EFFECTS OF FORCE, FREQUENCY & GRIPPING DURING A PUSH TASK

THE EFFECTS OF FORCE, FREQUENCY AND GRIPPING ON UPPER EXTREMITY MUSCLE ACTIVITY DURING A CYCLIC PUSH TASK

by

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Abstract

Risk factors for the development of upper extremity work-related musculoskeletal disorders (UE WMSD) include high repetition, high force, and the combination of high force and high repetition (Moore et al. 1991; Silverstein et al., 1986; Latko et al., 1999). This study examined the muscle activity in the upper extremity during a repetitive pushing and gripping task with differing force levels and differing frequencies. Ten males and 9 females performed a cyclic bimanual push and grip task for 120 s while 8 muscles of the upper extremity were monitored by EMG on the right side of the body. All combinations of 3 push load levels (1 kg, 2 kg, 4 kg), 3 frequencies (4/min, 8/min, 16/min) and 2 grip conditions (no grip and 30% relative to the individual's maximum) were randomized.

The paradigm of doubling frequency and load did not lead to a doubling of muscle activity. The increase in muscle activity was somewhat linear in many muscles with several exceptions but was much less than 1:1. The AEMG appears to reflect workload rather then the force and frequency parameters that were chosen. In the forearm, the load and frequency parameters and concurrent grip caused increased activity in all muscles. The addition of a grip superseded the effects that were expected due to load but not frequency. As well, as the frequency increased, muscle activity also increased while the amount of muscular rest (muscle activity $< 1\%$ maximum in seconds

per minute) decreased. The muscular rest of the extensor digitorum decreased during the grip the high frequency (16/min) condition regardless of load, all the trials were under 10% of rest.

For the shoulder, anterior deltoid activity increased when gripping for all participants but significant differences were noted between genders. The anterior deltoid muscle activity was also affected by the weight of the arm, thus was not directly proportional to the 1-2-4kg load applied. Although maximum strengths for the shoulder were not recorded in this study, the finding that female subjects had higher anterior deltoid activity than male subjects was expected due to the absolute push loads likely being a greater relative effort for women. Overall, male subjects required about 70-75% of the anterior deltoid activity of females but had the same amount of muscular rest based on muscular rest (muscle activity < 1% maximum in seconds per minute). This finding is quite interesting as often a single metric is used to analyze tasks leading to potentially misleading interpretations.

Through examining the EMG of the upper extremity muscles, the current data suggests the need to raise the importance on the frequency of work and to also increase the importance of gripping in ergonomic assessment tools. This thesis helps further the understanding of the physiological relationship between force, frequency and concurrent gripping, with the ultimate goal of establishing acceptable values.

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Chapter 1 – Introduction

Work related musculoskeletal disorders of the upper extremity are a major concern in the workplace, but the precise etiology of UE WMSD has eluded researchers. Work-related musculoskeletal disorders of the upper extremity (UE WMSD) currently rank second to lumbar spine disorders as the most common workplace injury claims in Ontario. Of the 93,000 lost time injuries reported in 2003, 30% involved the nerves, tendons, muscles and supporting structures associated with the shoulder, arm, elbow and hand/wrist (WSIB, 2004). Musculoskeletal disorders of the upper extremity include tendinitis, tenosynovitis, myalgia (muscle pain), epicondylitis and neuropathy. These disorders result from repeated use or exposure to a risk factor rather than a specific event (WSIB, 2004). Factors that place workers at an increased risk for the development of UE WMSD include high repetition (Latko et al., 1999; Silverstein et al., 1986, Fransson-Hall et al., 1995), high force (Silverstein et al., 1986; Malchaire et al., 1997), non-neutral (or awkward) postures (Malchaire et al., 1996), and high angular velocities (Marras & Schoemarklin.1993; Malchaire et al., 1997). There is also strong evidence that the combination of high force and high repetition places individuals at a higher risk of developing disorders (Moore et al., 1991; Silverstein et al., 1986).

By using electromyography (EMG) to examine the muscle "overload" of the upper extremity when faced with the combination of high force and high repetition (as well as gripping), we hope to further the understanding of how these risk factors affect the upper extremity. This has been recommended in the literature; for example, Jonsson (1991) suggested that "employing EMG studies will help to give detailed accounts of the coordination of muscular activity and will be important to future ergonomic research". Moore (2002) reiterated this sentiment by stating that there is an opportunity for research that "closely duplicate[s] circumstances more representive of the workplace". Recent EMG studies have shown that forearm and shoulder muscle activity is affected by several factors including posture, force and the nature of the exertions (MacDonell & Keir, 2005; Au & Keir, 2007). It was also found that a static pushing task did not have an effect on the anterior deltoid activity (Di Domizio, 2006).

While risk factors have been identified, there are still gaps in the knowledge base for the development of upper extremity injuries especially when compared to the lower back. Subsequently, there is a need to improve our understanding of force and repetition (or frequency) factors in the development of UE WMSD and how they can be incorporated into ergonomic assessment tools. As there are no studies in the literature that have examined EMG of the upper extremity muscles' response to force and frequency, this thesis will use a simple design involving a bimanual pushing and gripping task to examine the muscular response to force and frequency parameters. A concurrent grip will also be added to the design of the study to see its effects on the muscular response in the upper extremity.

Chapter 2 – Review of Literature

2.1 Risk Factors for Work Related WMSD

It has been shown that there is a high incidence of UE WMSD during jobs that involve high repetition (Latko et al., 1999; Silverstein et al., 1986, Fransson-Hall et al.,1 995), high force (Silverstein et al., 1986; Malchaire et al., 1997), awkward postures (Malchaire et al., 1996), high angular velocities (Marras & Schoemarklin 1993) and also the combination of high forces and high repetition (Moore et al. 1991, Silverstein et al., 1986). The detailed review of epidemiological literature by NIOSH (1997) indicated the need to concentrate on the combination of risk factors (force, repetition and non-neutral postures) associated with the development of distal upper extremity musculoskeletal disorders.

2.1.1 Repetition

In their benchmark study for workplace epidemiology, Silverstein et al. (1986) examined 574 active industrial workers in 4 groups: low force-low repetition (LOF-

LOR), high force-low repetition (HIF-LOR), low force-high repetition (LOF-HIR), and high force-high repetition (HIF-HIR). High repetition was defined by a work cycle that was less than 30 seconds or a fundamental work cycle constituting more than 50% of the total work cycle. It was found that the HIF-HIR group had a positive association with hand/wrist cumulative trauma disorders (CTD), independent of other factors, such as sex, age, plant worked at, and number of years at the job. Their logistic regression analysis showed the odds ratio (OR) for repetition (high repetition to low repetition) alone was 2.8, this was less than the independent OR for force (Silverstein et al., 1986). The found the opposite to be true with carpal tunnel syndrome (CTS) (Silverstein et al., 1987). It was found that repetitiveness, with an OR of 5.5, appeared to be a more important risk factor than force, which had an OR of 2.9 and was not statistically significant.

Using the categories designed by Silverstein et al. (1986), Moore et al. (1991) investigated the combination of effect and cumulative effect of force, postures, and repetition. Their results were "similar to Silverstein et al., who also did not find force as significant as repetition alone for the CTD they studied". They also found that their results for mechanical work factors, which were comprised tendon excursion, force and posture, could be compared to the effect of force and repetition found by Silverstein et al. (1986). Moore et al. (1991) found a similar trend of repetition being more significant than force. In their work the OR (for "cumulative work factor") was 6.0 for the low force – high repetition while the high force – low repetition OR was 2.0.

In a study of garment industry workers, Punnett et al. (1985) found an OR of 2.7 (95% CI 1.2-7.6) for persistent pain and numbness in the hand or wrist among workers whose jobs required repetitive hand movement (such as sewing and trimming) as compared to those jobs that didn't require repetitive hand movements (such as nurses and lab technicians). Barnhart et al. (1991) reported that carpal tunnel syndrome was present in either or both hands in 15.4% of those workers with "clearly highly repetitive" jobs, but only in 3.1% of those workers with "not repetitive" jobs. In a study examining the relationship of repetitive work and the prevalence of UE WMSD, Latko et al. (1999) found that repetitive work was related to upper limb discomfort, tendinitis and carpal tunnel syndrome in workers. They observed 352 workers at three different companies, and classified jobs using a 10-point scale and put them into three ranges of repetitiveness: low (0 - 3.3), medium (3.3 - 6.6) and high (6.6 - 10). Medical professionals conducted physical evaluations, questionaires and electrodiagnostic testing to determine the incidence of UE WMSDs. Using a variety of highly repetitive job categories, workers had a high incidence of wrist/hand/finger symptoms (46.5%), tendinitis (14.5%) and CTS (7.9%). There were only 19 CTS cases out of 352 participants, which is a prevalence of only 5.4% overall. This indicates that one or two cases of CTS could have change their results (and/or statistics) either way. From their work Latko et al. (1999) concluded that the risk of developing a WMSD was 2 to 3 times higher in workers performing jobs in the high repetition group compared to those in jobs with low repetition. It should be noted that the difference between the Latko et al. (1999) and the Barnhart et al. (1991) studies is that Latko et al. (1999) used categories of repetition, as determined by their visual-analog scale for rating repetition/hand activity as opposed to the binary approach used by Barnhart et al. (1991). Fransson-Hall et al. (1995) established that, as compared to the general population, assembly line workers had a higher prevalence (prevalence ratio (PR) of 1.2 for men and 3.6 for women) of high exposure to repetitive exertions, recognized as one of the major risk factors for work-related MSD. Hansson et al. (2000) compared female workers performing repetitive work in the laminate industry. Their investigation examined workers in the same plant engaged in non-repetitive work, office workers and workers who had recently resigned from all of the jobs in this study. It was found that women in the repetitive work group had a much higher prevalence (OR 2.0-7.5) of disorders in their neck, shoulders and wrists/hands. High frequency wrist movements for the left hand, (mean power frequency 0.53 Hz) were associated with an increased prevalence of hand/wrist disorders (56% of workers) as compared to low frequency wrist movement (0.28 Hz and 26%)(Hansson et al., 2000).

2.1.2 Force

Using bilateral EMG recordings from the forearm flexor muscles, Silverstein et al. (1986), estimated hand forces in their study. The "high" force condition wasdefined as an "adjusted force" ("adjusted force" = (variance/mean force) + mean force) of 6 kg. The "adjusted force" was used to help control for a large variance in the forces used between cycle and between jobs. The "low" force was less than the "adjusted force" of 6kg. When force was entered into a logistic regression analysis as the only exposure measure, the OR for high force was 4.4, which was greater than the OR for repetition, which was 2.8. Malchaire et al. (1997) used Silverstein's definition of repetition and force and attempted to prioritize the occupational risk factors at the wrist. Although they did not provide specific odds ratios, Malchaire et al. (1997) concluded that priority should be given to "the forces exerted by the wrist and the hand, the velocity of movement of flexion-extension and the repetitiveness" as occupational risk factors at the wrist.

2.1.3 Combination of force and repetition

In a comprehensive review of epidemiological studies, "strong evidence" was given to the combination of force and repetition as a causal factor for the development of CTS, epicondylitis and wrist tendinitis (NIOSH, 1997). Silverstein et al. (1986) found that force (OR of 4.4) and repetition (OR of 2.8) significantly and independently increased the risk of hand and wrist CTD, but the combination of both high force and high repetition had an OR of 30.3, compared to low force - low repetition. This is a substantial OR the combination of high force and high repetition really appeared to have a multiplicative tendency. Moore et al. (1991) found a multiplicative effect of force and repetition similar to the high force-high repetition condition found by Silverstein et al., which represented the highest OR in both studies. Moore et al. (1991) found the test condition that produced the highest cumulative loading or "cumulative work factor" was the high force-high repetition (HIF-HIR) condition with an OR of 9.2. After normalizing to LOF-LOR condition used by Silverstein et al. (1986), Moore et al. (1991) found that their HIF-HIR had an OR of 9.2 for cumulative work factor. These are the highest ORs found in both of the studies, and this demonstrates large increases in the risk of hand/wrist disorders when there is a combination of high force and high repetition. This shows the need for further research in this area such as EMG studies which could look at the muscular overload in the upper extremity.

2.1.4 Wrist motion

Wrist motion has also been associated with the development of wrist and forearm disorders (Malchaire et al., 1996), both in flexion-extension (Marras & Schoenmarklin, 1991, 1993; Malchaire et al., 1997) and in radioulnar deviation (Arvidsson., et al 2003). Marras and Schoenmarklin (1991, 1993) found that velocity and acceleration of the wrist in the sagittal plane were correlated to the development of wrist/hand disorders. They found a mean flexion velocity of 42°/s in the group considered to be at high risk for wrist/hand disorders, with an OR of 3.8 (95% CI was 1.5-9.6). A similar mean of 46°/s for the right wrist and 37°/s for the left wrist was found by Arvidsson et al. (2003). Of the 12 right handed volunteers in the Arvidsson et al. (2003) study, 25% were diagnosed with CTS and 67% had at least one of the specific symptoms for CTS. Hansson et al. (2000) found that workers engaged in "repetitive work" as judged by an experienced ergonomist were at high risk of injury and showed higher velocities (110°/s) than controls (71 – 93°/s). Also, Hansson et al. (2000) found significant differences in wrist posture in workers exposed to a high risk of injury due to the performance of repetitive job tasks as compared to a control group with non-repetitive job tasks. Thus, measurement of wrist postures and movements may be used to identify high-risk work tasks (Hansson et al. 2000).

Using a logistic regression model, Malchaire et al. (1997) found that the velocity of movement of flexion-extension was one of three major risk factors along with forces exerted by the wrist and hand and repetitiveness. They showed a significant association with the probability for development of wrist/hand disorders when the flexion velocity was greater than 50°/s. Malchaire et al. (1996) have also reported that wrist disorders were positively correlated with the percentage of time (42.7%) that wrist deviation exceeded 50% of the individual's maximum radioulnar deviation. In a follow up study it was found that the velocity of the motion of the wrist and not the angle of the wrist that posed the greater risk (Malchaire et al., 1996, Malchaire et al., 1997).

2.1.5 Relationship of muscle activity to risk factors

Electromyography (EMG) is used to evaluate muscle activity. EMG indicates which muscles are active and can be used to determine the relationship between muscle activity and worker capacity. Properly employed, EMG assists in evaluating the relative risks of working conditions. It is known that forearm and shoulder muscle activity is affected by several factors including posture, force, repetition and the nature of the exertion (MacDonell & Keir, 2005; Au & Keir, 2007; Laursen et al., 1998).

Posture has been shown to be a moderate risk factor of WMSD (NIOSH 1997), but has also been shown to increase muscle activity in the forearm. Mogk and Keir (2003a) found that flexing the wrist to 45° reduced the maximal grip force by 40-50% maximal voluntary grip force (MVG). They also found that the EMG remained elevated regardless of forearm posture. Both flexor and extensor muscle activity increased by simply holding the grip dynamometer especially when pronated and extended. Pronation of the forearm increased extensor activation while supination increased flexor activation due to gravitational effects. Another finding of this study was that the extensor muscles were more active than the flexors while holding the grip dynamometer without gripping to target levels; the "baseline" muscle activity of simply holding the tool reached 3-9% maximal voluntary exertion (MVE) especially in pronation. The authors suggested that "if the baseline is used to represent a continuous load during a work day, that the extensors would exceed suggested static load levels of 2 – 5% MVE" proposed by Jonsson (1978) with just the holding of the tool. The authors also suggested that the 10-14% MVE Jonsson (1978) set as the limit for intermittent or dynamic contractions could easily be surpassed when gripping a tool (Mogk & Keir, 2003a). Jonsson is one of the most-cited authors on specific quantitative thresholds for interpreting EMG data. In his 1978 article, he defined three levels of muscle load: static, dynamic and peak, based on the Amplitude Probability Distribution Function (APDF) (Jonsson 1978). The APDF is the distribution of the levels of muscle contraction during the observation period (Ankrum 2000). The graph can be used to identify the percentage of time that muscle activity was less than a given proportion of the person's maximum voluntary ability to use that muscle (maximum voluntary contraction (% MVC)) (Ankrum 2000).

Recent research examining the effects of multi-tasking found altered upper extremity muscle activity (MacDonell & Keir, 2005; Au & Keir, 2007). Concurrent performance of a submaximal (40% MVE) shoulder exertion and submaximal (30% MVE) hand grip increased forearm muscle activity by 2 – 4% MVE and decreased deltoid muscle activity by 2% MVE (Au & Keir, 2007). Also the addition of a grip (30% MVE) to a maximal shoulder effort decreased shoulder strength, while shoulder muscle activity did not change to the same extent (MacDonell & Keir, 2005). The findings of Au and Keir (2007) were small and significant, and could also be seen as important physiologically. Even small increases in muscle may be important over time as low continuous muscle activity has been suggested to produce muscle fatigue and injury (Aaras & Westgaard, 1987). It has also been found that applying a 30% grip force to a shoulder exertion (both static and dynamic) can elicit a redistribution of shoulder muscle activity from the deltoid group to the infraspinatus and biceps brachii (Antony, 2006). It appears that muscle forces, when transferred to the rotator cuff, may produce more injuries to the rotator cuff area (Antony, 2006).

In an associated study investigating grip, posture and an upper extremity push/pull task, it was found that there was no difference in shoulder muscle activity or force generation (Di Domizio, 2006). Di Domizio (2006) determined that adding a push or pull exertion to a grip task increased forearm extensor muscle activity. She speculated that the extensor muscles were activated to stabilize the wrist. Activation of antagonist forearm muscles (extensor muscles) to maintain a neutral wrist posture has previously been observed during gripping (Snijders et al., 1987). In terms of the forearm muscles, co-contraction of the extensor muscles has been found to be a control strategy to increase the joint stiffness in the wrist (De Serres & Milner, 1991; Snijders et al., 1987). Jonsson (1991) suggested that muscle coordination patterns during different postures and movements may have minor inter individual differences and that this may play an important role in identifying and preventing musculoskeletal injuries in workers. Physiological relationships and individual differences in the muscles of the upper extremity during work may be important in the development of WMSDs.

2.2 Ergonomic Assessment Methods for Occupational Tasks

The methods for assessing the risk of WMSD in the upper extremity each have their own advantages and limitations. RULA, "rapid upper limb assessment", is a screening tool that uses a posture matching checklist and requires no special equipment (McAtamney & Corlett, 1993). Although RULA provides a certain ease of use, it only assesses a single static posture and each of the posture categories has an element of subjectivity. While RULA includes "muscle" and "force" scores that are included, they are not necessarily physiologically based.

The Strain Index is another assessment tool for the distal upper extremity which is based on physiology, biomechanics, and epidemiology of distal upper extremity disorders. It is considered to be semi-quantitative and involves the measurement or estimation of six task variables: intensity of exertion, duration of exertion per cycle, efforts per minute, wrist posture, speed of exertion, and duration of tasks per day (Moore & Garg, 1994). The Strain Index is useful in jobs where there are complex distal upper extremity movements. Incorporating the concept of temporal patterns of exposure was one of the major developments within the Strain Index (Moore, 2002). The Strain Index predicts increased risk of distal upper extremity disorders in general (Moore & Garg, 1994) but it does not possess the ability to predict specific disorders (Moore, 2002).

