

**EFFECTS OF MUSCLE FATIGUE ON FORCE COORDINATION
AND PERFORMANCE IN MANIPULATION TASKS**

by

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ABSTRACT

The effects of muscle fatigue on force coordination and task performance during various handheld object manipulation tasks are explored. In both of the studies, grip force (GF; normal force component acting at the digits-object contact area) and load force (LF; tangential component that lifts and holds objects) were recorded prior to and after a specific fatiguing protocol. In the first study, a fatiguing protocol was applied with the aim of fatiguing both the distal (DAM; i.e., GF-producing) and the proximal arm muscles (PAM; LF-producing) at an equal rate using an oscillatory motion. Results revealed a marked fatigue-associated decrease in GF scaling (i.e., the magnitude of GF relative to LF) and GF-LF coupling (correlation between GF and LF), while task performance regarding the accuracy of exertion of the prescribed LF profiles remained unaffected. In the second study, two distinct fatiguing protocols were applied during different testing sessions in order to separately fatigue DAM and PAM. The results revealed a deterioration of GF scaling, GF-LF coupling, and task performance (i.e., the ability to exert a prescribed LF pattern) associated with DAM, but not PAM fatigue. In conclusion, muscle fatigue both partly decouples GF from LF and reduces the overall GF magnitude, which could potentially explain why hand-held objects are more likely to drop when manipulated with fatigued muscles. The unaffected task performance seen in the first study could be explained either by the relatively low level of muscle forces required by the tested tasks, the moderate level of the fatigue imposed, or both. Additionally, the observed selective effects of DAM and PAM fatigue represent a novel finding deserving of further research.

Chapter 1

INTRODUCTION

Coordination of grip force (GF) and load force (LF) is a well-known occurrence in manipulation tasks (Flanagan & Wing, 1993; Flanagan & Wing, 1995; Jaric, Russell, Collins, & Marwaha, 2005). A force analysis of this model defines GF as the force applied perpendicularly to the object to provide friction and enable control of the object's position and orientation. This same model defines LF as the tangential force that acts parallel to the object's surface to overcome the object's weight and inertia. Whether one is completing a complex motor task or simply performing an activity of daily living, during object manipulation GF is modulated with respect to the change in LF. Object manipulation is frequently based on a simple mechanical model of a vertically oriented handheld object (Figure 1A). The indices of measurement for the high coordination of GF and LF (i.e., GF-LF coupling and scaling) include low and stable GF/LF ratio (GLr), low GLr variability, high Pearson's correlation coefficient (r values), and a close to zero time lag between the change in GF and the change in LF.

The observed relationship between GF and LF has been explored in several different directions, including the effects of altered LF directionality (de Freitas, Markovic, Krishnan, & Jaric, 2008; Jaric, Knight, Collins, & Marwaha, 2005), increased experimental task complexity (Krishnan & Jaric, 2008; Uygur, de Freitas, &

Jaric, 2010; Westling & Johansson, 1984), and the fluctuations in force coordination instigated by neurological dysfunction (Hermsdörfer, Hagl, Nowak, & Marquardt, 2003; Marwaha, Hall, Knight, & Jaric, 2006; Nowak, Hermsdörfer, Marquardt, & Fuchs, 2002). However, few studies have focused on the effects of muscle fatigue on GF-LF coordination. Muscle fatigue can be defined as an exercise-induced reduction in the ability of muscle to produce force or power, whether or not the task can be sustained (Enoka & Duchateau, 2008).

Several synergistic muscles are responsible for the facilitation of object manipulation; among these are the GF-producing distal arm muscles (DAM) and the LF-producing proximal arm muscles (PAM). The DAM involve both extrinsic and intrinsic grip muscles. Included within the extrinsic DAM are the flexor digitorum longus, flexor digitorum profundus, and flexor digitorum superficialis (which serve to flex the first three phalanges). Intrinsic DAM include the abductor digiti minimi, flexor digiti minimi brevis, opponens digiti minimi (which flex the fourth phalanx) and the opponens pollicis (which opposes the pollex, drawing it across the palm and towards the phalanges). The PAM are predominantly primary elbow flexors and shoulder flexors (Gray, Pick, & Howden, 1974). In the present study, muscles responsible for producing a pinch grip will be referred to as ‘DAM’ and the muscle responsible for producing load force will be referred to as ‘PAM.’

1.1 Indices of GF-LF Coordination and Movement Control

Initial research within the field of GF modulation and control focused

primarily on simple, dynamic tasks that were translational or cyclical in nature. Numerous variables were altered to examine their effect on GF-LF coordination, including surface texture, changes in LF amplitude, (Johansson & Westling, 1988; Johansson, Riso, Häger, & Bäckström, 1992) and rate of imposed LF application (Johansson, Häger, & Riso, 1992). It is generally agreed upon that within this region of motor control, reliably strong indices of GF coordination include stable GLr, low variability, high Pearson's correlations, and relatively brief time lags between changes in manipulative force. GF and LF were found to be temporally coupled in both fluctuation and peak timing, such that GF maxima coincided with LF maxima over time (Flanagan & Wing, 1995). This phenomenon holds true even when the produced GF are significantly greater than necessary to prevent object slippage (Flanagan & Wing, 1993). Surface texture also affects GF modulation: the lower the object's friction, the higher the GF at any given LF (Johansson & Westling, 1984). This increase in GF produces increased GLr (i.e., less coordination) as well as increased safety margin to prevent object slippage. Additionally, movement frequency can also impact GF-LF coordination. With increased movement frequency, deterioration of the relationship between GF and LF is apparent (Flanagan & Wing, 1995; Hejduková, Hosseini, Johnels, Ingvarsson, Steg, & Olsson, 2002).

The previous findings relate to research involving dynamic tasks; however, the conducted studies utilize static manipulation tasks as well. Numerous studies, including several completed by this lab, have shed light on GF-LF coordination in static manipulation tasks under a number of conditions. While static manipulation

tasks yield no external movement, it is important to compare GF-LF coordination with data from similar dynamic tasks. It was found that, when compared with dynamic tasks, static manipulation tasks demonstrate a consistent and highly coordinated pattern of GF control under a range of frequencies (Jaric, Collins, Marwaha, & Russell, 2006). This find is vital to the validity of using static manipulation tasks in the assessment of motor control. Task directionality in bimanual static manipulation plays a significant role, as bidirectional tasks result in deteriorated coordination when compared to unidirectional tasks. The effect of task directionality was greater than the effect of task frequency on force coordination (Jaric, Russell, Collins, & Marwaha, 2005).

Also assessed were the effects LF range and frequency, surface friction and grasping technique, and experimental instructions in static manipulation tasks. LF frequency was found to have a greater effect on both GF-LF coupling (i.e., correlation coefficients) and GF modulation (i.e., change in GF relative to variation in LF) when compared to LF range. Therefore, frequency and not LF range should be taken into account when designing periodic manipulation tasks (Uygur, de Freitas, & Jaric, 2010). Surface friction was seen to have an effect on GLr: GLr in the fist and wrist grasp (i.e., non-specialized skin areas) was heightened when compared to the precision, fingers, and palm grasp (i.e., the specialized skin areas) (de Freitas, Uygur, & Jaric, 2009). Experimental instructions can also affect indices of GF-LF coordination as specific instructions can elicit a lower GLr, higher GF-LF coupling, and higher GF modulation (Jin, Uygur, Getchell, Hall, & Jaric, 2011).

Hand dominance is an elusive facet of object manipulation in static manipulation, as it can also play a role in GF-LF coordination. The motor lateralization model demonstrates that the dominant limb is specialized for dynamic, feed-forward tasks (Bagesteiro & Sainburg, 2002; Sainburg, 2002). The non-dominant limb is specialized for feedback-controlled error corrections (Bagesteiro & Sainburg, 2003). Studies that have focused on the effect of hand dominance on GF-LF coordination have alluded to the non-dominant arm as capable of providing slightly lower GF scaling and more accurate directionality (Ferrand & Jaric, 2006; de Freitas, Krishnan, & Jaric, 2007). However, these results are inconclusive, as other studies have failed to demonstrate a difference in GF-LF coordination other than a moderate time lag during modulation of GF with changes in LF (Jin, Uygur, Getchell, Hall, & Jaric, 2011).

Studies conducted on both dynamic and static tasks show a high level of GF-LF coordination through several facets of GF control: a relatively low and stable GLr, a continuous coupling of GF with changes in LF, and a highly modulated GF with respect to changes in LF. GF-LF coordination as a whole is seen as an indicator for some of the basic neural mechanisms of movement control. Local skin anesthesia (Johansson & Westling, 1984) makes GF-LF coordination less precise, but does not change the overall coordination pattern. Based on these observations it has been concluded that GF coupling is mainly controlled by a feed-forward mechanism: a central controller regulates the grip force according to the expected load force while a feedback mechanism, triggered by cutaneous sensation, acts if an assessment of an

expected load force happens to be erroneous (Zatsiorsky, Gao, & Latash, 2005; Ebied, Kemp, & Frostick, 2004). Continuous GF adjustments accommodate LF fluctuations to yield a stable GLr with virtually no time lag between such variations. These adjustments are presumably under the control of ‘open-loop’ mechanisms in static manipulation tasks (Jaric, Knight, Collins, & Marwaha, 2005).

1.2 Role of Central and Peripheral Fatigue

In a review conducted by Nowak and Hermsdörfer (2006), manual performance deficits in neurological movements disorders were evaluated. In the examination of object manipulation in several neurological disorders, it was determined that GF scaling, GF-LF coordination, and GF coupling can all be hampered in different pathological conditions, potentially leading to the dysfunctional object manipulation (Nowak & Hermsdörfer, 2006).

Chronic fatigue is a common symptom of neurological disease. In a review conducted by Behan and Chaudhuri (2004), chronic fatigue in the United States was found to account for 10-15 million visits to physicians every year:

Chronic fatigue can be part of medical and neurological disease (e.g., anemia, multiple sclerosis), an integral feature of the disease itself (e.g., post-stroke, chronic fatigue syndrome), mainly the result of a psychiatric disturbance in function (e.g., somatoform disorder), or a side-effect of drugs prescribed for previous disorders—e.g., antihypertensives, β -adrenergic blockers, lipid-lowering agents, proton-pump inhibitors, beta interferon, anxiolytics, antipsychotics, and surprisingly, antidepressants (Behan & Chaudhuri, 2004).

The prevalence of fatigue as a symptom has been the justification for numerous studies aimed at fatigue, yet the very definition of fatigue is often debated since the sensation of fatigue is subjective by nature. A review conducted by Enoka and Duchateau (2008) defined muscle fatigue as a referral to:

... a motor deficit, a perception or a decline in mental function, it can describe the gradual decrease in the force capacity of muscle or the endpoint of a sustained activity, and it can be measured as a reduction in muscle force, a change in electromyographic activity or an exhaustion of contractile function (Enoka & Duchateau, 2008).

In order to address this limitation of fatigue study, most investigators use a more tapered definition of fatigue as, “any exercise-induced reduction in the ability of muscle to produce force or power whether or not the task can be sustained” (Enoka & Duchateau, 2008). This concept is used as the working definition for fatigue in the conducted studies. While the definition of fatigue has been focused for the purposes of the following studies, the category of induced fatigue must also be distinguished between central fatigue and peripheral fatigue. A review conducted by Boyas and Guével (2011) sought to sublimate the causes and underlying factors of neuromuscular fatigue in healthy muscle:

‘Central fatigue’ designates a decrease in voluntary activation of the muscle (i.e. a decrease in the number and discharge rates of the motor units (MUs) recruited at the start of muscle force generation), and ‘peripheral fatigue’ indicates a decrease in the contractile strength of the muscle fibers and changes in the mechanisms underlying the transmission of muscle action potentials (Boyas & Guével, 2011).

This disparity between the potential causes of fatigue is a very important controlling factor since there are several sites which can lead to a decrease in force production, including: activation of the primary motor cortex, propagation of the command from the central nervous system (CNS) to the motor neurons, activation of the MUs and muscles, neuromuscular propagation (including propagation at the neuromuscular junctions), excitation-contraction coupling, availability of metabolic substrates, state of the intracellular medium, performance of the contractile apparatus, and blood flow (Boyas & Guével, 2011). For the purposes of the conducted studies, peripheral fatigue is the primary aim of the fatiguing protocols.

