funding to a previously unfunded project.

We wish you success with your research.

Approved:

Craig Tokuno, Chair
Health Science Research Ethics Board

Note: Brock University is accountable for the research carried out in its own jurisdiction or under its auspices and may refuse certain research even though the REB has found it ethically acceptable. If research participants are in the care of a health facility, at a school, or other institution or community organization, it is the responsibility of the Principal Investigator to ensure that the ethical guidelines and clearance of those facilities or institutions are obtained and filed with the REB prior to the initiation of research at that site.