In 2001, the American Conference of Governmental Industrial Hygienists (ACGIH) introduced a Threshold Limit Value (TLV) for Hand Activity Levels for mono-task hand tasks. The TLV for Hand Activity uses the Hand Activity Level (HAL) (Latko et al., 1997), a 10-point scale that includes the frequency of hand exertions and the duty cycle. It is based on epidemiological, psychophysical and biomechanical studies and is intended for similar sets of motion or exertions, referred to as monotasks, which are repeated for 4 or more hours per day (ACGIH, 2001). A study of 908 workers from 7 different job sites found that the prevalence of symptoms and specific disorders was substantial in jobs that were below the TLV action limit, suggesting that even at "acceptable" levels of hand activity many workers will still experience symptoms and/or upper extremity musculoskeletal disorders (Franzblau et al., 2005). The TLV does not attempt to integrate well known workplace risk factors for WMSD such as non-neutral postures, contact stresses, low temperatures or vibration (Franzblau et al., 2005), rather it suggests that professional judgment may be required to reduce the TLV below the action limit if one or more of the above risk factors are present. In addition the TLV is only intended for "mono-task" jobs which are defined as jobs that "involve performing a similar set of motions or exertions repeatedly" for more than 4 hours (ACGIH, 2001). This definition of a mono-tasks job is slightly restrictive, unclear, and may be hard to relate to the actual workplace. Although this tool has been questioned (O'Sullivan & Clancy, 2007), with better defined terms and more research to determine an "acceptable level" this tool can be more functional and can be used in a wider variety of jobs.

2.3 Summary

Work related musculoskeletal disorders of the upper extremity are a major concern in the workplace, but the precise etiology of UE WMSD has eluded researchers. Research has shown that there are risk factors to developing UE WMSD such as high repetition (Latko et al., 1999; Silverstein et al., 1986, Fransson-Hall et al., 1995), high force (Silverstein et al., 1986, Malchaire et al., 1997), non-neutral postures (Malchaire et al., 1996), angular velocities (Marras & Schoemarklin, 1993; Malchaire, 1997) and the combination of high force and high repetition (Moore et al., 1991; Silverstein, 1986). From the literature, high force, high repetition, and the combination of high force and high repetition appear to be very central in the development of UE WMSD. There are also findings to suggest that forearm and shoulder muscle activity is affected by several factors including posture, force, repetition and the nature of the exertions (MacDonell & Keir, 2005; Au & Keir, 2007; Laursen et al., 1998; Di Domizio, 2006). While risk factors have been identified, there are still gaps in the knowledge base for the development of UE WMSD. Consequently, there is a need to improve our understanding of force and repetition factors in the development of UE WMSD and how they can be incorporated into ergonomic assessment tools. In order to help further the understanding of the relationship between force and frequency, this thesis will examine the muscular response to force and frequency parameters as well as the addition of a concurrent grip.

2.4 Purpose

To quantify the effects of force, frequency and concurrent grip on muscle activity with implications for the prevention of workplace disorders of the upper extremity.

2.5 Hypotheses

1. The high load conditions will increase overall EMG activity of the upper extremity, and be proportional to load.

2. (a) Addition of a concurrent grip will increase forearm muscle activity in the extensor digitorum (ED), extensor carpi radialis (ECR), flexor digitorum superficialis (FDS) and flexor carpi radialis (FCR)
(b) Addition of a concurrent grip will decrease muscle activity in the shoulder muscles posterior deltoid (PD) and anterior deltoid (AD).

3. The muscular rest (gaps) will be inversely proportional to the task frequency, and therefore muscular rest will decrease with increases in frequencies.

Chapter 3 - Methods

Ten men and ten women participants were recruited from the McMaster University community. The protocol was approved by the McMaster Research Ethics Board (see Appendix A) and participants gave informed written consent. All participants were verbally screened for right hand dominance and no history of injury or pain in the upper extremity in the past year.

Participants performed a task that used the actions and forces recorded from actual auto parts assembly jobs, specifically a pushing and gripping task. To mimic the forces and action associated with automobile seat assembly, we constructed a custom dual track for pushing with a grip dynamometer (MIE Medical Research Ltd. Leeds, UK; mass = 0.45 kg; grip span = 5.25 cm) mounted on the right platform and a wooden post (grip span = 5.25 cm) on the left platform (Figure 1). Each handle was mounted on moveable platforms that were able to move with virtually no friction with ball bearings on the track. The handles moved forward on their own track and were not connected, thus they had independent motion. Weights were suspended by a cable and pulley system on the outside of the track and attached to the handle platforms on each side. The cable and pulley system allowed for the loads to be easily interchanged between tasks (note that the loads are hanging over the edge of the table out of view (Figure 1). These loads consisted of a bucket attached to the cable and pulley system and weights specifically designed for this study. Linear potentiometers were affixed to the handle platforms and were on the inside of the track. Linear potentiometers were used to monitor distance travelled and determine the position of the handle platforms. The track was affixed to an adjustable table to ensure that participants' elbows were at 90° for the testing start position (Figure 2).

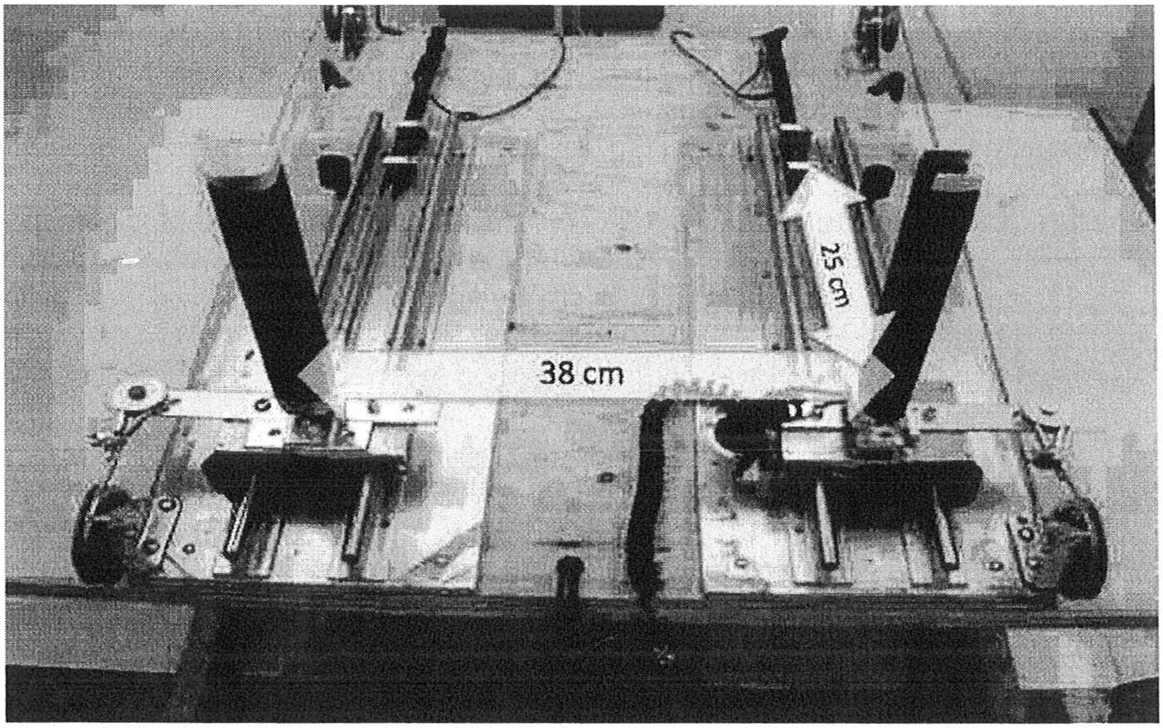


Figure 1. Dual track for pushing with grip dynamometer on right side and matching wooden post on left handle. Each track consisted of 2 rails with a linear potentiometer seen between rails

3.1 Protocol

Participants were required to attend one experimental session lasting approximately one hour. Prior to data collection, participants gave informed written consent. Mass, height, and ages were recorded and they were familiarized with the experimental tasks. Maximal voluntary grip force (MVG) was determined using the grip dynamometer on our setup in the start position (Figure 2). Participants were asked to ramp grip force up to their maximal grip and hold it while in the start position. MVG was found by taking an average in a 250 ms window about the peak force from a 10s trial. Two maximal trials were performed, if the peaks obtained were within 5% of each other, the two values were averaged. If the two trials were not within 5% of each other, addition trials were completed until the two trials were within 5% (occasionally 3 trials were required, one participant required 4 trials.

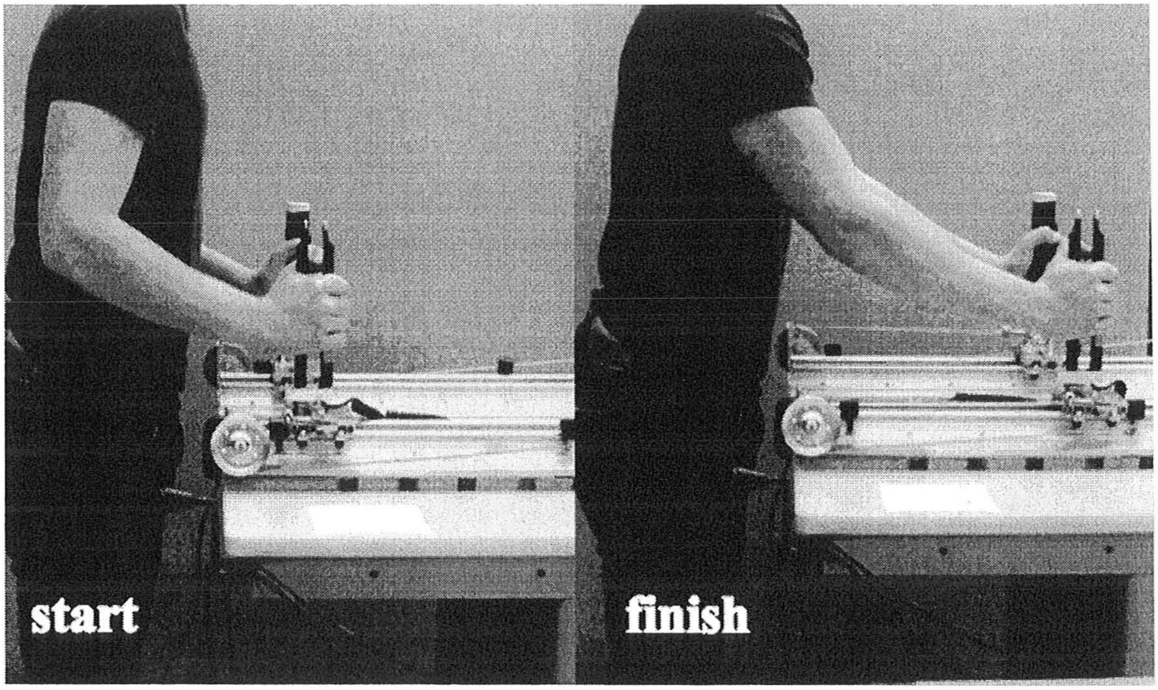


Figure 2. Participant posture at start (left) and finish (right) of push task. After the push the participants were instructed to simply allow the handles to return to the start position

Participants performed this bimanual push and gripping (right hand only) task with a combination of three force levels, three frequencies and two grip conditions for a total of 18 trials (Figure 3). Each trial was 120 s in duration with 120 s of rest provided between each. Force levels for each arm were low push load, 1 kg (9.8N), medium push load, 2 kg (19.6N), and high push load, 4 kg (39.2N). The push loads were chosen to replicate loads that were found in the automotive assembly plant but the frequency and loading profile were not directly taken from a specific task. The force levels were altered by changing premeasured weights in buckets attached to the cable and pulley system. The load included the full weight of the bucket and custom made weights. The premeasured weights were made of lead shot in sealed plastic containers. Push frequencies of 4/min, 8/min, and 16/min were chosen. The frequencies were chosen in include common definitions of low versus high repetition that are found in ergonomic assessment tools and the literature. The frequencies were emitted audibly with a computer metronome and presented via headphones. There were two grip conditions: no required grip and 30% MVG (right hand only), where participants followed visual feedback that displayed the target forces (30% MVG ±1.5%). All trials were presented in randomized order.

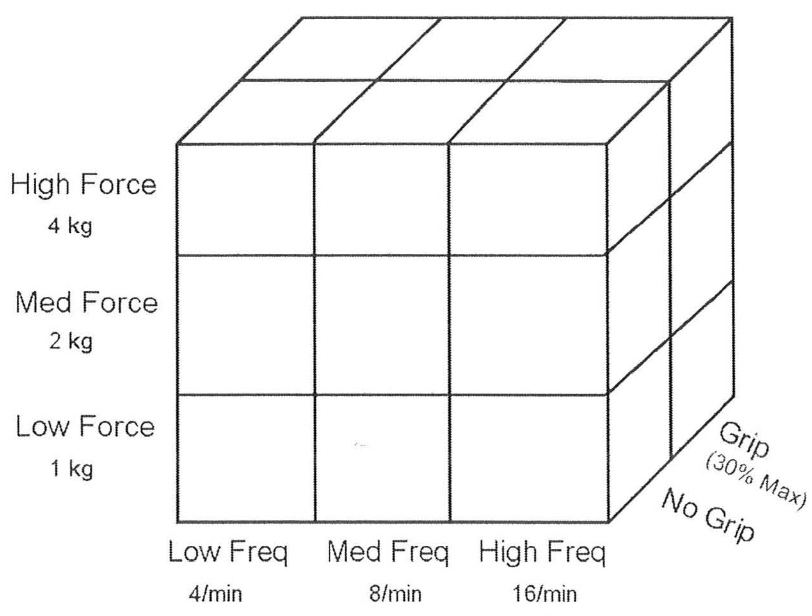


Figure 3. Experimental conditions (18 in total). Three force levels (1 kg, 2kg & 4kg), three frequencies (4/min, 8/min & 16/min) and two gripping conditions (no grip and 30% maximum)

Each participant was told the load level, the frequency and whether to apply a grip force. Participants were instructed at the sound of the metronome to grip (if grip was required), then to push both handles to the end of the track at which point the handle platforms hit a rubber stop placed at the end of the track. Once at the end of the track, the participants were instructed to release the grip (if grip was required) and allow the handles to return to the starting position (Figure 2). At the end of each trial, participants were asked to rate their perceived exertion on a scale from 0 – 10, with zero being no effort at all and ten being maximal exertion (Appendix B). Two isometric reference contractions were performed before and after the experiment to examine changes in electromyography. The two standardized contractions included: (i) right arm extended with right hand lightly gripping the grip dynamometer apparatus with grip dynamometer platform at end track, this position is to engage the forearm muscles (ii) same as above except with palmar side of hand above grip dynamometer approximately 3 cm to engage the anterior deltoid.

3.2 Data Collection

Surface EMG recording sites were shaved (if required) and cleansed with isopropyl alcohol before attaching, disposable Ag-AgCl surface electrodes (Meditrace, Kendall, MA, USA). The electrodes had an inter-electrode distance of 3 cm, and were affixed to the skin parallel to the muscle fibre orientation over the muscle bellies of eight muscles on the right upper extremity. The muscles that were monitored were posterior deltoid (PD), anterior deltoid (AD), biceps brachii (BB), triceps brachii (TB), extensor digitorum (ED), extensor carpi radialis (ECR), flexor digitorum superficialis (FDS) and flexor carpi radialis (FCR) on the right side. Following electrode placement, the subject performed a series of muscle specific isometric contractions to confirm electrode placement (Table 1). Calibration trials for each muscle were performed to obtain measures of maximal muscle activity (maximal voluntary excitation, MVE) with values used to normalize EMG signals to 100% maximum. Muscle activity was collected (AMT-8, Bortec Biomedical, AB, CAN: CMRR > 115 dB at 60 Hz, input impedance $\approx$ $10G\Omega$).

Table 1. Muscles of the upper extremity monitored. Actions, test contractions and electrode configuration. Adapted from Perotto (1994)

MUSCLE	ACTION	TEST CONTRACTION	ELECTRODE PLACEMENT
Anterior Deltoid (AD)	-shoulder abduction -transverse flexion -internal rotation	-resistance against shoulder flexion with elbow at 180° -resistance at wrist	-three fingers below the anterior margin of the acromion
Flexor digitorum superficialis (FDS)	-flexes the metacarpophalangeal proximal interphalangeal joints	-resistance against wrist flexion with fingers extended	-fully supinated
Flexor carpi radialis (FCR)	-flexes the wrist -radial deviates	-resistance against wrist flexion	-fully supinated -three to four finger breadths distal to the midpoint of a line connecting the medial epicondyle and biceps tendon
Extensor carpi radialis longus (ECRL)	-extends the wrist -radial deviates	-resistance against wrist extension	-fully pronated -two finger breadths distal to lateral epicondyle
Posterior Deltoid (PD)	-shoulder transverse extension -transverse abduction -external rotation	-resistance against external rotation with 90° elbow	-fully pronated -two fingers caudal to posterior margin of the acromion.
Extensor digitorum (ED)	-extends the metacarpophalangeal proximal and distal interphalangeal joints of the 2nd-5th digit. -extends wrist	-resistance against wrist extension with fingers extended	-fully pronated -four to five fingerbreadths distal to lateral epicondyle
Biceps brachii (BB)	-flexes elbow -supinates forearm	-resistance against flexion	-bulk of the muscle at mid-arm
Triceps brachii (TB)	-extends elbow	-resistance against elbow extension	-immediately posterior to the insertion of deltoid or deltoid tubercle

3.3 Data Analysis

Grip force data, potentiometer data and EMG were sampled at 2048 Hz using a custom made Labview program (Labview National Instruments, TX, US). After collection, raw EMG was full wave rectified and dual pass Butterworth filtered at 3 Hz low pass cut off. All EMG signals were normalized to maximum voluntary exertion (MVE) for each muscle. Average EMG (AEMG) was calculated for each muscle over the 120 s trials. Muscular rest was defined as gap time (Veiersted, 1990) and "gap time" was the sum of all periods when EMG $\leq$ 1% MVE for $\geq$ 0.2 s (Veiersted 1990) and presented as seconds per minute. Also, amplitude probability distribution functions (APDF) were calculated for the 120 s trials for each muscle. APDF is a method of profiling muscle loading throughout the duration of a given task. It is a cumulative probability that summarizes muscle activity over a period of time. The 10^{th}, 50^{th}, 90^{th} and 99^{th} percentile of the APDF were determined. Jonsson (1978) set out limits of 2-5% MVE for the 10^{th} percentile, 10-14% MVE for the 50^{th} percentile and 50-70% MVE for the 90^{th} percentile.

The AEMG, gap time and APDF were found using a custom MatLab (The MathWorks v 7.6) program. Grip force was filtered at 10 Hz and was normalized to maximum voluntary grip force (MVG).

For each muscle, a 3 (force) x 3 (frequency) x 2 (grip) x 2 (gender) repeated measures analysis of variance (ANOVA) was performed using SPSS (version 13.0 SPSS Inc, Chicago, IL) to determine the effect of the force level, frequency and concurrent grip on upper extremity EMG with significance set at $\alpha = 0.05$. A separate ANOVA was performed for each of the dependent variables, AEMG, muscular rest, and APDF (10^{th}, 50^{th} an d 90^{th} percentile). Significant main effects and interactions were further analyzed using a Tukey's honestly significant difference (HSD) post hoc test.