Several factors stimulate the proliferation of peripheral fatigue. These factors can be categorized as either changes in the intracellular environment or changes within the muscle fibers (Boyas & Guével, 2011). Changes within the intracellular environment include the accrual of lactate and hydrogen ions. Hydrogen ions are partially buffered by bicarbonate, which releases carbon dioxide to change the respiratory quotient during exercise. The accumulation of ammonia and heat also change the intracellular environment. Increased heat leads to greater sweat secretion. The water lost in sweat contributes to dehydration and, eventually, fatigue (Boyas & Guével, 2011). There are numerous changes within the muscle fibers associated with peripheral fatigue. Accumulation of both inorganic phosphate and hydrogen ions in the sarcoplasm elicit a drop in contractile force due to the inhibition of cross-bridge interaction (Boyas & Guével, 2011). The role of calcium is vital in muscle contraction. The accumulation of hydrogen ions, magnesium ions, and inorganic phosphate could

each lead to dysfunctional calcium release or reuptake. Glycogen reserve depletion can also lead to fatigue (Boyas & Guével, 2011).

There are numerous physiological mechanisms affected by neuromuscular fatigue and peripheral fatigue specifically. Therefore, it is vital that the fatiguing protocol designed for use in the proposed study features a method for eliciting peripheral fatigue and avoiding central fatigue as efficiently as possible. A study conducted by Sogaard et al. (2006) sought to investigate the effect of prolonged low-intensity contractions on supraspinal fatigue in human elbow flexors. Subjects in the study maintained a relatively weak isometric contraction of their elbow flexors (15% maximal voluntary contraction, MVC) for 43 minutes. At certain intervals during the prolonged contraction, subjects performed brief maximal efforts. Maximal voluntary force and voluntary activation, as well as electromyographic (EMG) responses to transcranial magnetic stimulation, were measured. The prolonged low-intensity contraction elicited slight peripheral fatigue, however, progressive central fatigue was produced. The generation of both peripheral and central fatigue contributed to an impaired MVC following the sustained isometric contraction (Sogaard, Gandevia, Todd, Petersen, & Taylor, 2006). Utilizing this data, the fatiguing protocols for the conducted studies feature brief, repeated high-intensity isometric contractions to generate predominantly peripheral fatigue within subjects' DAM and PAM.

1.3 Fatigue and GF-LF Coordination

While the conducted studies are some of the first to focus on the effects of

muscle fatigue on static manipulation tasks, other recent studies have focused on the effects of fatigue on hand muscle coordination and dynamic object manipulation. A study conducted by Danna-Dos Santos et al. (2010) determined that similar mechanisms are responsible for modulating and sustaining digit forces in both non-fatiguing and fatiguing contractions. Subjects gripped a manipulandum with thumb, index, and middle fingers while matching an isometric target force of 40% MVC for as long as possible. The coordination of the muscles used was quantified by way of EMG muscle activation patterns (MAP) vector and EMG-EMG coherence. EMG-EMG coherence is used as an index of muscle coordination by identifying the strength and periodicity of common frequency characteristics between two EMG signals (Danna-Dos Santos et al., 2010). During the fatigue protocol, EMG amplitude predictably increased. However, there was no change in MAP vector orientation, which indicates that a similar coordination pattern was used throughout the isometric contraction. EMG-EMG coherence also significantly increased at the end of the contraction, indicating that the CNS binds the neural drive to hand muscles that are similar during constant force isometric contractions in both fatiguing and non-fatiguing contractions (Danna-Dos Santos et al., 2010). Therefore, it can be assured that the muscle activation patterns used in the conducted studies' fatiguing protocols mimic the patterns of those same muscles during non-fatiguing contractions, often seen in activities of daily living.

A study conducted by Todd, Gandevia, and Taylor (2010) examined the effect of fatigue on hand dexterity. Subjects gripped and lifted an object in a dynamic

manipulation task before and after two interventions. One intervention involved a non-fatigued control, the other utilized a sustained maximal pinch grip that reduced maximal force by 60%. GF, LF, and first dorsal interosseous EMG activity were recorded. After two minutes of sustained MVC, subject generated an increased first dorsal interosseous EMG to lift and hold the manipulandum, but produced less GF and a greater GF fluctuation while holding the object (Todd, Gandevia, & Taylor, 2010). Additionally, there was a decrease in GF-LF coupling as assessed through the maximum cross-correlational coefficient under the fatigue condition. However, coupling did improve over time and subsequent lifts (Todd, Gandevia, & Taylor, 2010). This provides insight for the hypothetical outcome of the conducted studies: induced muscle fatigue will yield a reduction in GF, potentially effecting the GLr, as well as decreased GF-LF coupling.

1.4 Specific Aims and Hypotheses

Studies completed within the domain of muscle fatigue and object manipulation often assess force coordination through the use of dynamic tasks (Mattos, Domenech, Borges Junior, & Santos, 2012; Todd, Gandevia, & Taylor, 2010), while the effects of muscle fatigue on static manipulation tasks remain largely underexplored. Fatigue is a common symptom associated with numerous neurological conditions (Behan & Chaudhuri, 2004), and this specific symptom could be a major contributing factor to the GF-LF dyscoordination seen within this patient population (Nowak & Hermsdörfer, 2006). Considering both dynamic and static manipulation tasks are often used in countless activities of daily living, the effect of muscle fatigue on GF-LF coordination and task performance in various manipulation tasks should be explored.

1.4.1 Primary Aim

The effects of fatigue on GF-LF coordination have essentially remained undocumented, only recently has reduced GF-LF coordination in a simple lifting task utilizing a pinch grip been observed (Todd, Gandevia, & Taylor, 2010). Therefore, the primary objective of the present studies, and the focus of the first study, is to investigate the effects of muscle fatigue on GF-LF coordination and task performance across a variety of experimental tasks, including both static and dynamic manipulations.

1.4.2 Primary Hypothesis

Based on the previously studied effects of muscle fatigue on movement coordination and task performance (Allen, Lamb, & Westerblad, 2008; Bonnard, Sirin, Oddsson, & Thorstensson, 1994; Forestier & Nougier, 1998), as well as the specific

relationship between GF-LF coordination and task performance in manipulation tasks (Jaric, Collins, Marwaha, & Russell, 2006; Jaric, Russell, Collins, & Marwaha, 2005; Nowak & Hermsdörfer, 2006), it is hypothesized that general muscle fatigue will negatively affect GF-LF coordination and task performance. This will result in both impaired GF-LF coordination and task performance reduction.

1.4.3 Secondary Aim

While the overall effect of muscle fatigue on GF-LF coordination and task performance in both static and dynamic manipulation tasks is the primary focus, there remains the unresolved issue of fatigue effects on the two distinct muscle groups necessary for object manipulation. These groups include the LF-producing proximal arm muscles (or ‘PAM,’ which mainly include shoulder and elbow flexors) and the GF-producing distal arm muscles (or ‘DAM,’ which mainly include both intrinsic and extrinsic hand muscles) (Gray, Pick, & Howden, 1974). This premise forms the secondary objective for the present studies and the focus of the second study. Specifically, the aim is to examine the effect of targeted DAM and PAM fatiguing protocols on GF-LF coordination and task performance in both static and dynamic object manipulation tasks.

1.4.4 Secondary Hypothesis

Within this frame of localized DAM and PAM fatigue, previous studies have not provided a context for expectations of the selective fatigue effects on GF-LF coordination. However, it is hypothesized that fatigue of the DAM will lead to a relatively greater change in GF-LF coordination and task performance, when compared to PAM fatigue.

Chapter 2

EFFECTS OF MUSCLE FATIGUE ON GRIP AND LOAD FORCE COORDINATION AND PERFORMANCE IN MANIPULATION TASKS¹

2.1 Introduction

The ability to manipulate objects represents a crucial motor function of daily living, while the hand *per se* is a frequently used model in the studies of biomechanics and motor control phenomena (Jaric, Knight, Collins, & Marwaha, 2005; Johansson & Westling, 1984; Singh & Latash, 2011; Westling & Johansson, 1984). Among a number of different approaches, the force analysis of object manipulation has frequently been applied. This force analysis is typically based on a simple mechanical model of a vertically oriented handheld object (Figure 1A). The interaction force is decomposed into the load force (LF) that originates from friction and acts in parallel to the contact surface to overcome the object's weight and inertia, while grip force (GF) is applied perpendicularly to the object to provide both the friction and enable the control of the object's position (Flanagan & Wing, 1995; Jaric, Russell, Collins, & Marwaha, 2005; Johansson & Westling, 1984). In general, GF needs to be scaled high enough to prevent slippage, but not excessively high to cause either object deformation or muscle fatigue.

¹ Emge, Prebeg, Uygur, & Jaric (2013). *Neuroscience Letters*, 550, 46-50. See Appendix B.

Numerous studies, performed on a variety of static and free movement tasks, have consistently revealed a high level of GF–LF coordination through different aspects of GF control (Flanagan & Wing, 1995; Jaric, Russell, Collins, & Marwaha, 2005; Johansson & Westling, 1984; Westling & Johansson, 1984). Among others, GF is typically scaled to provide a relatively low and stable GF/LF ratio (Johansson & Westling, 1984), while continuous coupling of GF with ongoing LF changes has been observed through a high GF–LF correlation and a low GF-LF time lag (Flanagan & Wing, 1995; Johansson & Westling, 1984; Krishnan & Jaric, 2010; Uygur, Jin, Knezevic, & Jaric, 2012), indicating the involvement of “feed-forward” neural control mechanisms (Johansson & Westling, 1988; Johansson & Westling, 1984). However, various factors can adversely affect GF-LF coordination, such as a frequent switching of LF direction (de Freitas, Markovic, Krishnan, & Jaric, 2008; Jaric, Knight, Collins, & Marwaha, 2005), an increase in the task complexity (Krishnan & Jaric, 2010; Uygur, de Freitas, & Jaric, 2010; Westling & Johansson, 1984), or the presence of neural diseases (Hermsdörfer, Hagl, Nowak, & Marquardt, 2003; Marwaha, Hall, Knight, & Jaric, 2006; Nowak, Hermsdörfer, Marquardt, & Fuchs, 2002). Of importance for the present study is the reduced GF-LF coordination, observed either in various tasks or in different patient populations, usually associated with impaired task performance (Krishnan & Jaric, 2008; Nowak & Hermsdörfer, 2006). Therefore, it has been concluded that the GF-LF coordination in manipulation tasks could not only be a 'window' into the neural mechanisms of muscle control and movement coordination (de Freitas, Markovic, Krishnan, & Jaric, 2008; Jaric, Knight, Collins, & Marwaha,

2005; Johansson & Westling, 1984; Singh & Latash, 2011), but also a basis for developing standard quantitative tests of hand function in various populations (Krishnan & Jaric, 2008; Marwaha, Hall, Knight, & Jaric, 2006; Nowak & Hermsdörfer, 2006).

Muscle fatigue represents an exercise-induced reduction in the force-generating capacity of muscle, caused by changes within both the CNS and the acting muscles (Enoka & Duchateau, 2008). Fatigue typically decreases maximal voluntary activation of muscle (Gandevia, 2001), disrupts excitation–contraction coupling (Allen, Lamb, & Westerblad, 2008) and impairs both the movement coordination (Bonnard, Sirin, Oddsson, & Thorstensson, 1994; Forestier & Nougier, 1998) and performance (Boyas & Guével, 2011). Regarding the effects on hand function, the muscle fatigue was shown to reduce the applied GF (Mattos, Domenech, Borges Junior, & Santos, 2012; Todd, Gandevia, & Taylor, 2010), to increase the fluctuation of GF, and to decrease the coupling between GF and LF in simple lifting tasks (Todd, Gandevia, & Taylor, 2010). The effects of fatigue on both the coordination of individual fingers producing GF and its adaptation have also been studied (Danion, Latash, Li, & Zatsiorsky, 2000; Singh & Latash, 2011). However, taking into account both the role that GF-LF coordination has played in the studies of hand function and its potential importance for future neurological testing, it is surprising that the effects of fatigue on GF-LF coordination have been largely neglected. Only recently has deteriorated GF-LF coordination in a simple lifting task performed with a pinch grip been observed (Todd, Gandevia, & Taylor, 2010).