Chapter 4 – Results

Ten men and ten women subjects participated in this study. Data from one women was removed from the analysis due to technical difficulties with the EMG. Table 2 shows the anthropometrics and maximum grip force for the remaining nineteen participants. An adjusted table was used to ensure an approximate elbow flexion of 90° and the mean table height was 92.3 cm (± 4.7 cm).

Table 2. Participant information (n=19 ♂ = 10 ♀ =9). Sex, age, height, mass and maximum grip force.

Subjects #	*Sex*	*Age*	*Height (cm)*	*Mass (kg)*	*Max grip (N)*
1	male	25	175	78.0	767
2	male	38	175	78.2	579
3	male	29	176	62.0	580
4	male	22	182	87.6	587
5	male	37	179	82.8	790
6	male	26	182	88.6	678
7	male	28	179	79.7	493
8	male	23	194	101.0	715
9	male	29	179	85.7	626
10	male	20	169	100.6	483
Mean		**27.7**	**179.5**	**84.4**	**629.8**
Std Dev		**6.0**	**6.8**	**11.4**	**95.4**
11	female	26	155	71.9	347
12	female	24	174	70.2	301
13	female	19	173	70.0	327
14	female	26	169	67.0	395
15	female	19	165	59.8	327
16	female	22	160	57.7	267
17	female	28	152	45.7	263
18	female	24	173	61.7	391
19	female	25	172	75.9	383
Mean		**23.7**	**165.9**	**64.4**	**333.5**
Std Dev		**3.1**	**8.4**	**9.2**	**50.2**
Overall Mean		**25.8**	**172.8**	**75.0**	**481.7**
Std Dev		**5.1**	**9.9**	**14.4**	**173.3**

4.1 Grip Force

Participants were consistent in producing the 30% grip force during the pushing task. The participants followed a visual feedback that displayed the target forces, 30% MVG ±1.5% (28.5% to 31.5%). The mean grip force was 28.5% (SD 2.4%) of grip maximum, thus they targeted the lower limit. During the "no grip" trials the grip force recorded was between 1% and 2% maximum, being marginally higher in the 4 kg push condition (Figure 4).

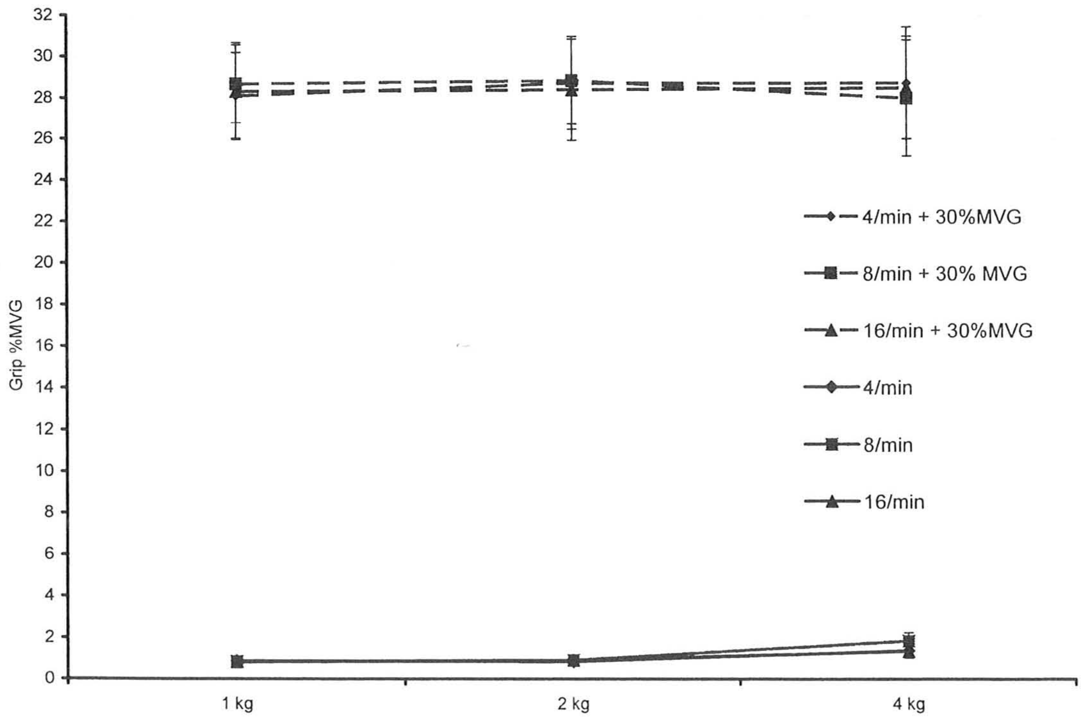


Figure 4. Mean relative grip force in % MVG (± standard deviation).

The 50th or median percentile of the grip force increased when the participants were required to grip during the high frequency condition (12% MVG) as compared to the low (1.4% MVG) or medium (4% MVG) frequency in the high load condition (Figure 5). There was an increase in the 99th percentile value in the 30% MVG conditions as the frequency increased. Averaging across the loads, the 99th percentile for the low frequency condition was 32.6%, 33.4% for the medium frequency and 36.3% for the high frequency condition.

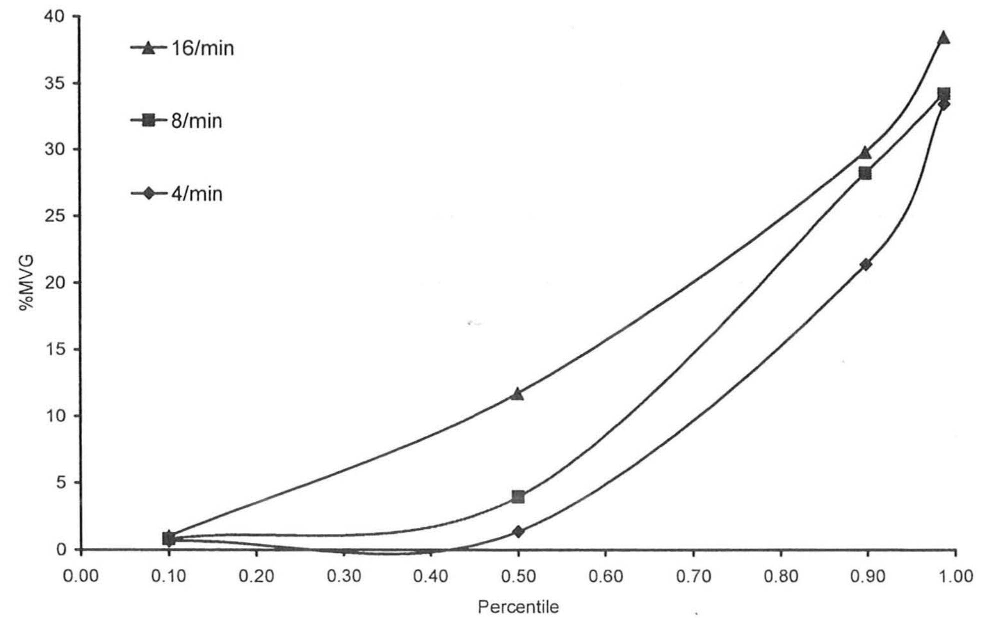


Figure 5. APDF of grip force reconstructed from 4 points (10th, 50th, 90th and 99th percentiles) for the high load condition with 30% grip for all participants

4.2 Muscle Activity

A gender effect was seen in the anterior deltoid during the push task (all $F_{1, 17} > 72.1$, $p < 0.001$). Posterior deltoid and triceps brachii had gender effects as well but because of their small % MVE values were pooled across gender. All the remaining muscles (BB, ED, ECR, FDS and FCR) were also pooled across gender.

Overall there was an increase in the mean muscle activity due to the effect of load and frequency (Table 3). In general, the increasing load levels caused an increase in mean muscle activity. However, the doubling effect that the load levels were expected to cause was not seen; for example, the medium load (2kg) did not produce a mean muscle activity that was double that of the low load level (1kg). The frequency had a similar pattern, where there was an increase in mean muscle activity with the increasing of the frequency (4/min → 8/min → 16/min), but there was not the double effect that might have been expected. Upon addition of the grip we found a different pattern, especially in the forearm where the load no longer had an effect on the mean muscle activity of the forearm muscles. The grip also appeared to enhance the effect of increasing frequency, mostly in the forearm muscles.

The amplitude probability distribution function (APDF) of the muscle activity in the upper extremity (Table 4) shows that only the high frequency, gripping trials produced results that were above the limits set out by Jonsson (1978) (2-5% for the 10^{th} percentile, 10-14% for the 50^{th} percentile and 50-70% for the 90^{th} percentile).

The AEMG appears to reflect workload rather than force or frequency per se. Although not systematically investigated, a relationship of AEMG to workload appears as a distinct pattern (Table 3). For example, combining load and frequency (multiplying) in the non-gripping trials, the AEMG (for all muscles) of 16/min at 1kg is similar to the AEMG of 8/min at 2kg and the AEMG of 4/min at 4kg. Thus AEMG is consistent at a "workload" of 16 kg/min. This pattern exists for other AEMG workload levels as well (e.g.. 8 kg/min, 32kg/min). The same pattern seen in the gripping trials for the non-gripping muscles (PD, AD, BB, TB). However, a different pattern appears in the forearm muscles. The forearm muscles in the 16/min at 1kg trial were higher than the forearm muscle activity in the 4/min at 4kg trials. The ED AEMG for the 16/min at 1kg trial was 14% MVE, at 8/min and 2 kg the activity was 8.9% MVE and at the 4/min at 4kg the activity was 6.7% MVE.

Table 3. AEMG for all muscles in all conditions with standard deviations. (Three load levels, three frequency levels and two gripping conditions). Posterior deltoid (PD), anterior deltoid (AD), biceps brachii (BB), triceps brachii (TB), extensor digitorum (ED), extensor carpi radialis (ECR), flexor digitorum superficialis (FDS) and flexor carpi radialis (FCR).

Frequency	*4/min*	*8/min*	*16/min*	*4/min*	*8/min*	*16/min*
		No grip			*30% MVG*	
			1 kg			
PD	1.5 (0.8)	1.8 (1.0)	2.2 (1.3)	1.5 (0.9)	1.9 (1.3)	3.6 (3.6)
AD	2.8 (4.7)	3.9 (5.5)	5.8 (6.7)	2.4 (4.0)	3.6 (4.9)	7.6 (9.3)
BB	0.9 (0.7)	1.0 (0.7)	1.4 (0.9)	1.0 (0.9)	1.3 (1.1)	2.6 (2.3)
TB	1.3 (0.9)	1.5 (1.1)	2.1 (2.0)	1.3 (1.2)	1.8 (1.8)	3.6 (4.0)
ED	2.1 (1.9)	2.8 (2.0)	3.4 (2.2)	5.2 (7.1)	8.3 (9.4)	14.0 (11.3)
ECR	2.0 (1.1)	2.0 (1.3)	2.4 (1.5)	5.3 (8.5)	10.2 (12.9)	17.4 (17.0)
FDS	1.7 (1.0)	2.0 (1.2)	2.4 (1.6)	7.3 (11.2)	12.4 (15.6)	21.3 (18.6)
FCR	1.6 (0.8)	1.7 (0.8)	2.2 (1.4)	2.7 (2.6)	3.9 (3.7)	7.2 (6.0)
			2 kg			
PD	1.7 (1.2)	1.9 (1.4)	2.3 (1.6)	1.7 (1.4)	2.2 (1.9)	3.1 (2.1)
AD	3.2 (5.6)	4.9 (7.1)	7.8 (8.5)	3.2 (5.9)	5.5 (8.0)	9.7 (9.5)
BB	1.1 (1.0)	1.2 (1.1)	1.7 (1.4)	1.3 (1.4)	2.0 (2.2)	2.7 (2.16)
TB	1.3 (0.9)	1.7 (1.3)	2.4 (2.0)	1.5 (1.4)	2.0 (2.0)	3.0 (2.6)
ED	3.0 (2.4)	4.0 (2.9)	5.2 (2.6)	5.8 (7.8)	8.9 (10.0)	14.5 (11.6)
ECR	2.4 (1.8)	2.8 (2.0)	3.4 (1.8)	5.5 (9.1)	8.8 (11.7)	15.0 (14.8)
FDS	2.5 (1.8)	2.7 (2.0)	4.0 (1.8)	7.9 (12.3)	12.6 (15.5)	19.5 (18.9)
FCR	1.7 (1.0)	1.9 (1.2)	2.4 (1.4)	2.9 (2.9)	4.3 (4.0)	6.4 (4.7)
			4 kg			
PD	2.2 (2.3)	3.1 (3.4)	4.1 (3.7)	2.3 (2.9)	3.3 (3.2)	4.6 (4.0)
AD	4.9 (9.6)	8.6 (13.4)	13.8 (15.5)	5.5 (11.0)	9.3 (14.0)	15.1 (16.9)
BB	1.7 (2.4)	2.7 (3.5)	3.3 (3.4)	2.2 (3.4)	3.3 (4.2)	4.7 (4.6)
TB	1.8 (1.6)	2.3 (2.2)	3.4 (3.0)	1.9 (2.0)	2.5 (2.5)	4.1 (3.7)
ED	3.0 (3.1)	5.4 (4.4)	6.7 (4.1)	6.7 (9.5)	11.2 (11.3)	15.9 (11.9)
ECR	2.0 (2.1)	3.4 (3.1)	4.0 (2.9)	5.9 (10.0)	11.3 (14.4)	17.3 (16.7)
FDS	2.1 (1.6)	3.0 (2.0)	3.7 (2.4)	8.1 (12.6)	13.8 (16.1)	21.0 (18.5)
FCR	1.9 (1.4)	2.4 (1.8)	2.8 (2.0)	3.2 (3.5)	4.8 (4.1)	6.7 (4.8)

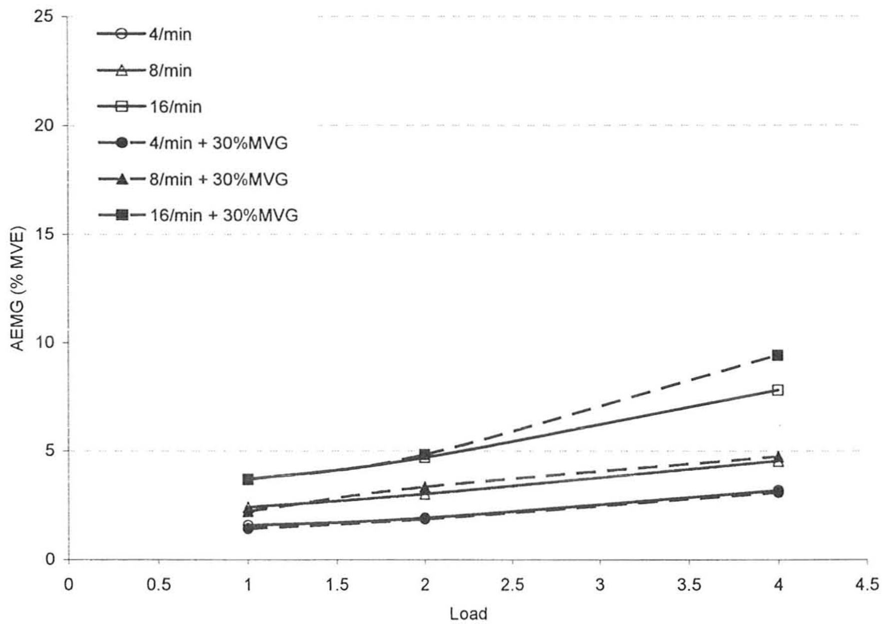
Table 4. APDF data for all muscles in all conditions (10^{th}, 50^{th} and 90^{th} percentiles). The values highlighted (in bold) are values that are above the limits set out by Jonsson (1978) for 10^{th} percentile (2-7%), 50^{th} percentile (10-14%) and 90^{th} percentile (50-70%). (Standard deviations may be found in Appendix C)

No Grip									
Frequency		*4/min*			*8/min*			*16/min*	
	10th	*50th*	*90th*	*10th*	*50th*	*90th*	*10th*	*50th*	*90th*
1 kg									
Post Del	0.7	1.3	2.8	0.9	1.5	3.7	0.9	1.9	4.8
Ant Del	0.7	1.3	6.7	0.8	1.5	14.1	0.9	3.2	19.2
Biceps	0.4	0.9	2.0	0.5	1.0	2.5	0.6	1.3	3.4
Triceps	0.8	1.5	2.6	0.8	1.4	3.0	0.9	1.9	5.2
ED	0.8	1.5	2.9	1.0	2.2	5.6	1.1	2.6	6.2
ECR	0.9	1.4	2.5	0.6	1.2	2.9	0.6	1.4	3.6
FDS	0.9	1.4	2.7	0.8	1.6	3.4	1.0	1.9	4.8
FCR	0.7	1.6	2.8	0.9	1.5	2.7	0.9	1.8	4.2
2 kg									
Post Del	0.5	1.4	2.7	0.8	1.5	3.3	0.7	1.6	4.0
Ant Del	0.8	1.9	7.2	0.7	1.5	13.2	1.0	3.3	17.9
Biceps	0.5	1.2	3.3	0.6	1.3	6.5	0.7	1.8	7.9
Triceps	0.8	1.3	3.0	1.0	1.7	6.2	1.0	2.0	8.8
ED	0.6	1.5	3.7	0.9	2.1	6.5	1.0	2.4	7.5
ECR	0.5	1.4	2.7	1.1	1.8	3.6	0.9	1.7	4.0
FDS	0.9	2.0	3.5	1.0	2.0	4.1	1.0	2.3	5.0
FCR	1.0	1.8	3.0	1.0	1.8	3.7	1.0	2.2	4.6
4 kg									
Post Del	0.9	1.5	3.5	0.8	1.7	6.3	1.1	2.2	8.0
Ant Del	1.0	1.8	10.4	0.9	1.9	23.2	0.9	4.8	30.7
Biceps	0.9	1.6	6.1	0.8	1.7	10.9	0.8	2.9	13.2
Triceps	0.6	1.5	3.8	1.1	2.1	7.9	1.0	2.1	10.6
ED	0.7	1.7	5.7	1.1	2.9	11.0	1.4	4.1	11.8
ECR	0.8	1.5	3.7	0.8	1.8	6.5	0.8	2.3	6.1
FDS	0.8	1.9	4.3	1.0	2.5	10.5	1.2	3.0	6.6
FCR	1.2	1.8	3.9	1.0	1.9	5.9	1.2	2.4	6.0
30% Maximum Grip									
Frequency		*4/min*			*8/min*			*16/min*	
	10th	*50th*	*90th*	*10th*	*50th*	*90th*	*10th*	*50th*	*90th*
1 kg									
Post Del	1.0	1.4	2.6	0.7	1.6	4.2	1.1	2.2	10.6
Ant Del	0.8	1.4	6.9	0.8	1.7	13.6	1.2	4.2	23.8
Biceps	0.6	1.1	2.7	0.4	1.1	3.3	0.9	2.3	7.0
Triceps	0.8	1.3	2.5	0.8	1.7	4.4	1.0	2.4	10.8
ED	1.1	2.3	17.4	1.1	3.1	23.2	1.9	**13.0**	29.4
ECR	0.8	1.6	18.2	0.8	2.3	29.5	1.2	**14.0**	34.7
FDS	1.1	2.6	26.4	1.0	2.9	34.1	1.3	**17.3**	38.5
FCR	1.2	2.2	8.2	1.1	2.4	10.3	1.9	6.8	16.9
2 kg									
Post Del	0.9	1.4	2.8	1.0	1.5	4.4	1.1	2.1	5.2
Ant Del	0.7	1.2	7.5	1.0	1.9	16.1	1.0	4.7	21.2
Biceps	0.5	1.2	3.3	0.6	1.4	5.5	0.8	2.2	5.7
Triceps	0.7	1.3	2.7	0.9	1.6	4.8	1.4	2.4	6.7
ED	0.9	2.0	17.9	1.2	4.0	22.4	1.9	**12.4**	27.4
ECR	0.8	2.2	17.9	0.9	3.5	24.4	0.7	9.8	32.0
FDS	1.1	2.7	27.7	1.1	5.4	34.6	1.2	**15.0**	42.1
FCR	1.4	2.3	8.5	1.3	3.3	11.5	1.8	6.0	14.1
4 kg									
Post Del	0.9	1.7	4.3	1.0	2.1	6.7	1.2	2.8	9.3
Ant Del	0.9	2.4	15.4	1.0	1.8	27.5	1.1	6.6	37.7
Biceps	0.4	1.1	6.9	0.6	1.8	10.1	0.9	3.6	11.8
Triceps	0.9	1.5	3.6	1.0	1.7	5.7	1.2	2.7	9.0
ED	1.1	2.4	21.7	1.4	5.9	25.4	**2.1**	**14.0**	29.1
ECR	0.6	1.7	20.4	1.5	5.5	32.9	0.9	**13.7**	37.4
FDS	1.1	2.6	29.0	1.3	7.2	37.9	1.5	**19.2**	42.9
FCR	0.9	2.1	9.6	1.3	3.9	12.8	1.7	6.8	14.5

4.2.1 Anterior deltoid

There was a 4-way, load x frequency x grip x gender interaction in the anterior deltoid (AD), ($F_{4, 68} = 3.03$, $p < 0.023$) (Figure 6). Muscle activity changed with gender, the male participants had lower activity compared to female participants at the same load. At the high load level, males and females showed a different pattern in the AEMG. This can be seen by comparing Figure 6a and 6b. For the same frequency there was a gender difference such that the female participants had higher muscle activity (Figure 6b). For the low frequency condition (4/min) the mean muscle activity of the males was 2.1% MVE and the mean muscle activity of the females was 5.4% MVE. For the medium frequency condition (8/min) the mean muscle activity of the males was 3.4% MVE and the mean muscle activity of the females was 9.1% MVE For the high frequency condition (16/min) the mean muscle activity of males was 5.7% MVE and the mean AEMG of the females was 15.2% MVE.

a)



b)

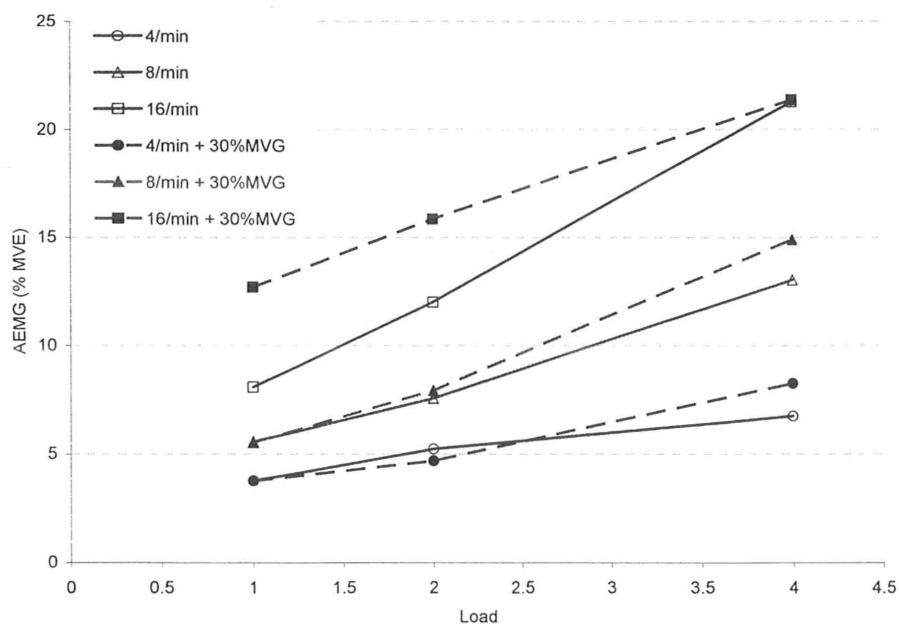


Figure 6. Mean anterior deltoid (AD) AEMG (% MVE) for all conditions: a) Males and b) Females

In contrast to the AEMG results, the muscular rest showed no main effect for gender ($F_{1, 17} = 3.2$, $p < 0.092$) in the AD muscular rest (gap time in seconds per minutes) (Figure 7). There was a significant interaction in the AD muscular rest, frequency x grip ($F_{3, 34} = 4.04$, $p < 0.03$). The high frequency condition intensifies the effect of the addition of gripping (Figure 7).

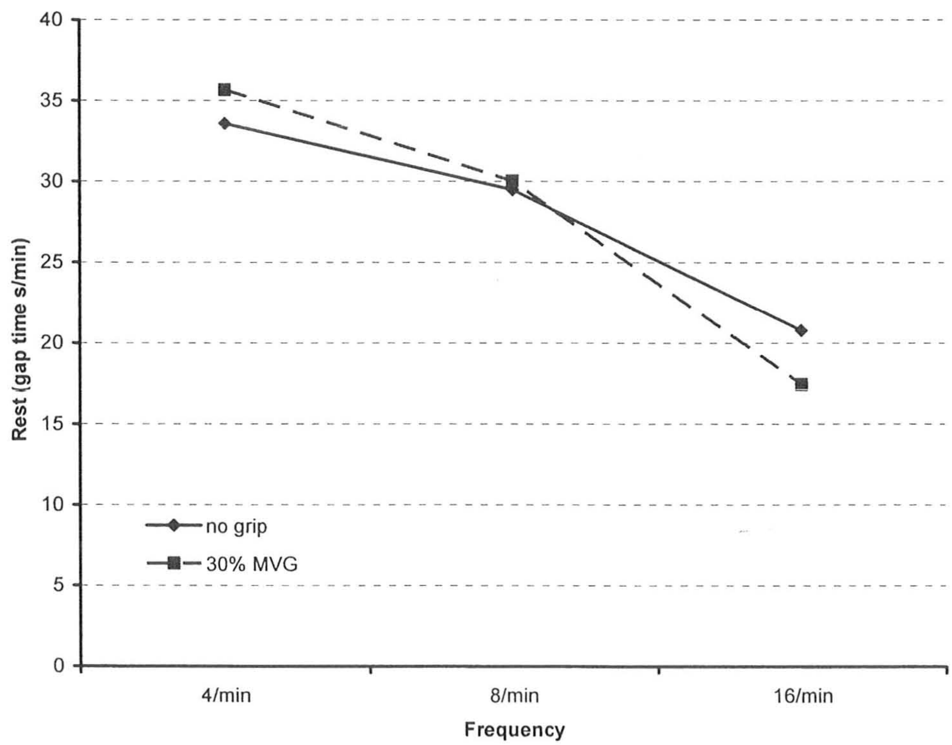


Figure 7. Muscular rest (gap time in s/min) for the anterior deltoid. (AD).

The amplitude probability distribution function (APDF) of the anterior deltoid (AD) showed that for the 10^{th} percentile, there was a load x frequency x grip x gender interaction ($F_{4, 68} = 2.95$, $p < 0.03$). The 90^{th} percentile of the APDF of the AD showed a load x frequency x gender interaction ($F_{4, 68} = 2.88$, $p < 0.029$) None of the APDF data for the AD reached the limits set by Jonsson (1982) of 2-5% for the 10^{th} percentile, 10-14% for the 50^{th} percentile and 50-70% for the 90^{th} percentile.

4.2.2 Posterior deltoid

For the posterior deltoid (PD) all AEMG were under 5% MVE. There were no interactions with the PD AEMG but main effects for load ($F_{2, 34} = 16.92$, $p < 0.001$), frequency ($F_{2, 34} = 14.14$, $p < 0.001$) and grip ($F_{2, 34} = 4.49$, $p < 0.05$). The load, frequency and the addition of gripping all increased mean muscle activity.

4.2.3 Biceps brachii

The AEMG of the biceps brachii (BB) was under 5% MVE for all trials. Even with this low activity level, there were interactions for the frequency x grip ($F_{2, 34} = 9.10$, $p < 0.001$) (Figure 8). Grip increased the AEMG and the high frequency (16/min) condition caused a larger effect.

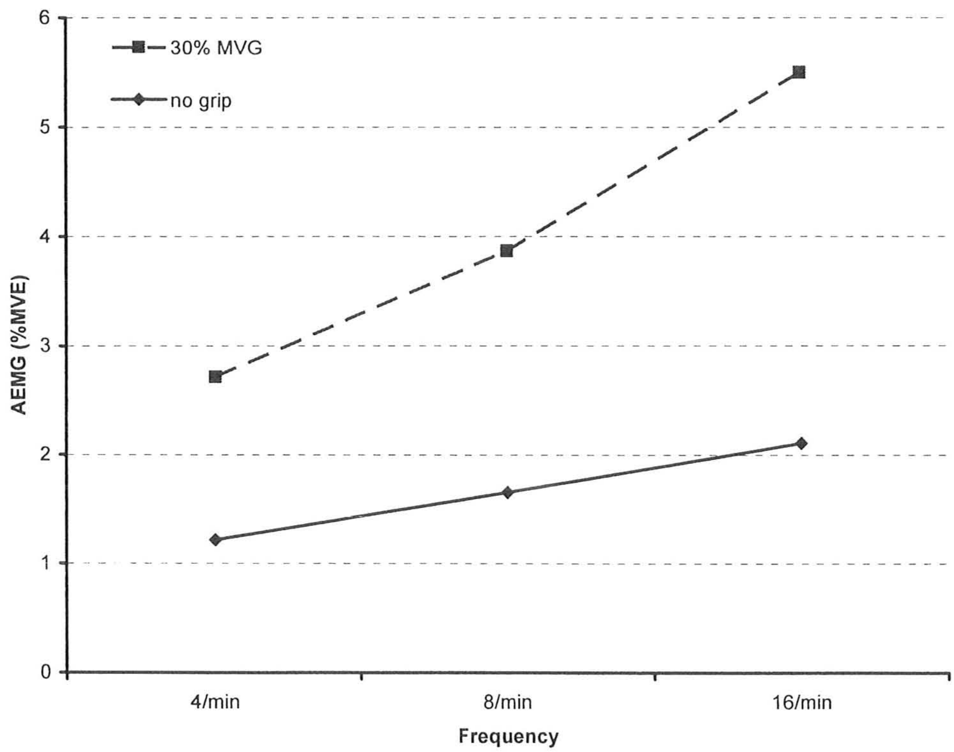


Figure 8. Average EMG (AEMG) (%MVE) of the biceps brachii (BB).

4.2.4 Triceps brachii

The AEMG of the triceps brachii (TB) was also under 5% MVE. Main effects of load ($F_{2, 34} = 15.03$, $p < 0.001$), frequency ($F_{2, 34} = 13.98$, $p < 0.001$) and grip ($F_{1, 17} = 6.3$, $p < 0.02$) were found. The load, frequency and the addition of gripping all produced increases in the mean muscle activity.

4.2.5 Extensor digitorum

In the extensor digitorum (ED) there was a significant interaction for frequency x grip ($F_{2, 34} = 68.62$, $p < 0.001$). In the ED the grip amplified the effect of frequency on the AEMG (Figure 9). For example in the non-gripping trials the AEMG was 2.6%, 4.0% and 4.4% for the low, medium and high frequency conditions respectively and for the gripping trials the muscle activity was 6%, 9.6% and 15%. In the high frequency condition there was a greater than 3 times increase in muscle activity in the ED with the addition of concurrent grip. There was also an interaction for load x frequency ($F_{2, 34} = 2.82$, $p = 0.031$). The load x frequency interaction becomes clear when looking at the medium load to high load condition because the effect of load (from medium load to high load) is heightened by the frequency conditions.

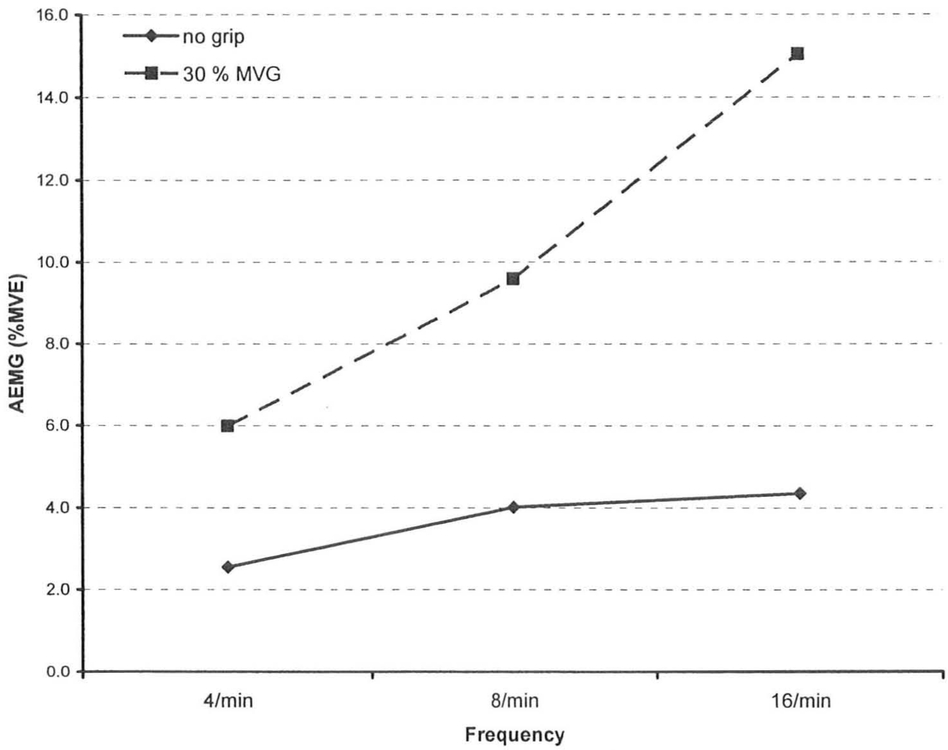


Figure 9. Average EMG (AMEG) (%MVE) of the extensor digitorum (ED)

The muscular rest (gap time) of the ED was also affected by frequency, load and grip. There were no interactions for gap time in the ED, but there were main effects for load ($F_{2, 34} = 6.91$, $p < 0.003$), frequency ($F_{2, 34} = 23.09$, $p < 0.001$) and grip ($F_{1, 17} = 6.14$, $p < 0.024$). The load, frequency and the addition of the gripping, all produced a decrease in the muscular rest.

The 10th percentile EMG of the ED demonstrated a frequency x grip interaction ($F_{2, 34} = 8.659$, $p < 0.001$). The grip increased the 10th percentile value, with an amplifying effect created by the increase in frequency. The 10^{th} percentile EMG of the ED was within the proposed 2-5% limit (Jonsson 1982). In the 30% grip, high load, high frequency condition, the 10^{th} percentile value was 2.1%. The 90^{th} percentile values for the ED followed the same pattern as the 10^{th} percentile values, with a frequency x grip interaction ($F_{2, 34} = 8.659$, $p < 0.001$). The grip increased the 90^{th} percentile value and again there was an amplifying effect created by the increase in frequency. A main effect of load ($F_{2, 34} = 19.62$, $p < 0.001$) was found for the 90^{th} percentile ED. None of the 90^{th} percentile APDF data for the ED reached the limits set by Jonsson (1978) of 50-70% for the 90^{th} percentile.

4.2.6 Extensor carpi radialis

The extensor carpi radialis (ECR) also showed a significant interaction between grip x frequency ($F_{2, 34} = 19.70$, $p < 0.001$). This grip x frequency interaction again showed that frequency heightened the effect of the grip. There was one interaction for the muscular rest in the ECR, load x grip ($F_{2,34} = 4.81$, $p < 0.015$). In the ECR during the no gripping trials, the high load condition affected the muscular rest (low load = 29.2s/min, med load = 26.2s/min and high load = 21.5s/min) and in the gripping trials the load did not affect the grip at all (low load = 15.6s/min, med load = 16.7s/min and high load = 15.7s /min).

4.2.7 Flexor digitorum superficialis

The effects of grip and frequency continue in the flexor muscles of the forearm. There was an interaction for frequency x grip ($F_{2, 34} = 9.96$, $p < 0.001$), there is a clear pattern of gripping (Figure 10) in the FDS. The high frequency condition produces an enhanced effect of gripping.

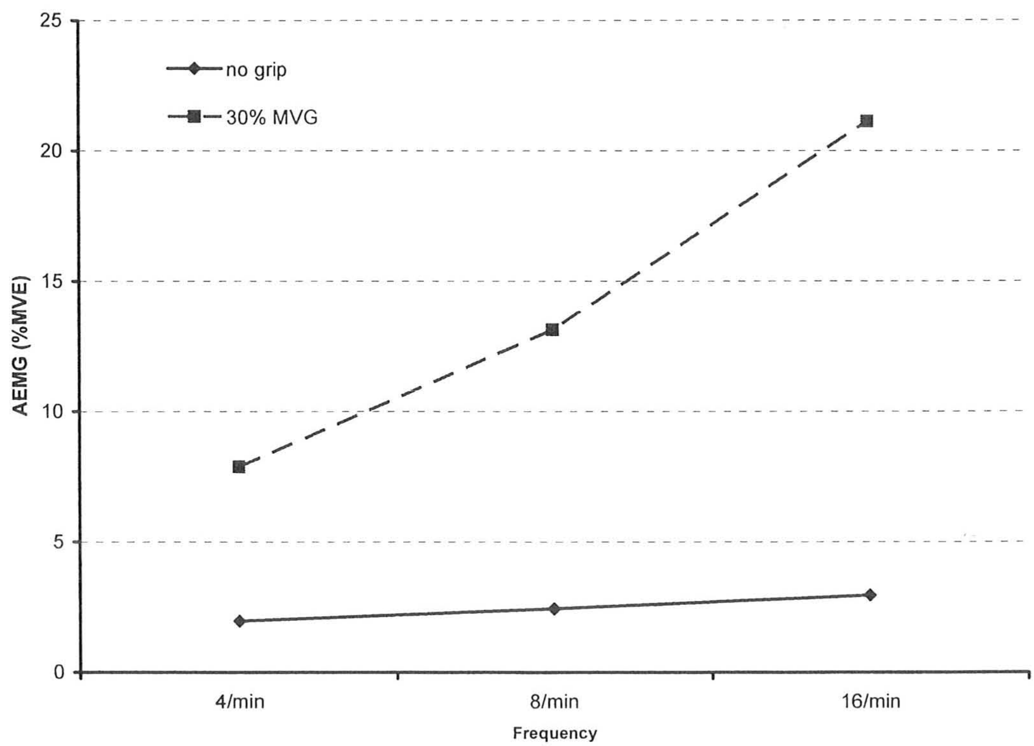


Figure 10. AEMG (%MVE) of the flexor digitorum superficialis (FDS).