The purpose of the present study is to investigate the effects of muscle fatigue on the GF-LF coordination and performance in a variety of manipulation tasks. Based on the previously documented general effects of muscle fatigue on both task performance and movement coordination (Allen, Lamb, & Westerblad, 2008; Bonnard, Sirin, Oddsson, & Thorstensson, 1994; Forestier & Nougier, 1998; Gandevia, 2001), as well as on the positive relationship between the GF-LF coordination and performance in manipulation tasks (Jaric, Collins, Marwaha, & Russell, 2006; Jaric, Russell, Collins, & Marwaha, 2005; Nowak & Hermsdörfer, 2006), it is hypothesized that the applied fatiguing procedure would result in both impaired GF-LF coordination and deteriorated manipulation performance.

2.2 Method

2.2.1 Participants

Fifteen healthy right-handed participants were recruited (ten males and five females, 20–30 years of age). Maximum scores on the Edinburgh Handedness Inventory were used to assess hand dominance within each subject (Oldfield, 1971). The participants were without neurological problems or recent injuries to upper limbs. The experiment was approved by the IRB of the University of Delaware and conducted in accordance with the Declaration of Helsinki.

2.2.2 Experimental Device

A custom designed device, used in the previous studies of hand function (Jin, Uygur, Getchell, Hall, & Jaric, 2011; Uygur, Jin, Knezevic, & Jaric, 2012), was utilized to record GF and LF produced by the participants (Figure 1A). The instrumented handle used in this study consisted of two parallel grasping surfaces covered with high friction rubber and connected by a single axis force transducer (WMC-50, Interface Inc., USA). A multi-axis force transducer (Mini40, ATI, USA) was attached beneath each handle either to allow for attachment of the handle either to a fixed external support or to an added brass weight. The single-axis force transducer within the handle records the compression force exerted against the one side of the handle, while the multi-axis force transducer underneath the handle records all three components of the net force applied against the handle (Jin, Uygur, Getchell, Hall, & Jaric, 2011; Uygur, Jin, Knezevic, & Jaric, 2012). The externally fixed handle served for testing static manipulation tasks, while the other handle was attached to a 200 g mass (total weight 5 N) and could be freely manipulated, which was utilized for both determining maximum precision GF (i.e., the force exerted upon the handle by the tips of the fingers and the thumb) and performing a simple lift task. Located on the same table as the experimental devices and directly facing the participants, a computer monitor was placed to provide visual feedback during the three experimental tasks.

2.2.3 Experimental Procedure

2.2.3.1 Experimental Tasks

Three tasks were tested utilizing a precision grip (i.e., using the pads of the four fingers and the thumb but not including contact between the object and the participant's palmar surface) for object manipulation. The *ramp-and-hold task* required participants to trace a line of prescribed force as shown on the computer monitor. This was achieved by pulling up on the externally fixed handle to produce a tension force over a 10 s period (Jin, Uygur, Getchell, Hall, & Jaric, 2011; Krishnan & Jaric, 2008). The displayed line of prescribed force remained constant at 0 N for 2 s, increased thereafter gradually from 0 N to 10 N at a constant rate for 4 s, and finally remained constant at 10 N for the final 4 s. The *oscillation task* required the participant to produce an oscillating force within the tension force range of 2 N to 10 N for 12 s at a frequency of 1.5 Hz, as paced by a metronome (Jaric, Collins, Marwaha, & Russell, 2006; Jin, Uygur, Getchell, Hall, & Jaric, 2011; Krishnan & Jaric, 2008). This frequency was chosen because it lies within the middle of the frequency range that allows for comfortable execution of this type of task (Jaric, Collins, Marwaha, & Russell, 2006; Uygur, de Freitas, & Jaric, 2010). Tracing the prescribed LF profile in the ramp-and-hold task inevitably requires ongoing feedback-based corrections; however, the relatively high frequency of the oscillation task does not allow for those adjustments (Jaric, Collins, Marwaha, & Russell, 2006). While the first two tasks were static (i.e., both tasks were performed against the externally fixed

device), the third task was performed with the free manipulation handle of the experimental device. Specifically, in the *simple lift task*, participants were instructed to pick up the free-manipulation handle from the table surface, lift it approximately 20 cm, hold the handle in place for a minimum of 4 s, and then replace it back to the table (Krishnan & Jaric, 2008; Todd, Gandevia, & Taylor, 2010).

2.2.3.2 Fatiguing Procedures

The fatiguing protocol resulted from pilot testing designed to reveal both the properties of the fatigue device and a procedure based on bouts of consecutive lifts, that led to a similar rate of fatigue in the ‘proximal arm muscles’ (i.e., PAM, the LF-producing muscles) and ‘distal arm muscles’ (i.e., DAM, the GF-producing muscles). The fatigue device consisted of a plastic bottle-like container filled with heavy material (diameter 6 cm, length 21 cm, net mass approximately 2.1 kg). When coated in acetate tape to reduce friction, the pilot subjects reported that the maximum number of the consecutive lifts was limited by a fatigue affecting ‘both their arm and hand muscles.’

The participants’ voluntary maximum precision grip (VPG_{MAX}) first was assessed using the free-manipulation handle (see below for VPG_{MAX} testing details) and was ultimately compared with the maximum post-fatigue force output, in order to assess the level of fatigue (Enoka & Duchateau, 2008). The subjects then oscillated the fatigue device up and down from the shoulder to the hip level at a frequency of 1 Hz (paced by a metronome) until they were no longer able to maintain either the

frequency or amplitude of the fatiguing oscillation (see Figure 1B for fatigue stance). Thereafter, participants were immediately tested for their VPG_{MAX} . Verbal encouragement was applied, while a stopwatch was used to track the duration of each fatigue bout. This process was repeated until their VPG_{MAX} dropped below the target level of 70% of their initial value (e.g., a 30% reduction in VPG_{MAX}). Participants needed between two and five bouts of lifting to complete the fatiguing procedure. The first bout lasted between 34 and 120 s, while consecutive bouts were gradually shorter. Once the target level of fatigue was reached, the participants immediately initiated the testing procedure. However, based on pilot experiments, a brief ‘fatigue maintenance’ protocol of 15 oscillatory repetitions was applied immediately after each of the three experimental tasks. This additional protocol was implemented to maintain fatigue conditions within the participant. Note that even immediately after fatiguing procedures, the VPG_{MAX} (e.g., 79 N; data averaged across the subjects) exerted by non-fatigued subjects were about one order of magnitude higher than the VPG_{MAX} exerted by fatigued subjects while performing the tested manipulation tasks.

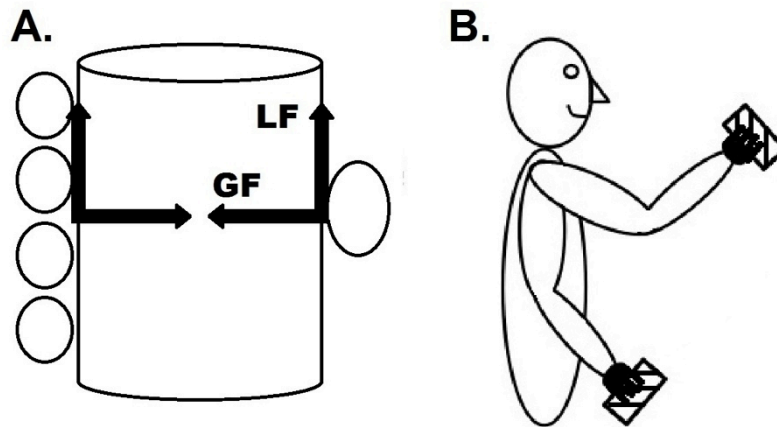


Figure 1: A) Simple model of object manipulation. The circles illustrate the tips of all five digits applying a precision grip to produce the contact force that can be decomposed into the normal (i.e., grip force; GF) and parallel component (i.e., load force; LF). B) Illustration of the fatigue protocol. Participants oscillated the weighted object from the shoulder to hip level, and back.

2.2.4 Experimental Protocol

Prior to testing, participants washed and dried their hands. The handles of the experimental device were washed with isopropyl alcohol to eliminate any residue from prior testing sessions. The participants stood facing the table that contained the device handles and the computer screen designed to provide visual feedback. Immediately, subjects' VPG_{MAX} was assessed using the free-manipulation handle. Specifically, the volunteers were instructed to grasp the free handle with a precision grip (see Figure 1A for grip designation), with their upper arm positioned vertically and their elbow in 90° of flexion. With the use of verbal encouragement from the experimenter and given the instructions to 'squeeze as hard as possible,' participants were given 4 s to record

their VPG_{MAX} . This measure was taken both before and after the fatiguing protocol. Following the VPG_{MAX} testing, subjects began the randomized experimental protocol. In the non-fatigue condition, participants would begin the familiarization procedure, followed straightaway by the testing procedure. In the fatigue condition, participants would begin the familiarization procedure, followed by the fatiguing procedure, which would then be followed by the experimental testing procedure and the intermittent fatigue maintenance protocol.

Two experimental sessions were conducted with one to two days of rest between them. Each of the sessions consisted of a familiarization procedure, followed by the testing procedure. Each procedure included two trials of each of three experimental tasks. The procedures were administered identically, with the exception of the fatiguing protocol preceding the fatigue experimental session. The sequence of both the three experimental tasks (i.e., ramp-and-hold, oscillation, and simple lift) and the two experimental sessions (non-fatigue and fatigue) were randomized across the participants. Each task was demonstrated prior to the first familiarization procedure.

2.2.5 Data Processing and Analysis

Raw signals from the force transducers were sampled at 200 Hz and low-pass filtered at 10 Hz with a fourth order Butterworth filter. The first of two trials of each task was taken for further analysis unless it was considered unsuccessful, such as because of either a late initiation, or dropping the object, which only occurred twice. In the ramp-and-hold task, the first and final 1 s of each phase were discarded, as were

the first 3 s and the last 1 s in the oscillation task. This exclusion was used to account for the potential effect of the preceding and anticipated transitions (Jaric, Knight, Collins, & Marwaha, 2005). In the simple lift task, only the middle 2 s of steady holding was analyzed (Krishnan & Jaric, 2008). GF–LF coordination was evaluated through GF scaling and GF coupling (Flanagan & Wing, 1995; Jaric, Knight, Collins, & Marwaha, 2005; Jin, Uygur, Getchell, Hall, & Jaric, 2011; Johansson & Westling, 1984; Krishnan & Jaric, 2008; Todd, Gandevia, & Taylor, 2010). GF scaling was calculated as a ratio between the averaged values of GF and LF. GF–LF coupling was assessed through the time lags observed from the oscillation task (Nowak, Hermsdörfer, Marquardt, & Fuchs, 2002; Uygur, de Freitas, & Jaric, 2010; Uygur, Jin, Knezevic, & Jaric, 2012), as well as from the correlation coefficients observed between GF and LF in both the ramp phase of the ramp-and-hold task and oscillation task (Flanagan & Wing, 1995; Jaric, Russell, Collins, & Marwaha, 2005; Krishnan & Jaric, 2008; Nowak, Hermsdörfer, Marquardt, & Fuchs, 2002). Due to the nature of the tested tasks, task performance was evaluated through the subjects' ability to produce the prescribed LF profiles (Danion, Latash, Li, & Zatsiorsky, 2000; Jin, Uygur, Getchell, Hall, & Jaric, 2011; Krishnan & Jaric, 2008; Nowak & Hermsdörfer, 2006). A series of dependent t-tests were used to analyze the differences between the conditions (non-fatigue vs. fatigue) on GF–LF coordination and movement performance variables (SPSS 19.0 for Windows). The level of significance was set to 0.05.

2.3 Results

Figure 2 illustrates typical force profiles obtained from a representative participant performing all three tasks. Note that the changes in GF closely reflect the changes in LF without any discernible time lag between them.