The effects of frequency and gripping hold true when looking at the muscular rest (gap time (s)/min) of the FDS (Figure11). The gap time shows that there is a significant interaction between frequency and grip ($F_{2, 34} = 5.15$, $p < 0.011$); again we find that the addition of grip caused decreases in the muscular rest and the high frequency condition amplifies this effect of gripping.

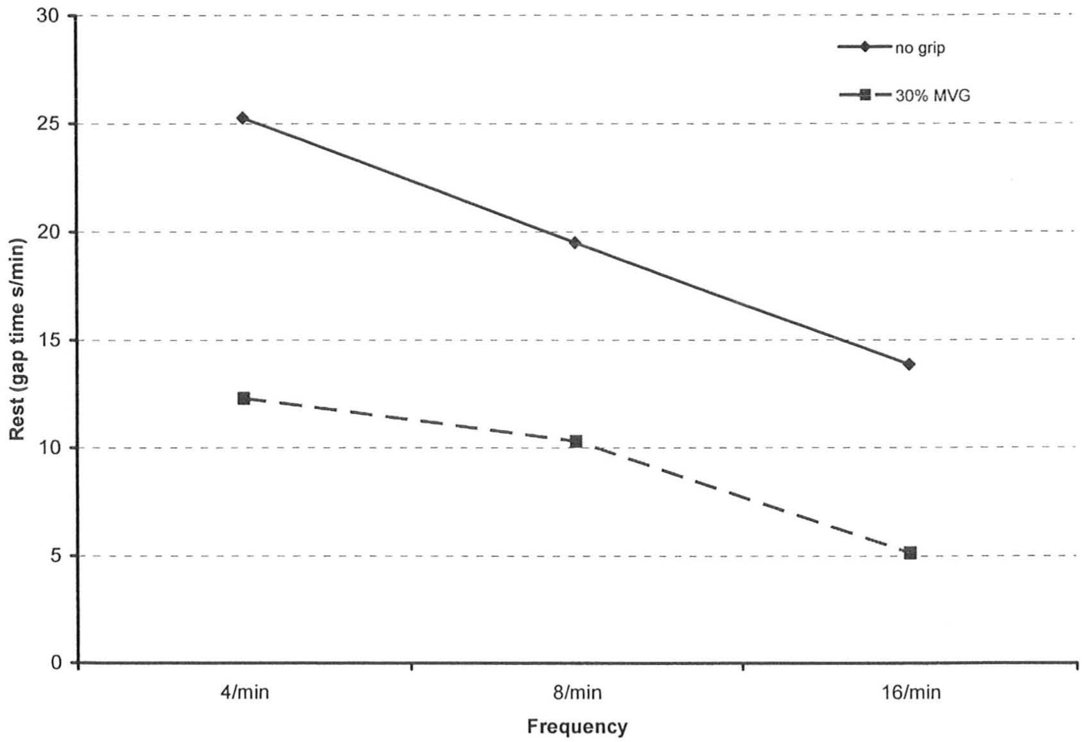


Figure 11. Muscular rest (gap time in s/min) for the flexor digitorum superficialis (FDS)

4.2.8 Flexor carpi radialis

The FCR had very low level of activation; in all trials it was less than 2%. Nevertheless the FCR still had a significant interaction for frequency x grip ($F_{2, 34} = 18.94$ $p < 0.012$). The gap time showed that there was a significant three way interaction of load x frequency x grip ($F_{4,68} = 3.00$, $p < 0.024$). The muscular rest was affected by the grip at all load and frequency levels and by the high load condition, the high frequency condition without grip.

4.3 Rate of perceived exertion (RPE)

The rate of perceived exertion (RPE) was taken after each trial. These data showed a large difference between men and women. The increase in load appeared to affect women more than men (Figure 12 a &16b). Both genders appeared to adjust their RPE score with the addition of concurrent grip. Men reported a disproportional number of "0" and "1" values.

Table 5 – Overall rate of perceived exertion (RPE) means (SD) for all conditions.

	0% MVG			30% MVG		
Frequency	4/min	8/min	16/min	4/min	8/min	16/min
1 kg	0.3 (0.3)	0.5(0.6)	0.7 (0.6)	0.9 (0.7)	1.4 (0.9)	2.3 (1.6)
2 kg	0.9 (0.8)	1.0 (0.9)	1.1 (0.9)	1.4 (1.0)	1.7 (1.0)	3.9 (6.9)
4 kg	1.8 (1.2)	2.3 (1.7)	3.1 (1.9)	2.3 (1.6)	2.6 (1.5)	3.9 (1.8)

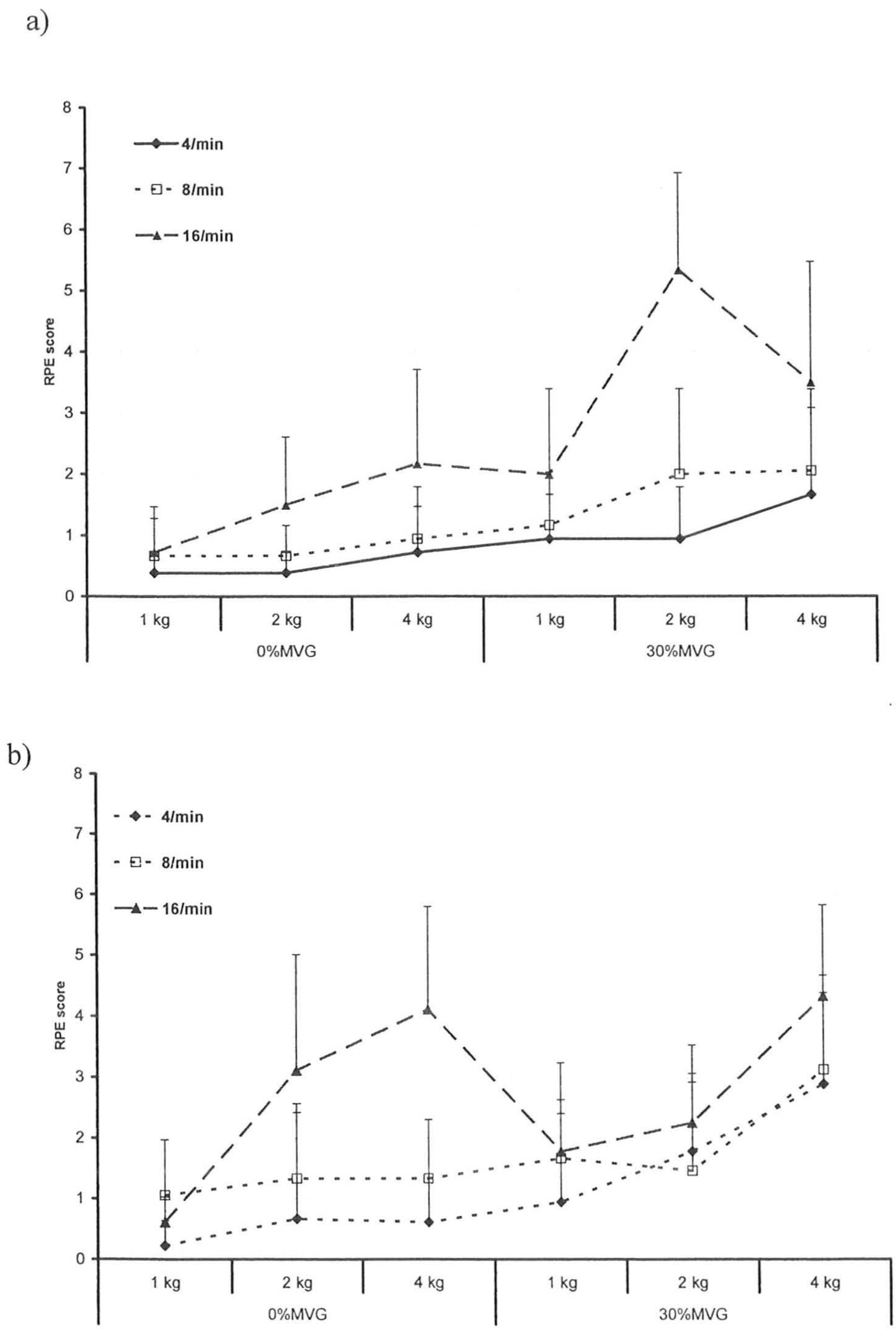


Figure 12. Rate of Perceived Exertion (RPE) scores for a) males and b) females

Chapter 5 - Discussion

Upper extremity muscle activity was examined during a dynamic cyclic task to identify the effects of force, frequency and concurrent gripping. This is the first study to examine EMG of the upper extremity muscles in a force and frequency controlled task with gripping. The protocol used actions and forces recorded from actual auto parts assembly jobs. In general, increasing the levels of load and frequency increased the mean muscle activity. Tasks involving simultaneous performance of the push exertion and grip task showed specific increases in forearm muscle activity depending on the frequency of the task, and to a lesser extent, the load level (Figure 13). Our dynamic pushing and gripping task also affected shoulder muscle activity (Figure 13). As seen in the figure below, the muscle activity of the anterior deltoid increased with an increase in force, frequency and it also increased with the addition of a concurrent grip.

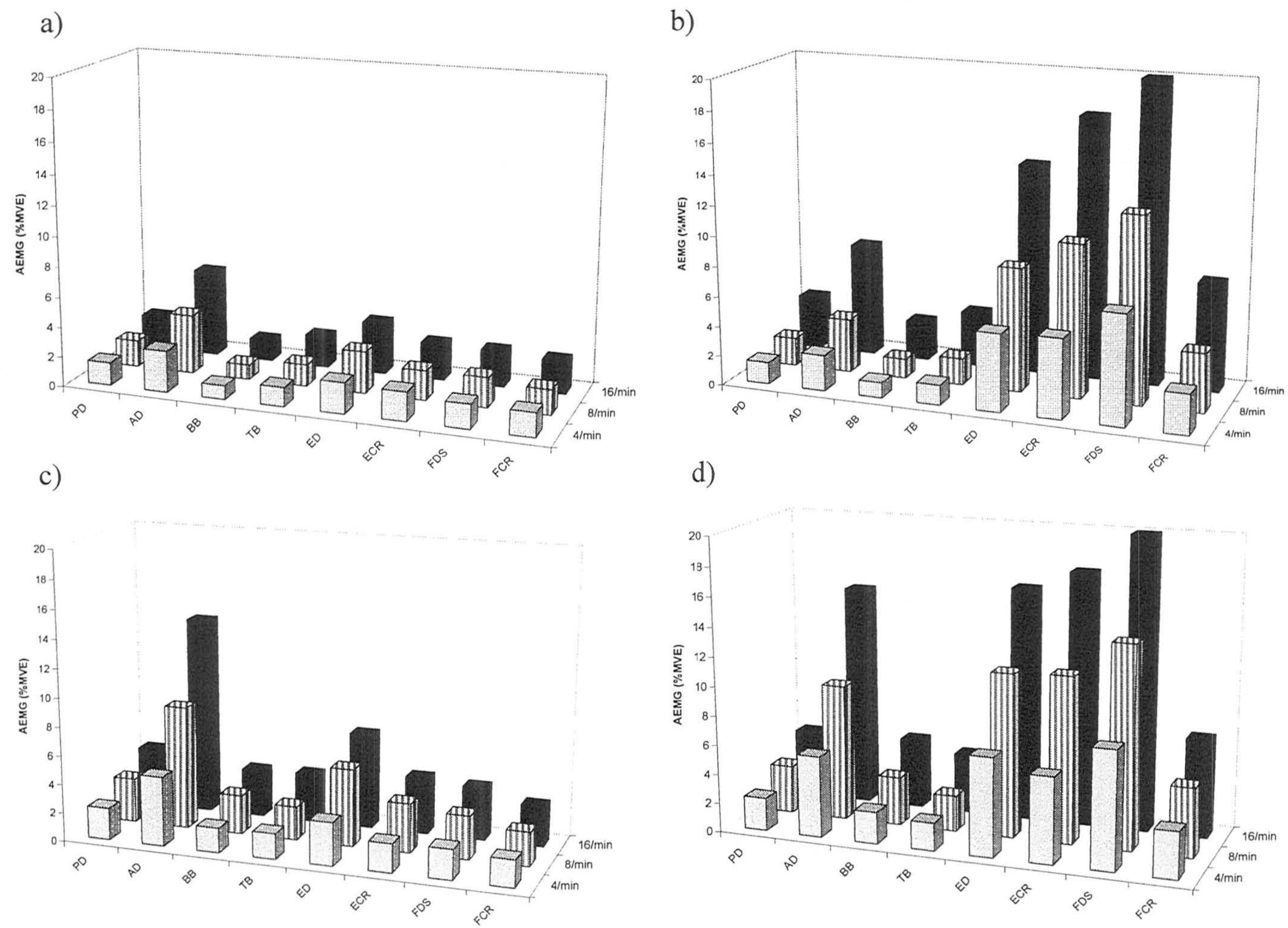


Figure 13. Mean AEMG (% MVE) for (a) low push load, no grip, (b) low push load with grip, (c) high push load, no grip, and (d) high push load with grip. Muscle abbreviations found in text. Note that in (b) & (d) the forearm muscles' mean muscle activity only increased a small amount from the low push load (1 kg) to the high push load (4 kg). Posterior deltoid (PD), anterior deltoid (AD), biceps brachii (BB), triceps brachii (TB), extensor digitorum (ED), extensor carpi radialis (ECR), flexor digitorum superficialis (FDS) and flexor carpi radialis (FCR).

Examining the combination of force and frequency, we found that there was a significant increase in mean muscle activity in the high load - high repetition condition as compared to the other conditions. The high load - high repetition condition produced the highest mean muscle activity in non-gripping trials. This supports the research by Silverstein et al. (1986) and Moore et al. (1991), as well as the review by NIOSH (1997) which stated there was "strong evidence" for the combination of force and repetition as a causal factor for the development of CTS, epicondylitis and wrist tendinitis. The logistic regression in the Silverstein et al. (1986) study produced an OR of 30.3 for the risk of hand and wrist cumulative trauma disorders (CTD) for the combination of force and frequency. Compared to the OR for force (OR of 4.4) and repetition (OR of 2.8) by themselves and this represents a greater than a six fold increase. Our EMG data did not show this large of an increase but, in general, all muscle activities showed an increase in the high load – high repetition condition. For example in the ED, the low load – low frequency (no grip) condition the AEMG was 2.1% MVE and in the high load – high frequency (no grip) condition the AEMG was 6.7% MVE. This is showing only a threefold increase in muscle activity. Furthermore this increase in OR could be representative of the muscle activity already inherent in their data (OR). It could be that a threefold increase in muscle activity is the basis for the large OR in conjunction with other factors. Moore et al. (1991) found a similar multiplicative effect of force and repetition. In both Moore et al. (1991) and Silverstein et al. (1986) the OR for high force – high repetition were the largest of any other OR produced, 9.2 and 30.3 respectfully. This difference could be attributed to the repetition criteria used by Silverstein et al.

(1986), which would define all conditions in the study as "high repetition" (greater than 2 cycles/min).

With respect to "workload" the frequency of the task becomes very important to the mean muscle activity. Although not systematically (or statically) investigated a pattern of workload appeared. Multiplying the load and frequency (a rough estimate of "workload") the AEMG values appears to be similar for similar amounts of work (ie. 16/min at 1kg trial, 8/min at 2kg trial & 4/min at 4kg trial). This pattern of workload would be somewhat expected as we are averaging over the entire trial. Therefore with a decrease in time that the participants are pushing we find an increase in AEMG. Interestingly, in the gripping conditions, the forearm muscles in the 16/min at 1kg trial were higher than the forearm muscle activity in the 4/min at 4kg trials. During gripping the frequency appeared to become very important to the mean muscle activity.

In the current study, we found that adding a concurrent grip to a dynamic pushing task increased overall forearm muscle AEMG (grip appears to supersede the muscle activity and produce smaller increases expected due to load) (Figure 13). In reviewing Figure 13, one can see that the forearm muscle activity in the high load condition is larger than in the low load condition (Figure 13 a and c). However, there is no apparent difference between these conditions when a grip was performed simultaneously (Figure 13 b and d). For example, the ED in the high frequency, high load and grip condition the mean muscle activity was 15.9% MVE and same condition without grip the mean muscle activity 6.5% MVE. That is an almost 10% MVE increase in the mean muscle activity of the ED due to grip. Mogk and Keir (2003a) found AEMG levels, at their 50% MVG trials the ED was approximately 30% MVE and in our study at 30% MVG our ED ranged from 6 - 15% MVE. The FDS AEMG in the Mogk and Keir (2003a) was approximately 21% at 50% MVG and in our study at 30% MVG there was a range in the FDS of 4 – 14 % MVE. The increase found at 50% MVG could also be because at over 40% maximum force on the force - EMG curve is nearing the non-linear section of the curve. Although the participants in each study were gripping at different levels we could still see the trend for the extensors to have a slightly higher mean muscle activity when gripping. Di Domizio (2006) determined that adding a push or pull exertion to a grip task increased forearm extensor muscle activity and she speculated that the extensor muscles were activated to stabilize the wrist as previously observed during gripping (Snijders et al., 1987; Mogk & Keir, 2003). The activity in the extensors could be a control strategy to increase the joint stiffness in the wrist (De Serres & Milner, 1991; Snijders et al., 1987).

In terms of muscular rest, which was defined as the gap time per minute (in seconds) in the current study, all forearm muscles monitored showed a large decrease in muscular rest with the increase of push frequency and the addition of grip. Both parameters also independently decreased muscular rest as well. In particular, the ED while gripping at the high frequency (16/min), all the trials were under 10% of rest. The forearm flexor muscles showed similar decreases in muscular rest. For example, in the high load – high frequency condition when gripping the gap time for the FDS was only 4.04 per min of rest. This was less than 7% rest in this muscle. Escorpizo and Moore (2007) examined a repetitive pick and place task and found that when the cycle time was below 2 s, the muscles did not "simultaneously shut off" at the end of each cycle but required time to deactivate and reactivate. Thus the forearm muscle can't utilize all of the rest provided. In a review paper, Muggleton (1999) suggested that job automation may in fact reduce the load placed on the body but may require the worker to work at a faster rate therefore increasing repetitiveness. Increasing the repetitiveness may transfer the load to another body part and therefore increase the injury potential (Muggleton, 1999). The current data support this claim, as it was found that increasing the frequency of the task increased the muscle activity, especially in the forearm when gripping is involved in the task (Table 3, p 28) The increase in the frequency is also consistent with Laursen et al. (1998) who found an overall increase in muscle activity as the speed demand increased in a shoulder tracking task.