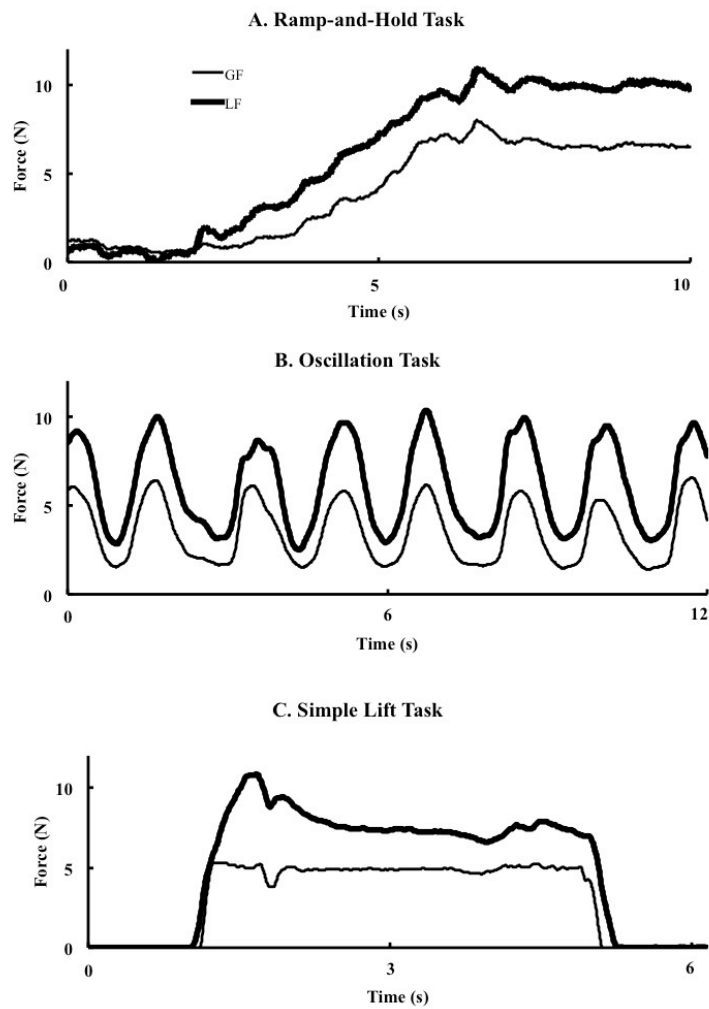


Figure 2: Profiles of the grip force (GF) and load force (LF) recorded in a representative subject performing the A) ramp-and-hold, B) oscillation, C) and simple lift task.

Figure 3A illustrates the effect of fatigue on GF scaling through the GF/LF ratio for each of the three experimental tasks. No effect of fatigue was observed in the oscillation task ($t = 0.38$, $p = 0.71$). Regarding the ramp-and-hold task, the hold phase revealed a significant drop in GF scaling associated with fatigue ($t = 2.17$, $p = 0.048$), but not the ramp phase ($t = 0.54$, $p = 0.56$). In the simple lift task, GF scaling decreased significantly following fatigue ($t = 2.63$, $p = 0.020$).

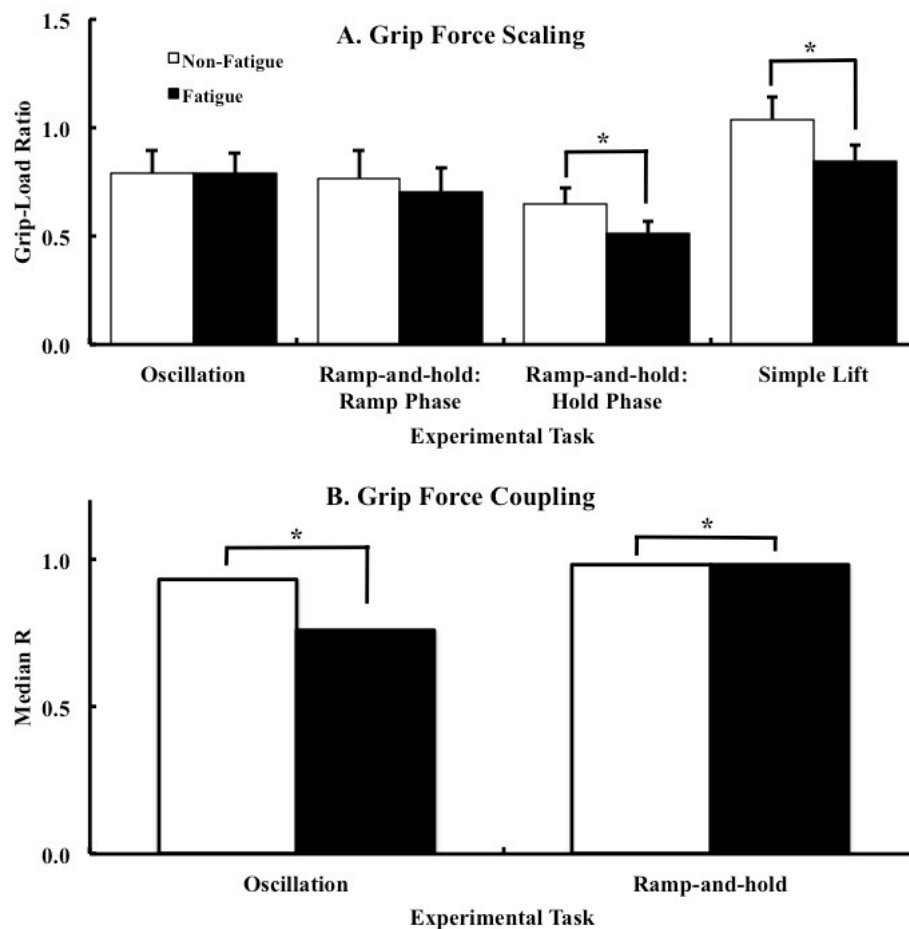


Figure 3: A) GF scaling assessed through the GF/LF ratio, represented by mean values with standard error bars (* $p < 0.05$). B) GF coupling observed through the median values of the GF-LF correlation coefficient.

GF–LF coupling was assessed through the time lags observed from the oscillation task (Nowak, Hermsdörfer, Marquardt, & Fuchs, 2002; Uygur, de Freitas, & Jaric, 2010; Uygur, Jin, Knezevic, & Jaric, 2012), as well as from the correlation coefficients observed between GF and LF in both the ramp phase of the ramp-and-hold task and oscillation task (Flanagan & Wing, 1995; Jaric, Russell, Collins, & Marwaha, 2005; Krishnan & Jaric, 2008; Nowak, Hermsdörfer, Marquardt, & Fuchs, 2002). The time lags revealed 0.002 ± 0.005 s and 0.024 ± 0.022 s under the non-fatigue and fatigue conditions, respectively. Although the difference remained below the significant level ($t = 1.14$, $p = 0.27$), it should be noted that two subjects markedly increased the GF lag from virtually zero to 0.29 s and 0.15 s under the fatigue conditions. However, the Fisher-transformed correlation coefficients decreased significantly following fatigue in both the oscillation task ($t = 2.42$, $p = 0.03$) and the ramp phase of the ramp-and-hold task ($t = 2.63$, $p = 0.02$; Figure 3B). Relatively steady GF and LF over both the hold phase and the simple lift task did not allow for testing GF–LF coupling (Krishnan & Jaric, 2008).

We assessed the root mean square errors (RMSE) when tracing a line (i.e., the ramp-and-hold task) and the absolute errors (AE) of the LF maxima and minima (oscillation task), while the nature of the simple lift did not allow for testing the task performance. RMSE of the ramp phase and holding phase under the non-fatigue condition were 0.56 ± 0.05 and 0.55 ± 0.01 N (mean \pm SE), respectively, while under the fatigue conditions the same values were 0.55 ± 0.06 and 0.61 ± 0.05 N. AE of the oscillation task performed under the non-fatigue and fatigue condition were $1.75 \pm$

0.18 and 1.97 ± 0.16 N (data averaged across the maxima and minima), respectively.

None of the above presented effects of fatigue on the performance variables proved to be significant ($p > 0.05$; paired t-tests).

2.4 Discussion

The main aim of this study was to explore the effects of muscle fatigue on a variety of manipulation tasks. Regarding the hypothesized outcomes, we found a fatigue associated decrease in GF–LF coordination as seen through both a reduced GF scaling (as assessed through the GF/LF ratio) and partial decoupling of GF and LF (as assessed through GF–LF correlations). Conversely, the task performance (as assessed by the ability to exert the prescribed LF) remained unaffected by the applied fatiguing procedure.

It is generally known that a deteriorated GF–LF coordination is typically associated with impaired hand function (de Freitas, Markovic, Krishnan, & Jaric, 2008; Jaric, Knight, Collins, & Marwaha, 2005; Marwaha, Hall, Knight, & Jaric, 2006; Nowak, Hermsdörfer, Marquardt, & Fuchs, 2002; Uygur, de Freitas, & Jaric, 2010; Uygur, Jin, Knezevic, & Jaric, 2012; Westling & Johansson, 1984). From that perspective, the observed partial decoupling of GF and LF observed in the present study suggests that muscle fatigue could also be a factor that negatively affects GF–LF coordination. However, we also observed a reduced GF scaling that could be considered as somewhat unexpected. Namely, previous studies have typically demonstrated increased GF scaling associated with either impaired hand function

(Krishnan & Jaric, 2008; Marwaha, Hall, Knight, & Jaric, 2006; Nowak, Hermsdörfer, Marquardt, & Fuchs, 2002), or reduced GF–LF coordination (Flanagan & Wing, 1995; Jaric, Russell, Collins, & Marwaha, 2005; Uygur, de Freitas, & Jaric, 2010). We believe that the specific effects of the applied intervention could explain the observed phenomenon since fatigue per se impairs the muscles' ability to exert high forces. Note that a fatigue associated decrease in GF has been already reported (Mattos, Domenech, Borges Junior, & Santos, 2012), although the authors neither controlled the level of the associated LF nor assessed force coordination. In addition, note also that the tasks tested in our study required GF magnitudes (i.e., typically below 10 N; see Figure 2 for illustration) that were vastly lower than the maximum GF that fatigued muscles were able to exert. Therefore, future studies are needed to explore whether the observed reduced GF scaling originates predominantly from the central (e.g., the CNS reduces muscle excitation and allows for a higher risk of dropping the object to slow down further fatiguing) or peripheral level (e.g., the fatigued muscles exert lower GF although the 'central command' remains unchanged) (Todd, Gandevia, & Taylor, 2010). Nevertheless, the observed effects of fatigue on GF–LF coordination could explain why the hand-held objects were more likely to drop when manipulated by fatigued individuals. Namely, both the decoupled GF and LF and an overall drop in GF increase the chance of having GF/LF ratio temporary below the minimally needed to prevent the slip (Johansson & Westling, 1984).

It is well known that muscle fatigue has adverse effects on both movement coordination and task performance (Bonnard, Sirin, Oddsson, & Thorstensson, 1994;

Boyas & Guével, 2011; Enoka & Duchateau, 2008; Forestier & Nougier, 1998), and also negatively affect a simple lift of a hand-held object (Todd, Gandevia, & Taylor, 2010). Impairment of hand function is also typically associated with impaired ability to control LF in various manipulation tasks (Krishnan & Jaric, 2008; Marwaha, Hall, Knight, & Jaric, 2006; Nowak & Hermsdörfer, 2006). Therefore, the lack of the effect of fatigue on the movement performance observed in the present study could be considered unexpected, particularly when taking into account that the fatiguing protocol was designed to induce fatigue in the GF and LF producing muscles at a similar rate. One could only speculate that the observed phenomenon may originate from either a low level of the imposed fatigue or a low level of forces required by the tested tasks. Therefore, future studies could involve both more aggressive fatiguing interventions and a larger variety of manipulation tasks regarding the magnitude of the required GF and LF.

Regarding the applied methodology, we selected a fatigue procedure that closely resembles a number of repetitive daily tasks that result in muscle fatigue. The strength of our study could be the diversity of the selected static and free movement tasks that required feedback (e.g., ramp and hold) and feed-forward (e.g., oscillation) control of LF and a rather natural and a spontaneous task (e.g., simple lift) (Jaric, Collins, Marwaha, & Russell, 2006; Jin, Uygur, Getchell, Hall, & Jaric, 2011; Johansson & Westling, 1988; Krishnan & Jaric, 2008). However, future studies should extend this line of research to distinguish among the effects of different fatiguing

procedures and to explore the effects of fatigue at both the central (i.e., neural) and peripheral (i.e., muscular) level.

To conclude, we found that while the ability to exert the prescribed LF pattern remained unaffected, the applied fatigue protocol resulted in both a deteriorated coupling of GF with LF and reduced GF scaling. Both effects should increase the likelihood of dropping hand-held objects over the course of manipulation performed with fatigued muscles. Taking into account the importance of hand function in everyday life and motor control research, as well as the importance of GF–LF coordination for success of manipulative actions, this line of research should be extended to include different tasks and a variety of fatiguing interventions.

Chapter 3

SELECTIVE EFFECTS OF FATIGUE OF ARM PROXIMAL AND DISTAL MUSCLES ON FORCE COORDINATION IN MANIPULATION TASKS²

3.1 Introduction

A force analysis of manipulation tasks is often based on a simple model of holding a vertically oriented object that defines grip force (GF) as the force applied perpendicularly to the object to provide friction and enable control of the object's position and orientation (Figure 4A). This same model defines load force (LF) as the tangential force acting parallel to the object's surface to overcome the object's weight and inertia. A high level of coordination of GF and LF is a well-known occurrence in manipulation tasks (Flanagan & Wing, 1993; Flanagan & Wing, 1995; Jaric, Russell, Collins, & Marwaha, 2005). Whether one is completing a complex motor task or simply performing an activity of daily living that includes object manipulation, GF is coordinated with respect to ongoing changes in LF. The indices of this coordination most frequently reported are GF scaling [revealed through a low and stable GF/LF ratio (GLr)], GF-LF coupling [typically assessed by a high Pearson's correlation coefficient (r values)] and a close to zero time lag between the changes in GF and LF (Johansson & Westling, 1984; Flanagan & Wing, 1993).

² Emge et al., 2013. Manuscript submitted for publication. See Appendix B.

The properties of GF-LF coordination have been extensively explored in a number of different conditions, including the effects of altered LF directionality (de Freitas, Markovic, Krishnan, & Jaric, 2008; Jaric, Knight, Collins, & Marwaha, 2005) and increased experimental task complexity (Krishnan & Jaric, 2008; Uygur, de Freitas, & Jaric, 2010; Westling & Johansson, 1984) in both healthy individuals and populations with impaired hand function, such as neurological patients (Hermsdörfer, Hagl, Nowak, & Marquardt, 2003; Marwaha, Hall, Knight, & Jaric, 2006; Nowak, Hermsdörfer, Marquardt, & Fuchs, 2002). As a result, it has been demonstrated that even a mild level of hand function impairment is associated with deteriorated indices of GF-LF coordination (Johansson & Westling, 1984; Flanagan & Wing, 1993). This has been the motivation for the development of several routine tests of hand function based on the force coordination, assessed through simple manipulation tasks (Jaric & Uygur, 2013; Nowak & Hermsdörfer, 2006).

Despite a number of studies focused on the numerous properties of manipulation tasks, several potentially important aspects of GF-LF coordination remained relatively underexplored. Among them are the potential effects of fatigue, which can be defined as an exercise-induced reduction in the ability of muscle to produce maximum force or power whether or not the task can be sustained (Enoka & Duchateau, 2008). Muscle fatigue is generally known for disrupting coordination of complex movement tasks (Gandevia, 2001; Paillard, 2012). There are numerous potential causes for the exercise-induced reduction in muscle force production or task sustainment. These causes include altered activation of the primary motor cortex and

propagation of the command from the CNS to the motor neurons, a reduced activation of the motor units, neuromuscular propagation (including propagation at the neuromuscular junctions) and excitation-contraction coupling, increased availability of metabolic substrates, altered state of the intracellular medium and blood flow, and reduced performance of the contractile apparatus (Boyas & Guével, 2011).

Regarding manipulation tasks, it has been demonstrated that fatigue can cause a decrease in overall GF and increase GF variability during object holding, which would reduce GF-LF scaling and coupling (Todd, Gandevia, & Taylor, 2010; Danna-Dos Santos et al., 2010). Our recent study also revealed a fatigue-associated reduction in both GF-LF scaling and coupling, while task performance (i.e., the ability to exert a prescribed LF profile, or to perform a steady holding) remained unchanged (Emge, Prebeg, Uygur, & Jaric, 2013). However, unresolved issues still remain since actions of two distinctive groups of muscle are needed for performing the tested manipulation tasks. Specifically, the distal arm muscles (DAM; involving involve both extrinsic and intrinsic grip muscles) are responsible for exerting GF, while the proximal arm muscles (PAM; mainly involving shoulder and elbow flexors) exert LF when lifting and holding objects (Gray, Pick, & Howden, 1974). However, the fatiguing procedure applied in our previous study was designed to affect all muscles involved to a similar extent (Emge, Prebeg, Uygur, & Jaric, 2013; Flanagan & Wing, 1993). Therefore it remains unknown whether fatigue of the DAM or the PAM caused the observed deterioration of GF-LF coordination.

To address the above-presented problem, we designed a study to explore the effects of DAM and PAM fatigue on manipulation tasks. In line with typical effects of fatigue in a variety of movement tasks, we hypothesized that muscle fatigue will be associated with a marked deterioration of both the GF-LF coordination and tasks performance. However, previous studies have not provided a background for hypothesizing the selective effects of DAM and PAM fatigue.

3.2 Method

3.2.1 Participants

Twelve healthy, right-handed participants [as assessed by maximum scores on the Edinburgh Handedness Inventory (Oldfield, 1971)] were recruited (eight males and four females, 23–34 years of age). All participants were without neurological problems or recent injuries to upper limbs. The experiment was approved by the IRB of the University of Delaware and conducted in accordance with the Declaration of Helsinki.

3.2.2 Experimental Device

A custom designed manipulandum, used in previous studies of hand function conducted by this lab (Jin, Uygur, Getchell, Hall, & Jaric, 2011; Uygur, Jin, Knezevic, & Jaric, 2012), was employed to record GF and LF produced by the participants (Figure 4B). The instrumented handle consisted of two parallel grasping surfaces

covered with high friction rubber and connected by a single axis force transducer (WMC-50, Interface Inc., USA). Beneath the primary grasping surfaces was attached a multi-axis force transducer (Mini40, ATI, USA) to allow for attachment of the handle to either a fixed external support or an added brass weight. Within the handle, the single-axis force transducer recorded the compression force exerted against one side of the handle. The multi-axis force transducer underneath the handle recorded all three components of the net force applied against the handle (Jin, Uygur, Getchell, Hall, & Jaric, 2011; Uygur, Jin, Knezevic, & Jaric, 2012). GF was calculated as the average of two opposing forces acting perpendicularly against the handle, while LF corresponded to the vertical force recorded by the multi-axis transducer (Uygur, Prebeg, & Jaric, 2013; Flanagan & Wing, 1995). Two of these identical custom manipulandums were used in the current study: an externally fixed handle and a free-manipulation handle. The externally fixed handle was immovable and was used both in the DAM fatigue protocol and in the testing of the static manipulation tasks. The free-manipulation handle was attached to a 200 g mass (for a total weight of 5 N) and was used to assess maximum voluntary pinch grip (VPG_{MAX}) as well as for experimentally testing the simple lift task.

3.2.3 Experimental Procedure

3.2.3.1 Experimental Tasks

The three experimental assignments utilized two static tasks and one dynamic task, each having been previously established as reliable metrics for GF-LF coordination (Westling & Johansson, 1984; Flanagan & Wing, 1993; Flanagan & Tresilian, 1994; Flanagan & Wing, 1995). The experimental tasks included the ramp-and-hold task, the oscillation task, and the simple lift task (Jaric, Collins, Marwaha, & Russell, 2006; Krishnan & Jaric, 2008; Todd, Gandevia, & Taylor, 2010; Jin, Uygur, Getchell, Hall, & Jaric, 2011; Emge, Prebeg, Uygur, & Jaric, 2013). All participants completed each of the three experimental tasks using a precision grip. This specific grip involves opposing forces of the pads of the four fingers and the thumb and does not include contact between the object and the participant's palmar surface.

The *ramp-and-hold task* required participants to trace a LF pattern displayed on a computer monitor located just beyond the experimental device by exerting a tension force upward over 10 s (see Figure 5A for illustration). The LF pattern depicted a constant force of 0 N for 2 s, gradually increased from 0 N to 10 N at a constant rate for 4 s, and remained constant at 10 N for the final 4 s. The *oscillation task* required participants to produce an oscillating tensional LF within a force range of 8 N (i.e., between 2 and 10 N) for 12 s at a frequency of 1.5 Hz, paced by a metronome (see Figure 5B for illustration). The oscillatory frequency of 1.5 Hz was chosen because it lies in the middle of the frequency range that allows for comfortable

execution of this type of task (Jaric, Collins, Marwaha, & Russell, 2006; Uygur, de Freitas, & Jaric, 2010). Note that tracing the prescribed LF in the ramp-and-hold task utilized continuous feedback-based corrections, the relatively high frequency of the oscillation task did not allow for such adjustments (Jaric, Collins, Marwaha, & Russell, 2006), effectively limiting control of the oscillation task to feed-forward mechanisms. Since the above-described tasks were static in nature (i.e. both the ramp-and-hold and oscillation tasks were performed using the externally fixed device handle), the third task was performed with the free-manipulation handle. For the *simple lift task*, participants were instructed pick up the free-manipulation handle from the table surface, lift the device approximately 20 cm, hold the handle in place for a minimum of 4 s, then return the manipulandum handle back to its original position (Krishnan & Jaric, 2008; Todd, Gandevia, & Taylor, 2010).

3.2.3.2 Fatiguing Procedures

Both of the fatigued conditions featured protocols designed to instill location-specific muscle fatigue within each subject using brief, repeated high-intensity isometric contraction of the target muscle groups. The protocols were also designed to elicit primarily peripheral fatigue within subjects. While prolonged low-intensity contractions will yield slight peripheral fatigue, they produce significantly greater progressive central fatigue (Søgaard, Gandevia, Todd, Petersen, & Taylor, 2006) and therefore were not utilized in the protocol design.

The distal arm muscle (DAM) fatigue featured a force-matching task, based on the subject's VPG_{MAX} testing results. Using the fixed manipulandum handle and the computer monitor to display feedback, a target GF was set as 50% of the subject's individual VPG_{MAX} (see further text for details), with a range of 5 N above and 5 N below this value. This 10 N range was displayed as two straight red lines on the monitor. Participants were instructed to trace the prescribed level of GF by pinching the fixed device for as long as they were able to remain between the two lines. Verbal encouragement was applied for each subject. Once the subject was unable to maintain the prescribed GF range, VPG_{MAX} was then measured immediately and compared to the pre-fatigue VPG_{MAX} level. This process of force matching was repeated until the subject's GF dropped below 70% of their initial VPG_{MAX} (i.e. a 30% decrease in GF); thereafter subjects immediately began the experimental tasks.

The proximal arm muscle (PAM) fatigue condition featured consecutive bouts of isometric PAM contraction. Participants were instructed to stand with their backs against a wall (i.e., to account for any unwanted posterior movement of the trunk and upper arm) and with their dominant arm in 90° of elbow flexion (Figure 4C). With the use of a padded strap, a resistance equal to approximately 15% of the subject's individual body weight was attached to the participant's distal forearm. Subjects were then instructed to 'keep your palm open and your thumb facing up,' so as not to unintentionally fatigue the DAM. Participants then held this position for as long as possible, with verbal encouragement given by the experimenter. The applied fatiguing procedure focusing on the PAM resulted from numerous pilot experiments aimed at

distilling a posture capable of eliciting muscle fatigue within the shoulder flexors, elbow flexors, and wrist abductors (the predominant LF-producing muscle groups) at a similar rate. Repeated, high-intensity isometric holds of the applied resistance consistently produced the most ideal rate of fatigue within the target PAM. Once the participant could no longer maintain 90° of elbow flexion, the resistance was quickly removed by the experimenter and the participants swiftly began the experimental tasks.