The amplitude probability distribution function or APDF is another method of assessing the muscle activity is. Commonly used metrics from APDF are the 10th percentile, which means that muscle activation level is at or below that level for only 10% of the time (Jonsson, 1982). In the current study, the 10th percentile EMG of the ED was within the limit set out by Jonsson (1982) of 2-5% MVE for the 10th percentile, in the gripping high load - high frequency condition the 10th percentile value was 2.1% MVE. For example, in the ED we found a calculated static loading at 2.1% MVE for a 2-minute trial, meaning that the muscle was activate at or below 2.1% MVE level for only a period of 12 seconds. The 10th percentile EMG of the ED also indicates that the extensors (in particular, the ED) are not utilizing the rest they are being given. Considering that the trials only consisted of two minutes, to find significant lack of rest in some muscles would indicate that a long trial or an actual work shift would produce an enhance effect of lack of rest as muscle fatigued. These findings relating to muscular rest were also found in the anterior deltoid.

We found anterior deltoid activity increased with gripping (Figure 13). For example, in the high load – high frequency with grip the MVE was 15.1% and in the same condition without grip the MVE was 13.8%. However there were differences in the mean muscle activity due to gender. The increase in the anterior deltoid due to grip in this study was not found previously in our laboratory (MacDonell & Keir, 2005; Au & Keir, 2007). MacDonell and Keir (2005) found an interference effect during the combination of sub maximal grip and maximal shoulder exertion. This effect caused a decrease in shoulder strength, but only small changes in muscle activity. Another study found that the addition of sub maximal gripping produced a decrease in the muscle activity in the anterior deltoid during sub maximal shoulder exertions (Au & Keir, 2007). Two recent studies also found the decrease in anterior deltoid activity with the addition of the 30% MVG concurrent grip in two different protocols (Hodder, 2008; Smets, 2008). Di Domizio (2006) found during a static push that there was no difference in the anterior deltoid muscle activity when comparing the gripping and non-gripping trials. The current study was the only one of these studies that used a dynamic pushing task.

While the loads chosen for the study represented a doubling for each condition (1kg – 2kg – 4kg), the actual loads borne by the anterior deltoid were affected by the weight of the arm and thus did not match this paradigm. The moment created by the weight of the arm changes with the position of the handle as it was pushed forward. Rough estimates suggest the the average moment was approximately 6 Nm resulting in mean loads of 9, 12, and 18 Nm for the 1, 2 and 4 kg loads, respectively. Thus the loading for the anterior deltoid would have had a relative effect of 1, 1.33, 2 rather than the 1-2-4 of the loads added to the system. The ratio of 1, 1.33, 2 was seen in the AEMG of the AD (Table 3).

As expected, we found gender differences in anterior deltoid activity. There were expected as absolute push loads were used and females typically have lower anterior shoulder strength. Overall males had lower a mean muscle activity for the same task done by the females (Figure 6a & 6b). The males mean muscle activity for the high load – high frequency trial with grip was 15.1% MVE and was 13.8% MVE without grip. The females mean muscle activity for the high load – high frequency trial with grip was 21% MVE and was 20% MVE without grip. There was a small increase due to grip at the high load - high frequency condition for the women (Figure 6b). Although it was expected that the addition of grip would produce a continued trend of increasing the muscle activity as was seen in the other high load, gripping trials, this was not seen. It could be speculated that the high load – high frequency condition without grip was very difficult for female participants and the anterior deltoid reached a very high level of muscle activation, so the addition of the grip could not produce higher mean muscle activity levels.

Interestingly, while the mean muscle activity of the anterior deltoid was much lower for men (Figure 6a & 6b), the muscular rest showed no difference due to gender. So, even though the male participants had lower muscle activity levels, they experienced a similar amount of muscular rest. This lack of difference between genders was also found by Arvidsson et al. (2006), but in different muscles. This suggests that gap time is a useful addition to AEMG and APDF in order to look at muscular rest.

At the end of each trial participants were asked to rate their perceived exertion (RPE) on a scale from 0 – 10. In general, the women considered load to be harder and both genders responded to the addition of the 30% MVG grip. The frequency increases were not seen as strongly in the RPE score and this may lead us to believe that perhaps frequency is not as well represented in subjective ratings of participants. As well men reported a disproportional number of "0" and "1" values (Table 5). Previous research (De Domizio, 2006) found similar RPE scores with the highest RPE values was for the push with grip (3.2 ± 0.5). The mean RPE in the high load, high frequency with 30% MVG trial in our study was 3.9 ± 1.8.

5.1 Limitations

There were some limitations to our study. Healthy young adults who were not employed in manual labour jobs were examined, this may not be generalizable to labour workers or an injured population. The age range in this study was 19 years old to 38 years old, which may not be applicable to older workers but may be applicable to a young workforce. In this study, only eight muscles on the right side of the body were monitored, due to the equipment used. The results from the right arm are assumed to be similar to that which would be found on the left side as the task was bimanual and the participants were asked to keep their arm movements identical. There was also no postural constraint placed on the subjects, but the subjects were monitored for their position. Also the subject's feet were positioned in a designated area. Although the set up with the adjustable table and the configuration of the table while the participants were doing the task was fairly constrained. One smaller participant required a platform to stand on during the study due to the table adjustment limits. Her data and performance were well within the rest of these data collected. Some participants were unaccustomed to the MVE protocol thus there was there is a potential confound. In order to help control for fatigue there was two minutes of rest given between the two-minute trials. More time between the trials was given if needed and the trials were completely randomized. The participants did not practice the movement of the apparatus before starting and this might have introduced some learning effect into the results. The likelihood of cross-talk between the forearm muscles should be minimal as the common signal is minimal between properly placed electrodes for the same forearm muscles examined in current study (Mogk and Keir 2003b).

5.2 Summary

Overall, the load and frequency parameters and concurrent grip caused increases in all the muscles we monitored in the upper extremity. In the anterior deltoid, load, frequency and grip all increased the mean muscle activity, with differences for male and females, and decreased the muscular rest but no gender difference. In the forearm, the grip appeared to supersede the effects that were expected due to load and increased the AEMG as the frequency increased regardless of the loading condition. Frequency, along with increasing the AEMG also decreased the muscular rest (gap time). By examining the EMG of the upper extremity muscles, we found a need to raise the importance of the frequency of work and to also increase the importance of gripping in ergonomic assessment tools. This work provides a means of progression towards understanding the physiological relationship between force and frequency with an ultimate goal of establishing acceptable values for load thresholds, frequency thresholds and gripping limits.

Chapter 6 - Future Directions & Considerations

6.1 Future Directions

This thesis was aimed at furthering the knowledge of the force and frequency relationship on muscle activity in an attempt to better understand these risk factors. Future research on force and frequency in the upper extremity should be designed to be more representative of the workplace with longer trials and absolute loads. This data should provide a foundation for gaining insight into the development of muscle based UE WMSD as it is related to force, frequency and gripping. Additionally there has been a recent push in the literature to examine the physical variation at work.

In recent years, much emphasis has been given to physical variation at work as an important determinant of risk for developing WMSD (Mathiassen, 2006). With the linear potentiometers built into our dual track set up, we have data on the variation of the pushing and gripping task done in this study. A cycle-to-cycle analysis can be performed on this data (Figure 14). Using custom made software it is planned to use the potentiometer data to distinguish the cycles and parse out each individual cycle in order to analyze the variability of the task. Also using this method to analyzing the cycle-to-cycle work to rest time, AEMG, APDF and muscular rest (gap time). Thus we will also be able to see if spike loading occurs in certain cycles. Low cycle-to-cycle variability has been suggested to increase the risk of developing WMSD (Madeleine et al., 2008) and we would like to investigate this further.

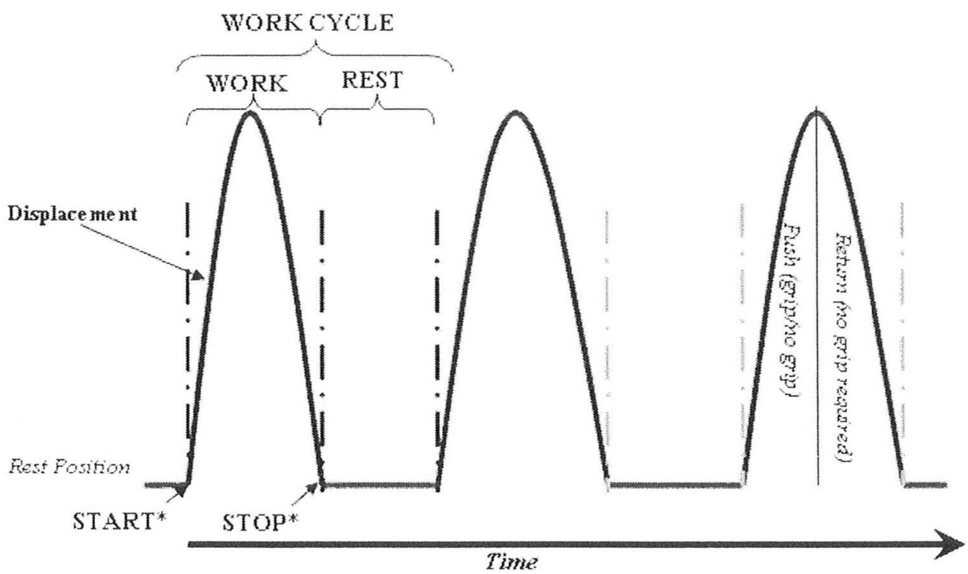


Figure 14. Cycle-to-cycle breakdown. Only potentiometer data shown. *Start/Stop at 0.25 mm from initial position.

This thesis also examined the muscle activity in the upper extremity and found in the forearm that both force and frequency produced increases in muscle activity. When required to grip the muscle activity showed a different pattern, the load only very slightly affected the muscle activity and the frequency increased the muscle activity. Further examinations should involve gripping and bimanual forearm EMG looking at different gripping forces other than 30% MVG. By examining the magnitude of the grip force, it would show if the same effects would be seen at higher/lower grip force. Analysis of absolute grip force should also be considered, as this is would be a better representative of loads experience while working.

In our study, the anterior deltoid showed an increase with the addition of the grip, which had not been seen before in the literature (MacDonell & Keir, 2005; Au & Keir, 2007; Di Domizio, 2006; Smets et al., 2008). This study used a dynamic task, and this showed a difference in the anterior deltoid activity as compared with previous research. In the future, assessments of the shoulder muscles should be extended to include more shoulder muscles other than the deltoid group. Examinations of the shoulder during differing grip levels, perhaps using absolute load levels representative of the workplace, would be able help to understand how loading and gripping affects these muscles.

Future research in the upper extremity is going to be important in order understand the relationship of risk factors and the development of UE WMSD. There is also a need to improve and/or modify the existing "acceptable limits" to better reflect the physiological relationship of force, frequency and gripping. The trend towards analyzing the physical variation in repetitive work will as also help to improve the understanding of the development of UE WMSD.

6.2 Considerations for Ergonomic Assessment Methods for Occupational Tasks

The methods for assessing the risk of WMSD in the upper extremity each have their own advantages and limitations. The Threshold Limit Value (TLV) for Hand Activity Levels was introduced by the American Conference of Governmental Industrial

Hygienists (ACGIH) in 2001 and offers the evaluation of job risk factors associated with UE WMSD. The TLV for Hand Activity uses the 10 point scale, the Hand Activity Level (HAL) (Latko et al., 1997). Worker exposures are categorized as above the TLV ("unacceptable"), below the TLV Action Limit (AL) ("acceptable") and in between these two lines, which is a caution zone.

In a recent study examining the TLV guidelines for discomfort in repetitive assembly work, O'Sullivan and Clancy (2007) suggested that there is a lack of information linking risk levels of the TLV to discomfort data. O'Sullivan and Clancy (2007) found that "discomfort increased by 50% between low and high levels of repetition and by 17% between low and high levels of force", this lead them to suggest that the action limit (AL) be moved so that it is parallel to the TLV line (Figure 15). Their modification of the AL line, allows for more discomfort ratings to be included, in particular the high repetition – low force score and the work in this thesis would support the move of the AL line. Currently the action limit is based on the highest HAL value (O'Sullivan & Clancy, 2007), leaving some high repetition low force values under the action limit (Figure 15). As well, on the figure below an estimation of the zone in which the current data would fit has been shaded.

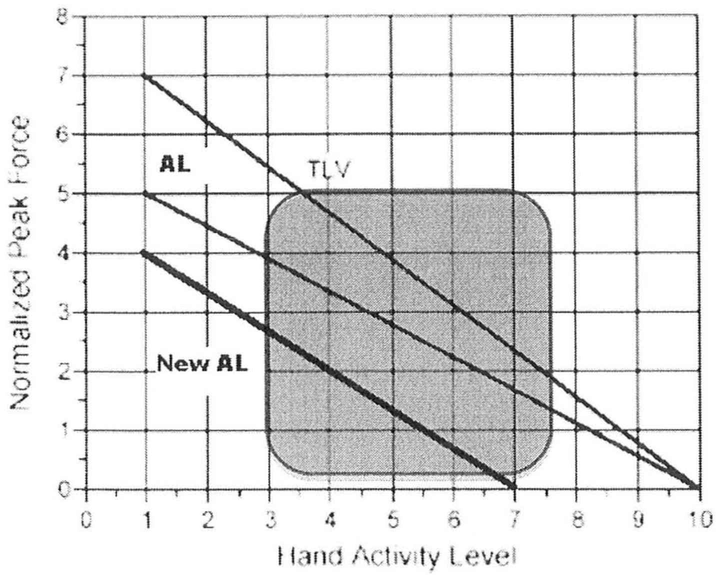


Figure 15. Threshold limit value (TLV) for mean discomfort scores. Original TVL (ACGIH, 2001) with modifications (New AL) from O'Sullivan & Clancy (2007). Shaded area is where this current data would be placed on the TLV

The normalized peak force (NPF) for the TLV is determined by using force gauge and establishing a percentage of the worker's maximal effort or grip, or it can be assessed using a subjective scale of the worker's rating. From the TLV documentation they discuss finding the NPF for the grip, but it is unclearly if the push force would be included. The NPF is designed to include the force being exerted by the hand but it is confusing as to how this should be done.

The Strain Index (SI) is another assessment tool, which is based on physiology, biomechanics, and epidemiology of distal upper extremity disorders. It consists of six task variables (Figure 16). Each task variable is given a multiplier. The multiplier values are primarily based on the authors' professional opinions with support from physiological, biomechanical, and epidemiological principals as opposed to a mathematical relationship between task variables (Moore & Garg 1994). The SI has one criterion for the intensity of exertion of the task with a multiplier score that is to a power of 1.6 with a maximum score of 13. The authors give reasons for this powerful relationship as based on "physiological, biomechanical and epidemiological principles". However the force exertion criterion, which is the most important multiplier, is also subjective (Moore & Garg, 1994). When considering the intensity of exertion for a task is gripping assumed to be part of this force/intensity, is gripping a separate force or is it to be included in the force requirement criteria. Looking at the efforts per minute, the multiplier has a maximum score of 3. From the increased mean muscle activity found with the increased frequency condition presented in this thesis it would suggest that the efforts per minute should have a greater multiplier. Another way to look at the SI would be to consider three of the categories as representative of the repetitiveness of work, duration of exertion, efforts/minute and speed of work. Also if all three maximums (3, 3, & 2) were multiplied together then this would be a total of 12, which is comparable to 13 for the intensity of exertion. This would fit with the work presented here, that the force and frequency should be equal when assessing UE WMSD. The SI also does take into consideration the hand/wrist posture, but no whether or not the worker is gripping.

Rating Criteria:

1	light	<10	<4	very good	very slow	≤1
2	somewhat hard	10-29	4-8	good	slow	1-2
3	hard	30-49	9-14	fair	fair	2-4
4	very hard	50-79	15-19	bad	fast	4-8
5	near maximal	≥80	≥20	very bad	very fast	≥8

Multiplier Table:

Rating	Intensity of Exertion	Duration of Exertion (% cyc)	Efforts/ Minute	Hand/Wrist Posture	Speed of Work	Duration per Day (hrs)
1	1	0.5	0.5	1.0	1.0	0.25
2	3	1.0	1.0	1.0	1.0	0.50
3	6	1.5	1.5	1.5	1.0	0.75
4	9	2.0	2.0	2.0	1.5	1.00
5	13	3.0•	3.0	3.0	2.0	1.50

•If duration of exertion is 100%, then efforts/minute multiplier should be set to 3.0

Figure 16. Strain Index (SI) Rating Criteria and Multiplier Table. The SI consists of six task variables-intensity of exertion, duration of exertion per cycle, efforts per minute, wrist posture, speed of exertion, and duration of task per day- seen above. These task variables are all given a rating and then the ratings are further multiplied by the value found in Multiplier Table. Moore & Garg 1994

Through examining the EMG of the upper extremity muscles, the current data suggests the need to raise the importance on the frequency of work and to also increase the importance of gripping in ergonomic assessment tools. In general, ergonomic assessment tools may negate the multiplicative effects of the combination of force and frequency. Ergonomic assessment tools also do not always including specific gripping limit or gripping is built into the force of the task and cause confusion to the user. This thesis provides means of progress towards understanding the physiological relationship between force, frequency and gripping.

Chapter 7 – Summary

Work-related musculoskeletal disorders (UE WMSD) of the upper extremity currently rank second to lumbar spine disorders as the most common workplace injury claims in Ontario (WSIB, 2004). Risk factors for the development of UE WMSD high repetition (Latko et al., 1999; Silverstein et al., 1986, Fransson-Hall et al, 1995), high force (Silverstein et al., 1986; Malchaire et al., 1997), non-neutral (or awkward) postures (Malchaire et al., 1996), and high angular velocities (Marras & Schoemarklin.1993). There is also strong evidence that the combination of high force and high repetition places individuals at a higher risk of developing UE WMSD (Moore et al. 1991; Silverstein et al., 1986). The purpose of this study was to examine the muscle activity in the upper extremity during a repetitive pushing and gripping task with differing force levels and differing frequencies.

The first hypothesis of this study was that the high load condition would increase the overall EMG of the upper extremity and that the increase would be proportional to load. This was true in the non-gripping trials, there was an increase in muscle activity in all the muscles of the upper extremity with the increase in load although not proportional to the doubling of load condition (1 kg → 2 kg → 4 kg). In the gripping trials however, the forearm muscles (extensor digitorum, extensor carpi radialis, flexor digitorum superficialis and flexor carpi radialis) did not response to the increase in load. Gripping appeared to supersede the loading effects that were anticipated in the study. The frequency during the gripping trials still acted to increase muscle activity. Although the increase was not proportional to the doubling of frequency (4/min → 8/min → 16/min), which was built into the design of the study, considerable increases were seen. In general, during the gripping condition there was a three-fold increase in the mean muscle activity in the forearm muscles due to frequency, with little to no increase due to push load.

The second hypothesis that the addition of a concurrent grip would increase forearm muscle activity was supported. However, the hypothesis that there would be a decrease in muscle activity in the anterior and posterior deltoids was not supported. The forearm muscles did increase with the addition of the grip. In particular, it was found that when the frequency increased the muscle activity of the forearm increased. The anterior deltoid increased with the addition of a concurrent grip. This increase was evident in all high load trials (4 kg) and during the high frequency (16/min) trials. There was a gender difference found in the anterior deltoid, which was expected due the absolute push loads that were used in this study.