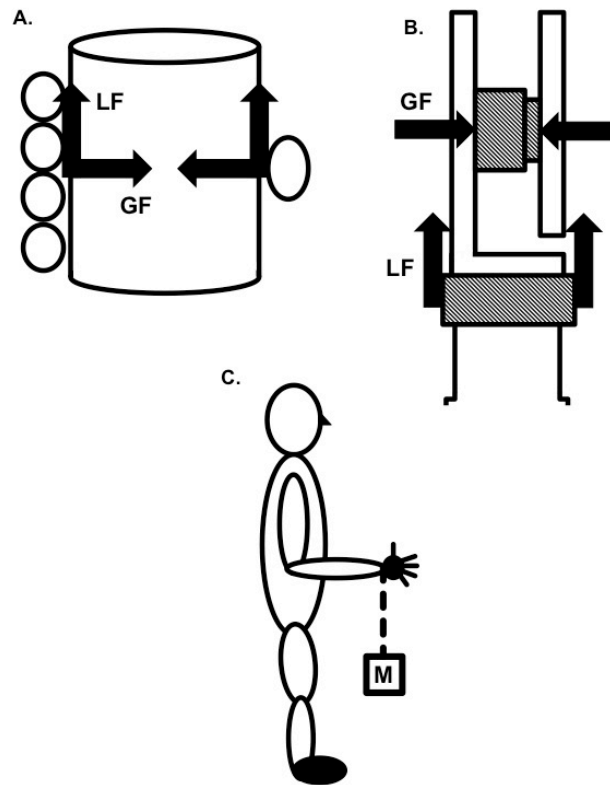


Figure 4: A) Simple model of acting forces during manipulating vertically oriented object. Circles illustrate the tips of the digits producing the interaction forces that can be decomposed into the grip force (GF) and load force (LF). B) Illustration of the instrumented handles used to record GF and LF. Shaded areas indicate positions of the load cells. C) Illustration of the body posture during fatiguing the proximal arm muscles (PAM). The distal arm muscles (DAM) were fatigued by simply squeezing the instrumented handle.

3.2.4 Experimental Protocol

Prior to testing, participants washed and dried their hands. The manipulandum handles were cleaned with isopropyl alcohol to eliminate any residue from previous testing sessions and to control for the device's surface friction. Participants stood

facing a table that contained the two handles of the manipulandum (one fixed and one free to move) and the computer monitor; the same monitor was used to provide visual feedback during the experimental sessions and DAM fatiguing procedure. Using the free-manipulation handle of the device, subjects' VPG_{MAX} was evaluated before and after each experimental session in all three conditions (i.e. no fatigue, DAM fatigue, and PAM fatigue).

For the VPG_{MAX} test, subjects were instructed to grasp the free handle with a precision grip (i.e. the tips of all five fingers were involved, see Figure 4A) with their upper arm positioned vertically and with 90° of elbow flexion. Through the use of verbal encouragement from the experimenter, participants were given the instructions to 'squeeze as hard as possible,' and upon initiation of the VPG_{MAX} test, subjects were then given 6 s to record their maximum voluntary precision grip. Each subject was given two trials to achieve their VPG_{MAX} , with the best trial recorded for each subject.

Following the VPG_{MAX} test, participants completed six to eight practice trials of the three experimental tasks, to account for possible familiarization effects (Granacher, Wolf, Wehrle, Bridenbaugh, & Kressig, 2010; Jin, Uygur, Getchell, Hall, & Jaric, 2011). Once the practice trials were completed and following a brief rest period, subjects began the two experimental trials for their specific conditional settings (i.e. non-fatigue, DAM fatigue, and PAM fatigue). A final VPG_{MAX} test was then administered to detect any fatigue effects induced by the practice trials or the experimental tasks. Both of the fatigued conditions also followed this basic procedure:

VPG_{MAX} testing followed by six to eight practice trials before the fatigue protocol and experimental trials.

The order of the experimental tasks (i.e., ramp-and-hold, oscillation, and simple lift) and the sequence of the conditional protocols (i.e., DAM fatigue, PAM fatigue, and non-fatigue conditions) were randomized across the subjects. The subjects were tested either through two or three sessions separated by two to three days of rest, depending of the sequence of conditions, since the testing sessions was not continued after completing either of the fatiguing protocols.

3.2.5 Data Processing and Analysis

Raw signals from the force transducers were sampled at 200 Hz and low-pass filtered with a 2nd-order Butterworth filter at 10 Hz in forward and backward directions so that a temporal shift in the output signal did not occur. Data were collected using National Instruments LabView software. In the ramp-and-hold task, the first and final 1 s of each phase was discarded, as were the first 3 s and the last 1 s in the oscillation task. This exclusion was used to account for the potential effect of preceding and anticipated transitions (Jaric, Knight, Collins, & Marwaha, 2005). Similarly, only the middle 2 s of steady holding in the simple lift task was analyzed (Krishnan & Jaric, 2008).

GF-LF coordination was evaluated through GF scaling and GF coupling (Todd, Gandevia, & Taylor, 2010; Danna-Dos Santos et al., 2010; Emge, Prebeg, Uygur, & Jaric, 2013). GF scaling was assessed through the GF/LF ratio. In the ramp-

and-hold task, GF/LF ratio was examined separately in the ‘ramp phase’ and the ‘hold phase’ of the task. GF coupling was assessed through Pearson’s correlation coefficients calculated between GF and LF of the ramp phase of ramp-and-hold and oscillation task. Time lags of GF with respect to LF were also calculated in the oscillation tasks. Correlational data was Fisher-transformed following collection.

Task performance was examined in the oscillation task and in the ramp-and-hold task. In the oscillation task, total absolute error (i.e., TAE; the absolute difference between target maximum LF and average achieved LF during the oscillation) was used to assess task performance (Krishnan & Jaric, 2008). In the ramp-and-hold task, root mean square error (i.e., RMSE; the difference between prescribed LF and average LF) was used to measure performance and was also measured separately during the ‘ramp phase’ and the ‘hold phase’ (Jin, Uygur, Getchell, Hall, & Jaric, 2011).

In addition to descriptive statistics, one-way repeated measures ANOVAs were used separately to assess the effects of fatigue conditions (i.e., DAM fatigue, PAM fatigue, and non-fatigue) on the variables of GF-LF coordination and task performance. All subsequent data were Greenhouse-Geisser corrected if Mauchly’s test of sphericity was significant. The significance level was set at alpha (p) = 0.05 and for post hoc analysis it was adjusted by Bonferroni corrections.

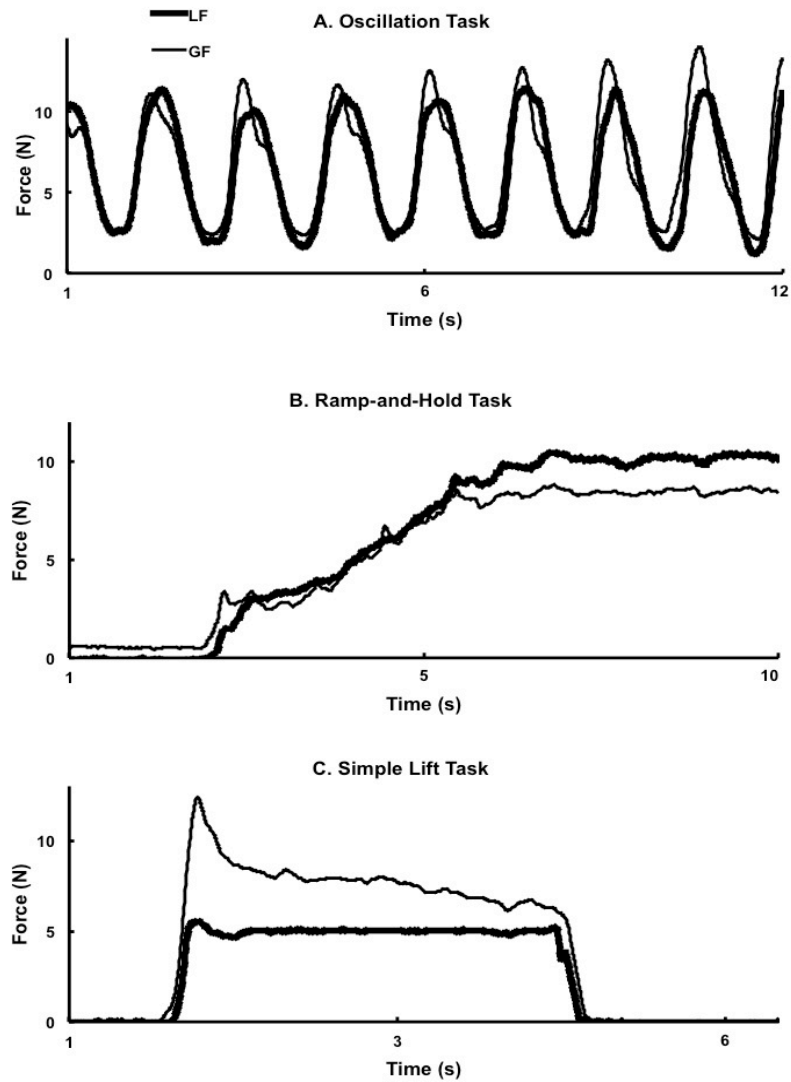


Figure 5: Representative profiles of the GF (thin line) and LF (thick line) obtained from three tested tasks.

3.3 Results

The average difference between the pre- and post-experimental task VPG_{MAX} for the no fatigue condition was 2.35 N, for PAM fatigue was 2.31 N, and for DAM fatigue was 18.9 N. These data suggest that only DAM fatigue had a meaningful effect

on muscle ability to exert maximum GF. Figure 5 demonstrates typical force profiles obtained from a representative participant across all three tasks under the no fatigued experimental condition. Note that all three sets of data suggest that the changes in GF closely mimic the changes in LF, without any apparent time lag between them.

Figure 6A illustrates the observed data regarding GF scaling for the three tasks. Within the oscillation task, the results show that GF/LF ratio was not significantly affected by either fatigue location, $F(1.36, 14.91) = 1.86, p = .195, \omega^2 = .0438$. As stated previously, GF/LF ratio in the ramp-and-hold task was recorded for the entire task as well its two component phases: ramp and hold. Throughout the complete ramp-and-hold task, the data demonstrate that GF/LF ratio was significantly affected by fatigue location, $F(2, 22) = 10.76, p = .001, \omega^2 = .4804$. During both the ramp phase [$F(2, 22) = 10.63, p = .001, \omega^2 = .4268$] and hold phase [$F(2, 22) = 9.22, p = .001, \omega^2 = .1229$] GF/LF ratio was significantly affected by fatigue location. In the simple lift task, GF/LF ratio was significantly affected by fatigue location [$F(1.17, 12.90) = 5.74, p = .032, \omega^2 = .2299$]. Note that all sets of data except the one observed from the oscillation task suggest that GF/LF ratio was lower under DAM fatigue than under the non-fatigue condition (Figure 6A).

Figure 6B shows the GF coupling data observed from the oscillation and ramp-and-hold tasks. In the oscillation task, the results demonstrated that the Fisher-transformed cross correlation values were significantly affected by fatigue location, $F(1.28, 14.13) = 6.61, p = .017, \omega^2 = .2754$. Similar to GF scaling, the coupling was lower under DAM than under the non-fatigue condition. The associated time lags (not

shown) proved to be on average close to zero (-0.8, 4.6 and -3.3 ms under non-fatigue, DAM and PAM fatigue conditions, respectively) revealing no differences among the conditions [$F(2, 22) = 2.77, p = .084, \omega^2 = -.0797$]. Finally, the ramp phase of the ramp-and-hold task revealed no significant differences in GF coupling among the fatiguing conditions [$F(2,22) = 1.69, p = .207, \omega^2 = .0949$].

Figure 6C illustrates the task performance data for the oscillation and ramp-and-hold tasks. The total absolute error (TAE) of the oscillation task differed among the fatiguing conditions [$F(2, 22) = 7.48, p = .003, \omega^2 = .7157$], being higher under DAM than under the non-fatigue condition. Regarding the ramp-and-hold task, the root mean square error (RMSE) differed among the conditions neither in the ramp phase [$F(2, 22) = .779, p = .471, \omega^2 = -.0146$] nor in the hold phase [$F(1.039, 11.424) = 2.108, p = .174, \omega^2 = .1229$]. Due to straightforwardness of the simple lift task, task performance data was deemed unnecessary for collection.

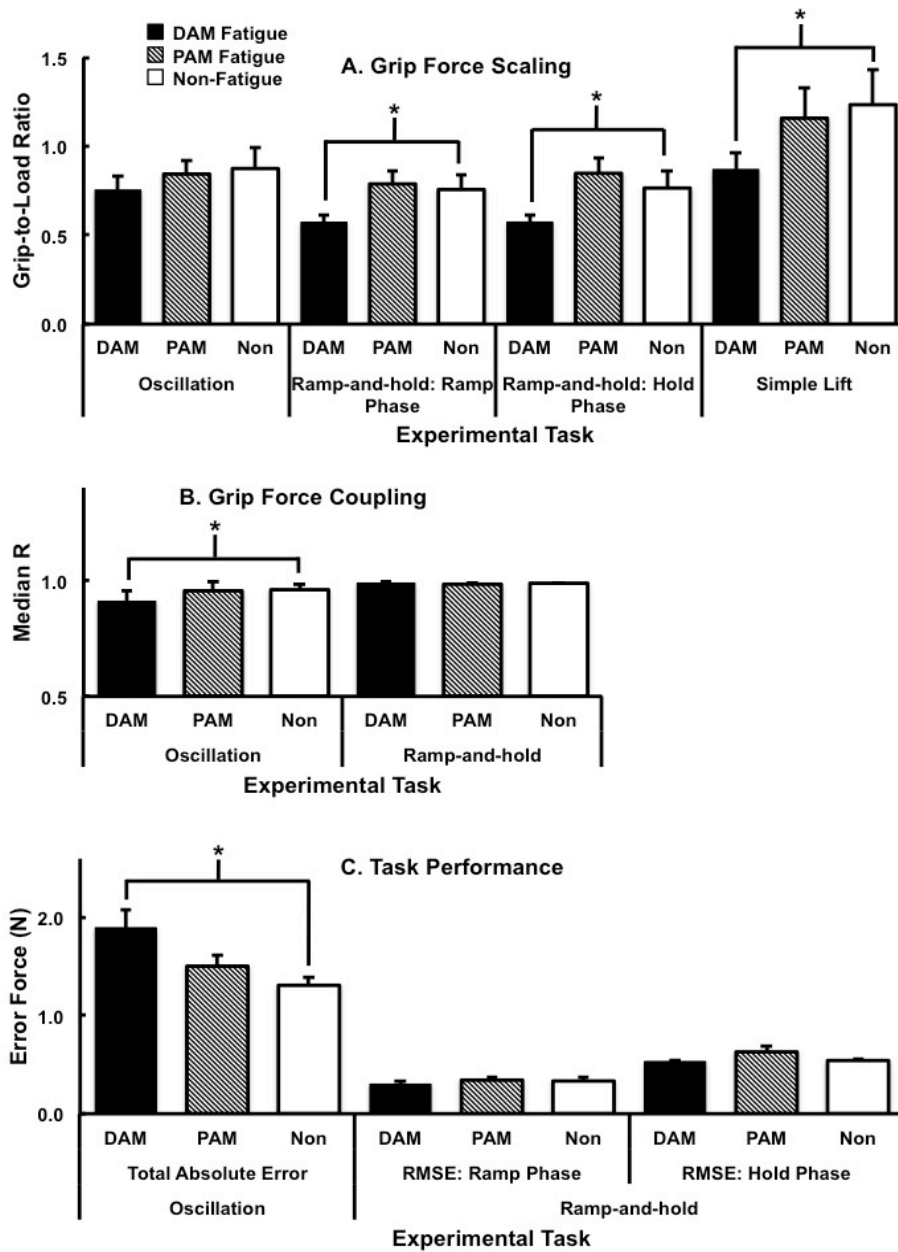


Figure 6: A) GF scaling assessed through the grip-to-load ratio, B) GF coupling assessed by the GF-LF correlations, C) task performance obtained from the oscillation (calculated as the total absolute error) and ramp-and-hold task (calculated as RMSE) obtained from the tested tasks under three fatiguing conditions. Significant differences among the conditions are also illustrated (* - $p < .05$).

3.4 Discussion

The present study aimed to explore the effects of muscle fatigue on manipulation tasks performed under both static and free movement conditions. Specifically either the GF-producing muscle ('distal arm muscle'; DAM) or LF-producing muscle ('proximal arm muscle'; PAM) were fatigued and both the indices of GF-LF coordination and task performance were compared with non-fatigued conditions. Regarding the hypothesized outcomes, we found that only DAM fatigue caused deterioration of GF-LF coordination as seen by reduced GF scaling (in the ramp-and-hold and simple lift task) and reduced GF coupling (oscillation task). The oscillation task also revealed deterioration of task performance (i.e., the ability to exert the prescribed force) under DAM, as compared with PAM and non-fatigue conditions.

It is well known that muscle fatigue impairs both the coordination and performance of large variety of movements (Gandevia, 2001; Gates & Dingwell, 2011; Paillard, 2012), while a deteriorated GF-LF coordination is well known to be associated with impaired hand function (Marwaha, Hall, Knight, & Jaric, 2006; Nowak, Hermsdörfer, Marquardt, & Fuchs, 2002; Westling & Johansson, 1984). Therefore, it should not be considered as unexpected that a number of variables we obtained generally reveal a deteriorated GF-LF coordination and manipulation performance associated with muscle fatigue. Since fatigue reduced both GF scaling and GF coupling, the general effects of fatigue on GF-LF coordination could explain why individuals with fatigued muscle are more likely to drop hand-held objects. Namely, the chance of having GF/LF ratio temporary below the minimally needed to

prevent the slip is higher when the overall level of GF is lower and GF and LF become partly decoupled (Johansson & Westling, 1984).

Although the general findings are in line with our previous study (Emge, Prebeg, Uygur, & Jaric, 2013), the present one allows for discerning the effects of different muscles fatigued. The results consistently revealed that the significant effects of fatigue appeared only in GF (i.e., DAM), but not LF (i.e., PAM) producing muscles. The finding specifically related to GF scaling should be considered as expected since the reduced GF/LF ratio observed under DAM fatiguing conditions could apparently be attributed to the reduced ability of DAM muscles to exert force. Moreover, since the applied fatiguing procedure could be the one that predominantly caused the peripheral (i.e., muscular) fatigue (Søgaard, Gandevia, Todd, Petersen, & Taylor, 2006), one could even speculate that the observed phenomenon mainly originates from deteriorated contractile performance of GF producing muscles, rather than from the altered central neural command (Boyas & Guével, 2011; Todd, Gandevia, & Taylor, 2010). Nevertheless, the findings could also explain the observed fatigue associated reduction in GF scaling although previous studies have typically demonstrated increased GF scaling associated with either impaired hand function (Krishnan & Jaric, 2008; Marwaha, Hall, Knight, & Jaric, 2006; Nowak, Hermsdörfer, Marquardt, & Fuchs, 2002), or reduced GF–LF coordination (Flanagan & Wing, 1995; Jaric, Russell, Collins, & Marwaha, 2005; Uygur, de Freitas, & Jaric, 2010).

While the selective effect of DAM fatigue on GF scaling could be in line with the general effects of fatigue on muscle force production and control, the same effect

on GF-LF coupling and, particularly, on task performance is more challenging to interpret. Specifically, one could expect that any alteration of force production mechanisms, such as those that could be associated with muscle fatigue at either central or peripheral level, or both, should adversely affect muscle coordination. Numerous studies performed on a variety of voluntary movement tasks have demonstrated fatigue associated impaired coordination (Todd, Gandevia, & Taylor, 2010; Danna-Dos Santos et al., 2010). Sustained maximum contraction during the DAM fatiguing procedure could have changed skin compliance and, consequently, alter the cutaneous neural feedback (Todd, Gandevia, & Taylor, 2010). Even more difficult to explain is why only DAM fatigue affected the task performance, since only PAM are involved in accurate exertion of the prescribed LF profiles. Here we could only speculate on the possible role of the difference in the relative forces of DAM and PAM (i.e., the maximum GF and LF in the tested tasks were about 10% and 3% of their pre-fatigue MVC, respectively). Namely, as compared to PAM fatigue, DAM needed to recruit a relatively larger number of motor units following DAM fatigue that could have had adverse effects upon the precision of the overall force control.

Regarding generalizability of our findings, note that we selected fatiguing procedures that closely resemble frequently performed daily manipulative actions. The selected tasks also correspond to manipulative actions that include both the static and dynamic tasks and involve a variety of neural control mechanisms, such as the feedback (e.g., ramp-and-hold and simple holding) and feed-forward tasks (e.g., oscillation) (Jaric, Knight, Collins, & Marwaha, 2005; Jin, Uygur, Getchell, Hall, &

Jaric, 2011; Johansson & Westling, 1988; Krishnan & Jaric, 2008). Nevertheless, a large number of both different tasks (e.g., uni- versus bimanual, tasks that require high level of GF and LF forces) (Johansson & Westling, 1988; Johansson, Riso, Häger, & Bäckström, 1992; Johansson, Häger, & Riso, 1992) and fatiguing procedures (e.g., 'central' vs. 'peripheral' fatigue) (Nowak & Hermsdörfer, 2006; Enoka & Duchateau, 2008; Boyas & Guével, 2011) remain unexplored. We also believe that exploration of the observed phenomenon implementing other levels of analysis (e.g., kinematic, or EMG) could shed a light on the neural mechanisms involved in the observed selective effects of DAM and PAM fatigue.

To conclude, the present findings suggest that muscle fatigue could adversely affect the force control seen through both the GF-LF coordination and task performance even in manipulation tasks that require exertion of relatively low forces. The observed deterioration in both GF scaling and coupling specifically reveal the mechanism that leads to a higher likelihood of dropping objects when they are manipulated by fatigued muscles. However, a particularly novel finding of the present study is that all these effects appear to be associated only with fatiguing the 'distal arm muscles' that exert GF, but not when the 'proximal arm muscles' (i.e., LF producing muscles) are fatigued. Taking into account the importance of hand function in both activities of daily living and motor control research, it is our recommendation that future research should focus on the neural mechanisms involved in the observed phenomenon.

Chapter 4

GENERAL DISCUSSION

4.1 Conclusions

The main aims of the conducted studies were to explore the general effects of proximal muscle fatigue on a variety of manipulation tasks. The first study focused primarily on using an ecologically valid oscillatory motion to equally fatigue both DAM and PAM before comparing the indices of GF-LF coordination and task performance with a non-fatigued condition. The second study attempted to take that premise one step further by isolating muscle fatigue within either the DAM or the PAM before comparing the observed variables with their non-fatigued counterparts. The results of the first study revealed a reduction in GF scaling (assessed through the GF/LF ratio) and a slight decoupling of GF and LF (assessed through GF-LF correlations). However, task performance (the ability to exert a prescribed LF) within the first study was unaffected by the fatiguing procedure. Results of the second study revealed a deterioration of GF-LF coordination followed by DAM fatigue as compared with PAM fatigue and non-fatigue conditions. This coordination dysfunction was evident through reduced GF scaling in the ramp-and-hold and simple lift tasks and decreased GF coupling in the oscillation task. Task performance in the oscillation task also deteriorated following DAM fatigue.

It is well known that muscle fatigue impairs both coordination and performance in a wide variety of movements (Gandevia, 2001; Gates & Dingwell, 2011; Paillard, 2012). It is also well known that GF-LF coordination dysfunction is associated with

impaired hand function (Marwaha, Hall, Knight, & Jaric, 2006; Nowak, Hermsdörfer, Marquardt, & Fuchs, 2002; Westling & Johansson, 1984). Therefore, it is not surprising that a number of variables observed in both studies reveal deterioration of GF-LF coordination, following an applied fatiguing protocol. Since muscle fatigue diminished both GF scaling and GF coupling, the overall impact of fatigue on GF-LF coordination could explain why individuals with fatigued musculature are more likely to drop handheld objects. Specifically, the probability of having a GF/LF ratio temporarily below the minimum threshold necessary to prevent object slippage is greater with a low level of overall GF and with a partial GF-LF decoupling (Johansson & Westling, 1984).