The final hypothesis of this study was that the muscular rest (gap time reported in seconds per minute) would be inversely proportional to the frequency therefore will decrease with the increase in frequency. This was supported by our findings and again it was found that the decrease in muscular rest was greater when the grip was added. In particular, the decrease in muscular rest in the forearm was considerable. In the case of the extensor digitorum for example, less than 10% rest during the gripping trials at the high frequency (16/min) condition regardless of load was found.

The major findings from this thesis were major changes in the forearm due to gripping, decreased muscular rest in the forearm in the high frequency condition with gripping, the increase in the anterior deltoid due to grip and the gender difference in the mean muscle activity of the anterior deltoid with no gender difference in the muscular rest in the anterior deltoid. The forearm, as expected, showed a large increase in muscle activity due to the addition of a concurrent grip. Interestingly, during the gripping trials the effects that were expected due to load were not seen and the effect of frequency was still substantial. Similarly in the muscular rest of the forearm it was found that a large decrease was seen due to gripping. There was also decreased muscle activity due to the increased frequency.

The increase in the anterior deltoid due to the addition of the grip was not expected. In previous research in the upper extremity, the addition of a concurrent grip had seen a null effect or a decrease in the muscle activity of the anterior deltoid (MacDonell & Keir, 2005; Au & Keir, 2007; Di Domizio, 2006; Smets et al., 2008). This was primarily due to the nature of the task, our task was dynamic whereas the other task were static. In the mean muscle activity of the anterior deltoid there were foreseeable differences due to gender. Female participants had higher muscle activity that was expected due to the absolute push loads that were used. Also the anterior deltoid muscle activity was also affected by the weight of the arm, thus was not directly proportional to the 1-2-4 load applied relationship.

In general, the load and frequency parameters and concurrent grip caused increases in all the muscles we observed. In the forearm, the grip superseded the effects that were expected due to load in the mean muscle activity. Additionally the mean muscle activity of the forearm increased as the frequency increased regardless of the loading condition. The AEMG appears to reflect workload rather then the force and frequency parameters that were chosen. Furthermore, frequency increased the mean muscle activity and decreased the muscular rest in the forearm muscles. In the shoulder load, frequency and grip all increased the overall mean muscle activity. By investigating the muscle activity of the upper extremity muscles, the current data suggests the need to raise the importance on the frequency of work and to also increase the importance of gripping in ergonomic assessment tools. This thesis provides a means of progression towards understanding the physiological relationship between force, frequency and concurrent gripping, with the ultimate goal of establishing acceptable values.

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Appendix A. Informed Consent form.

October 19, 2007

Letter of Information and Consent

Forearm muscle activity during simulated work tasks

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Research Sponsor: AUTO21 Network of Centres of Excellence (NSERC, CIHR, SSHRC - in partnership with Industry Canada)

Purpose of the Study
We are investigating muscle activity in the arm and shoulder during simulated work tasks. By simulating work tasks we can get detailed information on posture and muscle activity from the forearms, upper arm and shoulder. Then we can relate their potential contributions to the development of workplace disorders of the upper extremity.

Procedures involved in the Research
Anthropometric measures (height, weight, arm length, etc) will be recorded and you will be introduced to the protocol. Immediately following this you will have recording electrodes placed over 8 muscles of the forearm, upper arm and shoulder. These electrodes allow us to record the activity in the muscles under them. To know how active your muscles are, we first need to determine the maximum activity for each muscle through a series of tests for gripping and shoulder exertion. The protocol will mimic the actions and forces recorded from actual auto parts assembly jobs and will require a series of hand tasks (e.g. gripping, turning knobs) and arm movements (e.g. raises, extending arm), individually and combined. The participants will complete a series of simulated industrial work (according to video data from automotive industry). The simulation tasks will be completed for 20 minutes in each of three forearm postures: pronation, supination and neutral. The protocol may require more than one visit to the lab (one day of training and 1 or more experiment days) separated by 2-4 days.

Potential Harms, Risks or Discomforts
There is minimal risk associated with participation in this study. You may experience some muscle soreness as a result of the maximal shoulder exertions. Although very rare, you may experience a temporary reaction to the adhesive from the surface electrodes. Should you experience any serious discomfort following the study, please contact the principal investigator, Dr. Peter Keir. Due to the nature of the protocol, you will not be allowed to participate if you have been diagnosed with high blood pressure or have previous shoulder and wrist injuries.

Potential Benefits

We hope to understand the loads experienced within the body and relate them to injuries and disorders that develop in the workplace. Ultimately we hope to prevent workplace disorders.
The research will not benefit you directly.

Payment or Reimbursement:
You will receive $20 as remuneration for your time and participation in the study.

Confidentiality:
Your identity will be kept anonymous and the data collected will be used for teaching and research purposes only. Photo and video data will only be used with your consent.
The information directly pertaining to you will be locked in a cabinet for a maximum of 15 years.

Participation:
Your participation in this study is voluntary. If you decide to participate, you can decide to stop at any time, even after signing the consent form or part-way through the study. If you drop out of the study, your data will only be used with your explicit consent. If you decide to stop participating, there will be no consequences to you and the compensation will be prorated. If you do not want to answer some of the questions you do not have to, but you can still be in the study.

Information About the Study Results:
You may obtain information about the results of the study by contacting Dr. Keir or research lab members.

Information about Participating as a Study Subject:
If you have questions or require more information about the study itself, please contact Dr. Keir or Melissa Brown.

This study has been reviewed and approved by the McMaster Research Ethics Board. If you have concerns or questions about your rights as a participant or about the way the study is conducted, you may contact:

McMaster Research Ethics Board Secretariat
Telephone: (905) 525-9140 ext. 23142
c/o Office of Research Services
E-mail: ethicsoffice@mcmaster.ca

CONSENT

I have read the information presented in the information letter about a study being conducted by Dr. Peter Keir, or his students, of McMaster University. I have had the opportunity to ask questions about my involvement in this study, and to receive any additional details I wanted to know about the study. I understand that I may withdraw from the study at any time, if I choose to do so, and I agree to participate in this study. I have been given a copy of this form.

____
Name & Signature of Participant

In my opinion, the person who has signed above is agreeing to participate in this study voluntarily, and understands the nature of the study and the consequences of participation in it.

____
Signature of Researcher or Witness

Appendix B. Rating of perceived exertion scale.

Score	Symptoms
0	Nothing at all
0.5	Very very slight (but noticeable)
1	Very slight
2	Slight
3	Moderate
4	Somewhat severe
5	Severe
6	
7	Very severe
8	
9	Very very severe
10	Maximal

Appendix C. Standard Deviations of the APDF

Standard deviation of the APDF for the 0%MVG conditions

FREQUENCY	LOW				MED				HIGH			
Load												
1 kg	Static	Median	Peak	99%	Static	Median	Peak	99%	Static	Median	Peak	99%
Post Del	0.63	0.65	2.06	6.55	1.27	1.34	4.04	7.69	1.32	1.57	5.54	8.74
Ant Del	1.17	1.22	6.49	21.96	1.05	1.35	12.27	20.80	1.22	3.59	18.48	22.07
Biceps	0.32	0.40	1.03	3.88	0.43	0.49	1.22	4.43	0.55	0.75	2.21	4.28
Triceps	1.55	1.69	2.44	5.81	1.31	1.46	2.68	4.85	1.30	1.63	4.54	7.06
ED	0.62	0.84	1.82	4.81	0.90	1.60	4.28	7.66	1.09	2.06	4.61	6.65
ECR	1.76	1.66	1.71	2.99	0.56	0.68	1.61	3.60	0.50	0.64	2.02	4.23
FDS	0.82	0.98	1.97	5.26	0.80	1.00	2.44	5.74	0.91	1.38	3.82	7.19
FCR	0.63	1.03	1.76	4.36	1.27	1.33	1.85	3.91	1.24	1.42	3.19	7.37
2 kg	Static	Median	Peak	99%	Static	Median	Peak	99%	Static	Median	Peak	99%
Post Del	0.69	1.45	2.13	6.89	0.91	1.47	2.48	4.50	0.62	1.55	2.87	4.68
Ant Del	1.10	1.53	6.50	14.78	1.14	1.36	7.87	13.48	1.18	3.97	11.14	16.19
Biceps	0.29	0.75	3.36	13.61	0.65	0.80	12.56	16.88	0.67	1.52	14.38	17.21
Triceps	1.29	1.38	3.19	11.15	1.32	1.53	8.32	13.21	1.36	2.01	10.63	14.56
ED	0.49	0.84	2.20	5.94	1.10	1.88	4.33	7.78	0.98	1.64	5.75	8.84
ECR	0.57	0.91	1.65	4.04	1.79	1.77	2.04	5.96	0.85	0.99	2.10	4.59
FDS	1.04	2.24	3.80	6.49	0.97	1.90	3.46	5.91	0.94	1.74	4.00	6.46
FCR	0.74	1.54	1.95	4.74	0.97	1.58	2.84	5.65	0.78	1.71	3.18	5.45
4 kg	Static	Median	Peak	99%	Static	Median	Peak	99%	Static	Median	Peak	99%
Post Del	1.41	1.50	3.36	11.94	1.31	1.54	5.65	13.29	1.34	2.20	7.50	13.17
Ant Del	1.02	1.84	10.43	41.41	0.91	1.85	23.23	44.17	0.92	4.85	30.73	49.50
Biceps	0.85	1.63	6.06	17.92	0.77	1.70	10.94	21.29	0.76	2.86	13.20	20.86
Triceps	0.59	1.73	3.59	13.69	1.58	1.99	8.85	13.49	1.49	2.31	11.33	15.04
ED	0.88	1.10	3.44	11.87	0.74	2.04	5.47	8.43	0.93	2.43	6.91	11.16
ECR	0.55	0.74	1.53	6.79	0.56	0.78	4.82	10.75	0.56	1.46	3.47	9.63
FDS	0.94	1.84	3.45	5.75	0.93	2.55	24.11	23.59	0.96	2.20	4.69	8.50
FCR	1.36	1.48	2.76	6.08	0.96	1.47	5.78	9.25	1.21	1.88	3.95	7.16

Standard deviation of the APDF for the 30%MVG conditions

FREQUENCY	LOW				MED				HIGH			
Load												
1 kg	Static	Median	Peak	99%	Static	Median	Peak	99%	Static	Median	Peak	99%
Post Del	1.40	1.41	2.18	7.05	0.53	1.39	4.44	9.26	1.40	2.63	23.08	23.30
Ant Del	1.15	1.14	6.86	22.01	1.08	1.59	12.33	21.68	1.85	4.68	26.37	27.97
Biceps	0.44	0.68	1.47	4.44	0.45	0.63	2.25	4.81	0.78	1.64	8.13	12.63
Triceps	1.42	1.57	2.07	4.74	1.34	1.55	3.34	6.60	1.36	3.41	22.51	22.24
ED	0.77	1.25	8.19	15.14	0.80	1.79	14.78	18.55	1.40	8.16	14.53	20.28
ECR	0.54	0.65	9.09	14.01	0.58	1.37	20.38	22.63	1.02	18.70	20.16	25.14
FDS	1.34	3.50	23.28	22.86	0.82	2.54	23.23	26.76	1.01	23.01	23.96	27.09
FCR	1.34	1.58	4.94	7.67	0.76	1.65	6.52	9.36	1.66	4.86	21.78	23.19
2 kg	Static	Median	Peak	99%	Static	Median	Peak	99%	Static	Median	Peak	99%
Post Del	1.42	1.42	2.67	5.81	1.34	1.41	4.16	7.88	1.52	2.35	5.87	9.97
Ant Del	1.15	1.22	6.40	14.08	1.23	1.78	10.20	17.34	1.33	6.81	13.86	17.58
Biceps	0.76	1.09	2.22	5.39	0.54	1.01	3.82	8.57	0.60	1.18	3.14	5.28
Triceps	1.38	1.52	2.63	4.88	1.42	1.58	4.05	7.40	14.75	2.73	7.08	11.56
ED	0.73	1.17	7.81	10.98	1.04	2.78	8.77	14.84	1.25	6.92	10.22	12.57
ECR	0.79	1.69	7.20	12.74	0.77	5.63	8.98	21.71	0.59	8.79	14.19	20.53
FDS	1.30	2.97	22.36	23.45	1.24	7.50	22.72	25.76	1.01	12.32	23.00	24.00
FCR	1.40	1.62	5.04	8.40	1.32	2.70	7.01	10.40	1.70	3.98	9.18	12.54
4 kg	Static	Median	Peak	99%	Static	Median	Peak	99%	Static	Median	Peak	99%
Post Del	1.40	1.46	3.45	15.20	1.45	1.82	6.34	9.73	1.38	2.54	7.85	11.96
Ant Del	1.17	3.27	9.81	24.25	1.18	1.57	20.47	25.87	1.19	6.12	17.99	25.93
Biceps	0.30	0.63	4.99	12.22	0.42	1.08	7.81	15.40	0.68	2.12	8.94	14.40
Triceps	1.45	1.61	3.10	7.65	1.48	1.70	5.62	8.05	1.70	2.88	8.50	12.19
ED	1.13	2.04	10.00	12.02	1.17	7.00	8.80	11.38	1.24	7.36	10.54	14.22
ECR	0.58	1.16	8.58	13.78	1.68	6.92	21.99	22.56	0.62	13.68	21.05	21.96
FDS	0.96	2.06	22.42	23.33	0.87	9.09	23.30	23.96	1.15	24.11	24.36	24.83
FCR	0.59	1.42	5.12	8.66	0.95	2.72	7.60	11.18	1.40	4.39	8.08	12.85

Appendix D. ANOVA tables for AEMG
ANOVA table for AEMG of the AD

Source	SS	df	MS	F	p
Load	1643.421	2	821.7103	53.43916	0.0000
Load * Gender	301.5834	2	150.7917	9.806597	0.0004
Error(Load)	522.803	34	15.37656		
Frequency	2443.362	2	1221.681	61.96137	0.0000
Frequency * Gender	506.8415	2	253.4208	12.85303	0.0001
Error(Frequency)	670.3717	34	19.71682		
Grip	40.68787	1	40.68787	4.08211	0.0594
Grip * Gender	20.85164	1	20.85164	2.091992	0.1663
Error(Grip)	169.4452	17	9.967363		
Load * Frequency	263.279	4	65.81975	13.17736	0.0000
Load * Frequency * Gender	46.37208	4	11.59302	2.320966	0.0655
Error(Load*Frequency)	339.6539	68	4.994911		
Load * Grip	2.78436	2	1.39218	0.497088	0.6127
Load * Grip * Gender	4.686725	2	2.343363	0.836715	0.4419
Error(Load*Grip)	95.22275	34	2.800669		
Frequency * Grip	38.96928	2	19.48464	5.046521	0.0120
Frequency * Grip * Gender	13.90285	2	6.951427	1.800419	0.1806
Error(Frequency*Grip)	131.2741	34	3.861004		
Load * Frequency * Grip	12.1416	4	3.035401	1.021681	0.4025
Load * Frequency * Grip * Gender	35.95947	4	8.989868	3.025887	0.0234
Error(Load*Frequency*Grip)	202.027	68	2.970986		

ANOVA table for AEMG of PD

Source	SS	df	MS	F	p
Load	92.04119	1.471269	62.55904	16.92806	0.0000
Load * Gender	24.252	1.471269	16.48372	4.460387	0.0317
Error(Load)	92.43233	25.01158	3.695582		
Frequency	149.0786	1.169781	127.4415	14.13743	0.0008
Frequency * Gender	55.04562	1.169781	47.05634	5.220089	0.028837
Error(Frequency)	179.2643	19.88628	9.014472		
Grip	15.01551	1	15.01551	4.491262	0.049092
Grip * Gender	5.214639	1	5.214639	1.559741	0.228628
Error(Grip)	56.83563	17	3.343272		
Load * Frequency	12.78923	1.70665	7.493764	2.376979	0.117582
Load * Frequency * Gender	6.51241	1.70665	3.815903	1.210382	0.30682
Error(Load*Frequency)	91.46777	29.01305	3.152642		
Load * Grip	2.946362	1.203376	2.448412	1.038347	0.335133
Load * Grip * Gender	2.205183	1.203376	1.832496	0.777143	0.411234
Error(Load*Grip)	48.23834	20.4574	2.35799		
Frequency * Grip	12.96535	1.21817	10.6433	2.638426	0.114175
Frequency * Grip * Gender	7.610645	1.21817	6.247604	1.548753	0.231919
Error(Frequency*Grip)	83.53882	20.70889	4.033959		
Load * Frequency * Grip	4.229067	1.352683	3.126429	0.582009	0.502644
Load * Frequency * Grip * Gender	6.67227	1.352683	4.932619	0.918245	0.377486
Error(Load*Frequency*Grip)	123.5275	22.99561	5.371787		

ANOVA table for AEMG of BB

Source	SS	df	MS	F	p
Load	162.9589	1.101745	147.9098	18.91593	0.0000
Load * Gender	7.723944	1.101745	7.010644	0.896579	0.3659
Error(Load)	146.4533	18.72967	7.819323		
Frequency	113.912	1.715447	66.40369	43.14649	0.0000
Frequency * Gender	15.43628	1.715447	8.998403	5.846805	0.0098
Error(Frequency)	44.88207	29.16259	1.539029		
Grip	39.49668	1	39.49668	27.72828	0.0001
Grip * Gender	2.832661	1	2.832661	1.988644	0.1765
Error(Grip)	24.21511	17	1.424419		
Load * Frequency	14.83084	2.498818	5.935145	3.031207	0.0481
Load * Frequency * Gender	1.516597	2.498818	0.606926	0.30997	0.7818
Error(Load*Frequency)	83.17623	42.4799	1.958014		
Load * Grip	0.275439	1.418071	0.194235	0.145254	0.7921
Load * Grip * Gender	1.183911	1.418071	0.834874	0.624343	0.4910
Error(Load*Grip)	32.23627	24.10721	1.337205		
Frequency * Grip	15.87585	1.935717	8.201536	9.099381	0.0008
Frequency * Grip * Gender	2.240142	1.935717	1.157267	1.283957	0.2897
Error(Frequency*Grip)	29.6602	32.90719	0.901329		
Load * Frequency * Grip	3.56379	2.654278	1.342659	1.973182	0.1379
Load * Frequency * Grip * Gender	5.142045	2.654278	1.937267	2.847023	0.0541
Error(Load*Frequency*Grip)	30.70392	45.12272	0.680454		

ANOVA table for AEMG of TB

Source	SS	df	MS	F	p
Load	43.29671	2	21.64836	15.02566	0.0000
Load * Gender	26.64617	2	13.32309	9.247268	0.0006
Error(Load)	48.98581	34	1.440759		
Frequency	172.3716	2	86.18582	13.98333	0.0000
Frequency * Gender	59.71554	2	29.85777	4.844311	0.014089
Error(Frequency)	209.558	34	6.163471		
Grip	19.39549	1	19.39549	6.300409	0.02248
Grip * Gender	4.945713	1	4.945713	1.60656	0.222064
Error(Grip)	52.33364	17	3.078449		
Load * Frequency	4.095549	4	1.023887	0.966156	0.431846
Load * Frequency * Gender	5.222271	4	1.305568	1.231954	0.305568
Error(Load*Frequency)	72.06326	68	1.059754		
Load * Grip	4.009391	2	2.004696	1.676697	0.202083
Load * Grip * Gender	1.376836	2	0.688418	0.575782	0.567652
Error(Load*Grip)	40.65114	34	1.195622		
Frequency * Grip	14.36454	2	7.182271	2.734919	0.079183
Frequency * Grip * Gender	10.88049	2	5.440247	2.071578	0.141599
Error(Frequency*Grip)	89.28865	34	2.626137		
Load * Frequency * Grip	3.827346	4	0.956837	0.928087	0.452931
Load * Frequency * Grip * Gender	2.583725	4	0.645931	0.626523	0.645202
Error(Load*Frequency*Grip)	70.10647	68	1.030978		