With the exception of the oscillation task in the second study, one notable similarity between the two sets of data is the apparent lack of effect on task performance following both an overall fatiguing procedure and two targeted fatiguing procedures, when compared to their respective non-fatigue conditions. Numerous observations have been made regarding the adverse effects muscle fatigue has on movement coordination and task performance (Bonnard, Sirin, Oddsson, & Thorstensson, 1994; Boyas & Guével, 2011; Enoka & Duchateau, 2008; Forestier & Nougier, 1998), as well as the potential negative impact on the simple lift of a handheld object (Todd, Gandevia, & Taylor, 2010). Additionally, impaired hand function is typically coupled with impaired LF control in numerous manipulation tasks (Krishnan & Jaric, 2008; Marwaha, Hall, Knight, & Jaric, 2006; Nowak & Hermsdörfer, 2006). Therefore, the non-significant effect of either type of fatigue on task performance for either study is slightly unexpected. Given that the fatiguing protocols were designed to elicit muscle fatigue at a similar rate, it can only be

speculated that this observed phenomenon might originate from either the relatively low level of induced fatigue or the low force level required to complete the experimental tasks.

Regarding the applied methodology, the first study featured a fatiguing procedure that closely resembled several repetitive daily tasks that could result in muscle fatigue. The second study then sought to devise two separate fatiguing protocols that would fatigue the component segments of object manipulation at a similar rate. Additionally, static and free moving experimental tasks were chosen that required feedback (e.g., ramp and hold) and feed-forward (e.g., oscillation) control of LF in addition to a natural and ecologically valid task (e.g., simple lift) (Jaric, Collins, Marwaha, & Russell, 2006; Jin, Uygur, Getchell, Hall, & Jaric, 2011; Johansson & Westling, 1988; Krishnan & Jaric, 2008).

4.2 Limitations

Overall, the high quality of the collected data and the reliability of the assessed variables provide a relatively high degree of experimental assurance (Jaric, Russell, Collins, & Marwaha, 2005). However, there are several potential limitations to the preceding research. The experimental device allows for data collection along two axes of the typical three-dimensional coordinate system. Although the experimental posture and the uni-directionality of the experimental tasks were designed to minimize extraneous force components, any bending or torsional forces could affect the recorded data.

Other limitations reflect the typical challenges and problems of studying muscle fatigue. Frequency of stimulation can lead to very different muscle fatigue recovery timelines. The two muscle groups forming the focus of the fatiguing protocols (such as

in the second study) are vastly different in several facets, including size, function, and control. Although the fatiguing procedures for the DAM and PAM were designed to produce similar effects, absolutely identical procedures for each of the muscle groups could not be devised, thus potentially leading to dissimilar fatiguing effects in the DAM and PAM.

Force recovery after fatigue produced by repeated short tetani is generally completed within 30 minutes when tested at high frequencies, whereas the force at low-frequency stimulation may be markedly depressed for many hours (Allen, Lamb, & Westerblad, 2008). Therefore, it was critical that low-frequency stimulation be used to induce fatigue within participants. The exclusion of EMG data to provide muscle activation data with the onset of fatigue is another limitation (Danna-Dos Santos et al., 2010). Therefore, subject motivation was a key facet to the study and subsequently a significant limitation to the conducted research. Without the use of EMG data to identify the onset of fatigue, as muscles increase their neural activity to resist the fixed loads, keeping participants motivated became imperative. Additionally, the fatiguing protocols were designed in an attempt to separate peripheral fatigue from central fatigue. However, without other specific levels of analysis, a complete division of fatigue type could not be assured.

4.3 Future Directions

Numerous future studies can be used to address the current research limitations. Kinematic or electromyographic data could shed a light on the neural mechanisms specifically involved in the observed selective effects of DAM and PAM fatigue. EMG data would also serve to identify the overall onset of muscle fatigue within participants. Also to be explored includes whether the observed GF scaling reduction

primarily originates from the central (e.g., the CNS reduces muscle excitation and allows for a higher risk of dropping the object in order to slow down further fatiguing) or the peripheral (e.g., the fatigued muscles exert lower GF although the ‘central command’ remains unchanged) level (Todd, Gandevia, & Taylor, 2010). Therefore, future studies can extend into this line of research by attempting to initiate central fatigue within participants before experimental testing, or by distinguishing the effects of different fatiguing protocols at both the central (i.e., neural) and peripheral (i.e., muscular) level.

Additionally, there are numerous different tasks (e.g., uni- versus bimanual, tasks that require high level of GF and LF forces) (Johansson & Westling, 1988; Johansson, Riso, Häger, & Bäckström, 1992; Johansson, Häger, & Riso, 1992) that remain unexplored. Also note that the tested experimental tasks in the previous studies required force magnitudes that were significantly lower than the maximum force that the fatigued muscles were able to exert. Future studies could involve more persistent fatiguing protocols to examine any associated effect of increased muscle fatigue level. Different subject populations could also be explored, rather than the healthy young adults used in the current findings. Of particular interest would be the effect of muscle fatigue on grip force coordination and task performance in older adult or neurological patient populations, as both frequently experience fatigue. Any adaptive strategies utilized by these particular participant demographics to overcome the effects of muscle fatigue would be of great interest to further research, as the results could provide insight into how a significant portion of the population copes with muscle fatigue and its effect on their activities of daily living.

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Appendix A
INFORMED CONSENT FORM

Research Study: ASSESSMENT OF HAND FUNCTION THROUGH FORCE
COORDINATION IN MANIPULATION TASKS

Investigators: Slobodan Jaric, PhD (Health and Exercise Sciences)

1. PURPOSE/DESCRIPTION OF THE RESEARCH

Slobodan Jaric has requested your participation in this research study. The purpose of this research is to examine how people exert different patterns of forces along a hand-held device. You are one of approximately 30 individuals who are recreationally active adults without a neurological disorder between the ages of 18 and 60 who will participate in this study. You will be asked to attend either one or two testing sessions lasting between 1 and 1.5 hours each.

At each session, you will sit in a chair or stand still and comfortably hold a lightweight device in front of you with tips of your fingers. At the beginning of the session, there will be a handedness test to make sure you are right handed. Then you will grip that the device with as much force as you can exert with each of your hands. Next, you will be given instructions on how to hold the device and what kind of forces to produce with your hands while holding it. The most applied force you will be asked to use

during this part of the testing will not be greater than the forces produced while doing such things as eating with fork and knife, or lifting a glass of water.

2. CONDITIONS OF SUBJECT PARTICIPATION

Your participation is totally voluntary. The experimental results will be reported in aggregate form only. You will not be individually identified, except possibly by a subject number known only to the researchers. The results of the research study may be published but your name or identity will not be revealed. All data and records will remain confidential, securely stored as computer files or paper documents in a locked cabinet in the investigator's office indefinitely, and will only be accessed by the investigator. In the unlikely event of physical injury during laboratory testing procedures, you will receive first aid. If you require additional medical treatment, you will be responsible for the cost. Testing will be stopped if you cannot adequately perform the tasks. You may withdraw your consent and discontinue participation in this study at any time without penalty.

3. RISKS AND BENEFITS

There is a small risk of some transient muscle fatigue, however the task is not more strenuous than ordinary tasks of manipulating lightweight objects or using external supports we regularly perform during daily living. You will be given opportunity to rest during the testing session, if necessary.

There are no direct benefits to you for participation. However, this study should provide new information about the neural control of patterns of unimanual and bimanual forces in various manipulative tasks.

5. CONTACTS

If you have questions about the research study, you may call Dr. Slobodan Jaric (302/831-6174), Professor, Department of Health and Exercise Sciences. If you have questions regarding the rights of individuals who agree to participate in this research you may call the Chair of the University of Delaware IRB (302/831-2137).

6. SUBJECT'S ASSURANCES

I have read the above informed consent. The nature, demands, risks and benefits of the project have been explained to me. I understand that I may withdraw my consent and discontinue my participation in this study at any time without penalty or loss of benefit to myself. My participation in this research study is not related to any course grade associated with the University of Delaware. A copy of this consent form has been given to me.

7. CONSENT SIGNATURES

Subject's Signature: _____

Date: _____

Subject's Name (printed): _____

Date: _____

I certify that I have explained to the above individual the nature and purpose, the potential benefits, and possible risks associated with participation in this research study, have answered any questions that have been raised, and have witnessed the above signature. I have provided the subject with a copy of this informed consent document.

Signature of the Investigator: _____



Date: _____

Appendix B


PUBLICATIONS

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 **Neuroscience Letters** 

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Effects of muscle fatigue on grip and load force coordination and performance of manipulation tasks 

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H I G H L I G H T S

- Effects of muscle fatigue on various manipulation tasks were explored.
- The ability to control external loads remained unaffected by fatigue.
- Both the hand grip force and its coupling with external load were reduced.
- The findings explain why external objects are often dropped by fatigued muscles.

A R T I C L E I N F O

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A B S T R A C T

Muscle fatigue is known to be associated with a deteriorated muscle coordination and impaired movement performance in variety of voluntary movements. The aim of this study was to investigate the generally underexplored effect of muscle fatigue on both the coordination between grip force (GF; the force component perpendicular to the hand-object contact area that provides friction) and load force (LF; the parallel force component that can move the object or support the body) as well as movement performance in manipulation tasks. Fifteen participants performed a variety of static and dynamic manipulations both with and without a preceding procedure designed to fatigue the arm and hand muscles. The tasks involved exertion of ramp-and-hold and oscillation patterns of LF against an externally fixed instrumented device, and a simple lift of a freely moving device. The results revealed a fatigue-associated decrease in GF scaling (i.e. the magnitude of GF relative to LF) and GF-LF coupling (correlation between GF and LF), while the task performance regarding the accuracy of exertion of the prescribed LF profiles remained unaffected. We conclude that muscle fatigue both partly decouples GF from LF and reduces the overall GF magnitude, which could potentially explain why hand-held objects are more likely to drop when manipulated with fatigued muscles. However, the unaffected task performance could be explained either by the relatively low level of muscle forces required by the tested tasks, the moderate level of the fatigue imposed, or both.

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1. Introduction

The ability to manipulate objects represents a crucial motor function of daily living, while the hand per se is a frequently used model in the studies of biomechanics and motor control phenomena [12,15,23,27]. Among a number of different approaches, the force analysis of object manipulation has frequently been applied. This force analysis is typically based on a simple mechanical model of a vertically oriented handheld object

(Fig. 1A). The interaction force is decomposed into the load force (LF) that originates from friction and acts in parallel to the contact surface to overcome the object's weight and inertia, while grip force (GF) is applied perpendicularly to the object to provide both the friction and enable the control of the object's position [7,13,15]. In general, GF needs to be scaled high enough to prevent slippage, but not excessively high to cause either object deformation or muscle fatigue.

Numerous studies, performed on a variety of static and free movement tasks, have consistently revealed a high level of GF-LF coordination through different aspects of GF control [7,13,15,27]. Among others, GF is typically scaled to provide a relatively low and stable GF-LF ratio [15], while continuous coupling of GF with ongoing LF changes has been observed through a high GF-LF correlation and a low GF-LF time lag [7,15,18,26], indicating the

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Selective effects of fatigue of arm proximal and distal muscles on force coordination in manipulation tasks

Running head: Effects of fatigue on object manipulation

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Appendix C

IRB APPROVAL LETTER



RESEARCH OFFICE

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DATE: August 21, 2013

TO: Slobodan Jaric, PhD
FROM: University of Delaware IRB

STUDY TITLE: [186464-4] ASSESSMENT OF HAND FUNCTION THROUGH FORCE
COORDINATION IN MANIPULATION TASKS

SUBMISSION TYPE: Continuing Review/Progress Report

ACTION: APPROVED
APPROVAL DATE: August 21, 2013
EXPIRATION DATE: August 17, 2014
REVIEW TYPE: Expedited Review

REVIEW CATEGORY: Expedited review category # 4

Thank you for your submission of Continuing Review/Progress Report materials for this research study. The University of Delaware IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a study design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This submission has received Expedited Review based on the applicable federal regulation.

Please remember that informed consent is a process beginning with a description of the study and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the study via a dialogue between the researcher and research participant. Federal regulations require each participant receive a copy of the signed consent document.

Please note that any revision to previously approved materials must be approved by this office prior to initiation. Please use the appropriate revision forms for this procedure.

All SERIOUS and UNEXPECTED adverse events must be reported to this office. Please use the appropriate adverse event forms for this procedure. All sponsor reporting requirements should also be followed.

Please report all NON-COMPLIANCE issues or COMPLAINTS regarding this study to this office.

Please note that all research records must be retained for a minimum of three years.