ANOVA table for AEMG of ED

Source	SS	df	MS	F	p
Load	267.8121	2	133.906	24.12849	0.0000
Load * Gender	14.7432	2	7.371601	1.328287	0.2783
Error(Load)	188.69	34	5.549706		
Frequency	1650.042	2	825.0212	79.58437	0.0000
Frequency * Gender	7.62794	2	3.81397	0.367909	0.6949
Error(Frequency)	352.4652	34	10.36662		
Grip	3555.854	1	3555.854	77.46472	0.0000
Grip * Gender	205.2488	1	205.2488	4.471371	0.0495
Error(Grip)	780.349	17	45.90288		
Load * Frequency	39.24308	4	9.81077	2.822588	0.0315
Load * Frequency * Gender	5.718387	4	1.429597	0.411299	0.7999
Error(Load*Frequency)	236.3548	68	3.475806		
Load * Grip	7.729121	2	3.86456	1.710056	0.1960
Load * Grip * Gender	3.247391	2	1.623695	0.71848	0.4947
Error(Load*Grip)	76.83669	34	2.259903		
Frequency * Grip	773.3083	2	386.6541	68.61765	0.0000
Frequency * Grip * Gender	12.08479	2	6.042397	1.072315	0.3535
Error(Frequency*Grip)	191.5869	34	5.634908		
Load * Frequency * Grip	21.70259	4	5.425647	2.053227	0.0966
Load * Frequency * Grip * Gender	19.10655	4	4.776637	1.807622	0.1374
Error(Load*Frequency*Grip)	179.6898	68	2.642497		

ANOVA table for AEMG of ECR

Source	SS	df	MS	F	p
Load	55.10906	2	27.55453	2.0629	0.1427
Load * Gender	39.44386	2	19.72193	1.4765	0.2427
Error(Load)	454.1437	34	13.35717		
Frequency	2099.822	2	1049.911	25.5068	0.0000
Frequency * Gender	26.15868	2	13.07934	0.3178	0.7299
Error(Frequency)	1399.509	34	41.16203		
Grip	5936.175	1	5936.175	40.8997	0.0000
Grip * Gender	404.931	1	404.931	2.7899	0.1132
Error(Grip)	2467.377	17	145.1398		
Load * Frequency	19.07073	4	4.767683	1.1615	0.3356
Load * Frequency * Gender	3.686638	4	0.921659	0.2245	0.9238
Error(Load*Frequency)	279.1262	68	4.104798		
Load * Grip	47.66057	2	23.83029	2.3966	0.1062
Load * Grip * Gender	17.78255	2	8.891276	0.8942	0.4183
Error(Load*Grip)	338.0684	34	9.943188		
Frequency * Grip	1513.096	2	756.5481	19.7041	0.0000
Frequency * Grip * Gender	112.2374	2	56.11868	1.4616	0.2461
Error(Frequency*Grip)	1305.443	34	38.39538		
Load * Frequency * Grip	25.8205	4	6.455124	1.0529	0.3866
Load * Frequency * Grip * Gender	34.13721	4	8.534302	1.3921	0.2460
Error(Load*Frequency*Grip)	416.8801	68.0000	6.13059		

ANOVA table for AEMG of FDS

Source	SS	df	MS	F	p
Load	34.41519	2	17.2076	2.39976	0.1059
Load * Gender	8.314299	2	4.157149	0.579753	0.5655
Error(Load)	243.7987	34	7.170549		
Frequency	2745.027	2	1372.514	14.05997	0.0000
Frequency * Gender	187.2415	2	93.62074	0.959047	0.393383
Error(Frequency)	3319.029	34	97.6185		
Grip	10778.26	1	10778.26	11.95662	0.003007
Grip * Gender	1519.868	1	1519.868	1.686031	0.211464
Error(Grip)	15324.6	17	901.4472		
Load * Frequency	49.23665	4	12.30916	1.218248	0.311215
Load * Frequency * Gender	16.59157	4	4.147892	0.41052	0.800464
Error(Load*Frequency)	687.0711	68	10.10399		
Load * Grip	52.28134	2	26.14067	2.793521	0.07529
Load * Grip * Gender	10.8104	2	5.405198	0.577626	0.566641
Error(Load*Grip)	318.1586	34	9.357606		
Frequency * Grip	2031.177	2	1015.588	9.956245	0.000395
Frequency * Grip * Gender	255.9237	2	127.9619	1.254464	0.298097
Error(Frequency*Grip)	3468.176	34	102.0052		
Load * Frequency * Grip	50.54075	4	12.63519	1.615178	0.180461
Load * Frequency * Grip * Gender	17.40186	4	4.350464	0.556127	0.695229
Error(Load*Frequency*Grip)	531.9491	68	7.822782		

ANOVA table for AEMG of FCR

Source	SS	df	MS	F	p
Load	10.31648	2	5.158242	2.671573	0.0836
Load * Gender	0.051887	2	0.025943	0.013437	0.9867
Error(Load)	65.6468	34	1.930788		
Frequency	320.8944	2	160.4472	28.39036	0.0000
Frequency * Gender	6.450209	2	3.225104	0.570667	0.5705
Error(Frequency)	192.1499	34	5.651468		
Grip	604.2208	1	604.2208	31.41398	0.0000
Grip * Gender	2.07033	1	2.07033	0.107638	0.7469
Error(Grip)	326.9803	17	19.23414		
Load * Frequency	8.664486	4	2.166122	1.412872	0.2391
Load * Frequency * Gender	8.810592	4	2.202648	1.436697	0.2313
Error(Load*Frequency)	104.2531	68	1.533134		
Load * Grip	7.607077	2	3.803538	2.404479	0.1055
Load * Grip * Gender	0.857248	2	0.428624	0.270963	0.7643
Error(Load*Grip)	53.78309	34	1.581856		
Frequency * Grip	147.6678	2	73.83388	18.93811	0.0000
Frequency * Grip * Gender	4.94602	2	2.47301	0.634318	0.5365
Error(Frequency*Grip)	132.5556	34	3.898694		
Load * Frequency * Grip	9.893195	4	2.473299	1.921546	0.1168
Load * Frequency * Grip * Gender	7.27165	4	1.817912	1.412366	0.2392
Error(Load*Frequency*Grip)	87.52551	68	1.28714		

Appendix E. ANOVA tables for muscular rest
ANOVA table for muscular rest of AD

Source	SS	df	MS	F	p
Load	2164.896	2	1082.448	3.507372	0.0412
Load * Gender	349.1295	2	174.5647	0.565629	0.5733
Error(Load)	10493.11	34	308.6208		
Frequency	55623.93	2	27811.97	31.71152	0.0000
Frequency * Gender	1631.342	2	815.6709	0.930037	0.4043
Error(Frequency)	29819.04	34	877.0305		
Grip	101.2061	1	101.2061	0.290999	0.5966
Grip * Gender	164.5115	1	164.5115	0.473021	0.5009
Error(Grip)	5912.409	17	347.7887		
Load * Frequency	1186.402	4	296.6004	1.075945	0.3753
Load * Frequency * Gender	1879.103	4	469.7759	1.704154	0.1592
Error(Load*Frequency)	18745.23	68	275.6651		
Load * Grip	648.4727	2	324.2363	1.902229	0.1648
Load * Grip * Gender	524.5015	2	262.2508	1.538572	0.2293
Error(Load*Grip)	5795.326	34	170.4508		
Frequency * Grip	1699.165	2	849.5825	4.03764	0.0267
Frequency * Grip * Gender	379.8397	2	189.9199	0.902594	0.4150
Error(Frequency*Grip)	7154.13	34	210.4156		
Load * Frequency * Grip	997.3605	4	249.3401	1.986153	0.1064
Load * Frequency * Grip * Gender	869.8089	4	217.4522	1.732145	0.1530
Error(Load*Frequency*Grip)	8536.67	68	125.5393		

ANOVA table for muscular rest of PD

Source	SS	df	MS	F	p
Load	4767.769	2	2383.884	5.543138	0.0082
Load * Gender	1748.589	2	874.2947	2.032958	0.1466
Error(Load)	14622.06	34	430.0604		
Frequency	30070.24	2	15035.12	13.7449	0.0000
Frequency * Gender	107.3933	2	53.69667	0.049089	0.9522
Error(Frequency)	37191.54	34	1093.869		
Grip	3176.395	1	3176.395	6.913173	0.0176
Grip * Gender	31.41733	1	31.41733	0.068377	0.7969
Error(Grip)	7810.989	17	459.4699		
Load * Frequency	241.7464	4	60.4366	0.246594	0.9108
Load * Frequency * Gender	1251.232	4	312.808	1.276323	0.2879
Error(Load*Frequency)	16665.8	68	245.0853		
Load * Grip	175.0423	2	87.52115	0.341269	0.7133
Load * Grip * Gender	1253.257	2	626.6284	2.443399	0.1020
Error(Load*Grip)	8719.562	34	256.4577		
Frequency * Grip	950.8224	2	475.4112	3.654269	0.0365
Frequency * Grip * Gender	649.5385	2	324.7692	2.496353	0.0974
Error(Frequency*Grip)	4423.315	34	130.0975		
Load * Frequency * Grip	630.2059	4	157.5515	1.404025	0.2420
Load * Frequency * Grip * Gender	951.3978	4	237.8495	2.119603	0.0878
Error(Load*Frequency*Grip)	7630.563	68	112.2142		

ANOVA table for muscular rest of BB

Source	SS	df	MS	F	p
Load	7673.335	2	3836.668	7.92432	0.0015
Load * Gender	1085.623	2	542.8115	1.121132	0.3377
Error(Load)	16461.56	34	484.1636		
Frequency	50578.98	2	25289.49	26.75213	0.0000
Frequency * Gender	1478.866	2	739.4332	0.782199	0.4655
Error(Frequency)	32141.09	34	945.3261		
Grip	9830.679	1	9830.679	26.00376	0.0001
Grip * Gender	13.23366	1	13.23366	0.035005	0.8538
Error(Grip)	6426.823	17	378.0484		
Load * Frequency	3698.909	4	924.7272	2.493528	0.0510
Load * Frequency * Gender	2586.991	4	646.7477	1.743956	0.1505
Error(Load*Frequency)	25217.86	68	370.8509		
Load * Grip	607.7647	2	303.8824	1.693215	0.1991
Load * Grip * Gender	546.0669	2	273.0335	1.521327	0.2329
Error(Load*Grip)	6102	34	179.4706		
Frequency * Grip	3310.262	2	1655.131	9.131301	0.0007
Frequency * Grip * Gender	426.978	2	213.489	1.177811	0.3202
Error(Frequency*Grip)	6162.808	34	181.2591		
Load * Frequency * Grip	1873.256	4	468.3139	2.249033	0.0728
Load * Frequency * Grip * Gender	2004.052	4	501.0129	2.406067	0.0579
Error(Load*Frequency*Grip)	14159.57	68	208.229		

ANOVA table for muscular rest of TB

Source	SS	df	MS	F	p
Load	14745.44	2	7372.718	11.80048	0.0001
Load * Gender	4726.491	2	2363.245	3.782517	0.0329
Error(Load)	21242.56	34	624.7811		
Frequency	43390.19	2	21695.1	46.37455	0.0000
Frequency * Gender	279.7365	2	139.8682	0.298977	0.7435
Error(Frequency)	15905.99	34	467.8233		
Grip	1491.795	1	1491.795	8.594061	0.0093
Grip * Gender	1879.184	1	1879.184	10.82576	0.0043
Error(Grip)	2950.935	17	173.5844		
Load * Frequency	3369.861	4	842.4651	3.112497	0.0206
Load * Frequency * Gender	1463.475	4	365.8688	1.351706	0.2599
Error(Load*Frequency)	18405.68	68	270.6718		
Load * Grip	2053.554	2	1026.777	4.283206	0.0219
Load * Grip * Gender	155.5319	2	77.76594	0.324401	0.7252
Error(Load*Grip)	8150.534	34	239.7216		
Frequency * Grip	1461.766	2	730.8829	1.982896	0.1533
Frequency * Grip * Gender	101.0684	2	50.53422	0.1371	0.8724
Error(Frequency*Grip)	12532.18	34	368.5936		
Load * Frequency * Grip	382.6652	4	95.66629	0.458436	0.7659
Load * Frequency * Grip * Gender	2473.11	4	618.2775	2.962804	0.0257
Error(Load*Frequency*Grip)	14190.23	68	208.6798		

ANOVA table for muscular rest of ED

Source	SS	df	MS	F	p
Load	5042.42	2	2521.21	6.911243	0.0030
Load * Gender	2942.588	2	1471.294	4.033171	0.0268
Error(Load)	12403.14	34	364.7984		
Frequency	36390.98	2	18195.49	23.08982	0.0000
Frequency * Gender	981.8653	2	490.9326	0.622986	0.5424
Error(Frequency)	26793.05	34	788.031		
Grip	18326.03	1	18326.03	6.140555	0.0240
Grip * Gender	1638.016	1	1638.016	0.548855	0.4689
Error(Grip)	50735.24	17	2984.426		
Load * Frequency	217.7757	4	54.44394	0.2368	0.9166
Load * Frequency * Gender	1260.986	4	315.2466	1.37114	0.2531
Error(Load*Frequency)	15634.26	68	229.9157		
Load * Grip	624.8579	2	312.429	1.446583	0.2495
Load * Grip * Gender	1117.458	2	558.7292	2.586981	0.0900
Error(Load*Grip)	7343.228	34	215.9773		
Frequency * Grip	827.0422	2	413.5211	1.865391	0.1703
Frequency * Grip * Gender	166.2475	2	83.12375	0.374971	0.6901
Error(Frequency*Grip)	7537.143	34	221.6807		
Load * Frequency * Grip	2276.77	4	569.1925	2.190796	0.0792
Load * Frequency * Grip * Gender	1642.169	4	410.5422	1.580158	0.1895
Error(Load*Frequency*Grip)	17667.13	68	259.8108		

ANOVA table for muscular rest of ECR

Source	SS	df	MS	F	p
Load	3703.98	2	1851.99	6.610758	0.0038
Load * Gender	118.2694	2	59.13471	0.211084	0.8108
Error(Load)	9525.03	34	280.1479		
Frequency	29079.19	2	14539.6	19.91675	0.0000
Frequency * Gender	182.1639	2	91.08194	0.124767	0.8831
Error(Frequency)	24820.63	34	730.0185		
Grip	27932.49	1	27932.49	18.65063	0.0005
Grip * Gender	8254.686	1	8254.686	5.511686	0.0313
Error(Grip)	25460.39	17	1497.67		
Load * Frequency	887.4785	4	221.8696	0.573972	0.6824
Load * Frequency * Gender	730.9517	4	182.7379	0.472739	0.7556
Error(Load*Frequency)	26285.49	68	386.5513		
Load * Grip	2693.606	2	1346.803	4.807966	0.0145
Load * Grip * Gender	442.2748	2	221.1374	0.789441	0.4622
Error(Load*Grip)	9524.05	34	280.1191		
Frequency * Grip	605.2529	2	302.6265	1.070855	0.3540
Frequency * Grip * Gender	1130.679	2	565.3397	2.000475	0.1509
Error(Frequency*Grip)	9608.493	34	282.6027		
Load * Frequency * Grip	165.6758	4	41.41894	0.145447	0.9644
Load * Frequency * Grip * Gender	905.1061	4	226.2765	0.794591	0.5328
Error(Load*Frequency*Grip)	19364.42	68	284.7709		

ANOVA table for muscular rest of FDS

Source	SS	df	MS	F	p
Load	4332.311	2	2166.156	7.420787	0.0021
Load * Gender	1017.864	2	508.9318	1.743492	0.1902
Error(Load)	9924.728	34	291.9038		
Frequency	19006.39	2	9503.196	21.91435	0.0000
Frequency * Gender	900.45	2	450.225	1.038218	0.3650
Error(Frequency)	14744.16	34	433.6518		
Grip	33760.63	1	33760.63	17.18398	0.0007
Grip * Gender	1483.719	1	1483.719	0.755205	0.3969
Error(Grip)	33399.17	17	1964.657		
Load * Frequency	875.3266	4	218.8317	1.12099	0.3539
Load * Frequency * Gender	1355.584	4	338.8961	1.736034	0.1522
Error(Load*Frequency)	13274.47	68	195.2128		
Load * Grip	530.9412	2	265.4706	1.910094	0.1636
Load * Grip * Gender	94.38131	2	47.19066	0.339543	0.7145
Error(Load*Grip)	4725.422	34	138.983		
Frequency * Grip	1498.941	2	749.4707	5.144992	0.0112
Frequency * Grip * Gender	180.3893	2	90.19463	0.619171	0.5444
Error(Frequency*Grip)	4952.778	34	145.6699		
Load * Frequency * Grip	623.3785	4	155.8446	1.114283	0.3570
Load * Frequency * Grip * Gender	545.3049	4	136.3262	0.974728	0.4272
Error(Load*Frequency*Grip)	9510.538	68	139.8609		

ANOVA table for muscular rest of FCR

Source	SS	df	MS	F	p
Load	2399.422	2	1199.711	5.672574	0.0075
Load * Gender	1608.597	2	804.2983	3.80295	0.0323
Error(Load)	7190.771	34	211.4933		
Frequency	17810.81	2	8905.405	16.8936	0.0000
Frequency * Gender	298.9259	2	149.463	0.283532	0.7549
Error(Frequency)	17922.98	34	527.1465		
Grip	17858.85	1	17858.85	10.24754	0.0052
Grip * Gender	2117.947	1	2117.947	1.215294	0.2856
Error(Grip)	29626.66	17	1742.745		
Load * Frequency	233.5416	4	58.38539	0.461649	0.7636
Load * Frequency * Gender	537.7135	4	134.4284	1.062914	0.3817
Error(Load*Frequency)	8600.062	68	126.4715		
Load * Grip	660.7053	2	330.3527	2.028589	0.1471
Load * Grip * Gender	56.93655	2	28.46828	0.174815	0.8404
Error(Load*Grip)	5536.847	34	162.8484		
Frequency * Grip	1732.368	2	866.1842	5.033764	0.0122
Frequency * Grip * Gender	146.8455	2	73.42273	0.426691	0.6561
Error(Frequency*Grip)	5850.545	34	172.0748		
Load * Frequency * Grip	900.1371	4	225.0343	2.995597	0.0245
Load * Frequency * Grip * Gender	237.8516	4	59.46289	0.791554	0.5347
Error(Load*Frequency*Grip)	5108.274	68	75.12168		