The effect of weight and weight distribution on upper extremity muscular fatigue during static rifle aiming

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ABSTRACT

Modern weapon-mounted technologies, such as novel sighting devices, detachable grenade launchers, and telescopic butt stocks, add considerable weight to weapons and alter the center of mass (COM). Currently, few objective studies have investigated the effects of these alterations on soldiers' rifle handling.

The purpose of this study was to examine the effect of weight and weight distribution on upper extremity muscular fatigue during static rifle aiming. Custom testing rigs were designed to allow the weight and COM of the in-service C7A2 assault rifle to be altered using supplementary weights and an adjustable rail system. Seven rifle configurations, each of which represented the weight and COM of a potential future design, were assessed. Soldiers performed static rifle holds with each of the rifle configurations. Upper extremity muscle activity was monitored using surface electromyography (EMG) and a subjective scale of perceived exertion. Dependent measures included muscular activity level (integrated EMG), rate of muscular fatigue (slope of the median power frequency), and subjective ratings of perceived exertion (Borg CR10 scale). The body areas exhibiting the most muscular strain throughout testing were also subjectively assessed using a body map.

The results revealed that the muscle activation levels of the supporting arm were substantially greater (>30% increase) when the COM was shifted forward 7cm. This objective finding was supported by the soldiers' subjective perceptions of muscle effort. Conversely, muscle activity levels did not make evident the effects of added weight; although this may have been largely due to the fact that muscle activity from the lower back was not captured. Rates of muscle fatigue were found to be greater in the anterior

deltoid than other extremity muscles and fatigue levels were greater in the supporting arm than the trigger arm. However, using rates of fatigue it was not possible to differentiate between weight conditions and COM positions. Despite the limitations of this study, it has provided a starting point toward developing a standardized protocol for assessing muscular demands during rifle aiming.

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GLOSSARY OF ABBREVIATED TERMS

AD	Anterior Deltoid
ANOVA	Analysis of Variance
BB	Biceps Brachii
BR	Brachioradialis
COM	Center of Mass
cRPE	CR10 Ratings of Perceived Exertion
DRDC	Defense Research and Development Canada
EMG	Electromyography
iEMG	Integrated EMG
MDF	Median Power Frequency
MNF	Mean Power Frequency
MUAP	Motor Unit Action Potential
RMS	Root Mean Squared
RPE	Ratings of Perceived Exertion
SA	Supporting Arm
SARP	Small Arms Replacement Project
sMDF	Slope of the MDF
TA	Trigger Arm

CHAPTER 1: INTRODUCTION

The Canadian Forces will soon start the process of replacing its fleet of small arms weapons. In order to develop an enhanced weapons system, Defense Research and Development Canada (DRDC) partnered with ten NATO countries in the Small Arms Replacement Project (SARP). The objective of this collaborative group was to develop novel small arms technology with enhanced lethality, fire control, and human factors integration. One specific goal of the group was to investigate the effects of changes in weapon weight and centre of mass (COM) on soldier performance.

Modern weapon-mounted technologies, such as novel sighting devices, detachable grenade launchers, and telescopic butt stocks, add considerable weight to weapons and alter the COM. Currently, studies designed to investigate the effects of these alterations on soldiers' rifle handling rely heavily on soldiers' subjective feedback and shot accuracy. As part of the SARP, DRDC is committed to improving objective weapon-systems evaluation capabilities.

Upper extremity and rifle kinematics during aiming and firing have previously been quantified using optoelectronic motion capture systems (Zatsirsky and Aktov, 1990; Era et al, 1996; Mononen et al., 2003a; Mononen et al., 2003b; Pellegrini, 2005), and goniometers (Yuan and Lee, 1997). Force plates have also been used to assess postural stability during aiming (Yuan and Lee, 1997; Era et al, 1996), while electromyography has been used to assess muscular activity (Yuan and Lee, 1997; Wardrop and Roach, 1992; Konttinen et al, 1998; Larue et al, 1989). Each of these objective measures has provided valuable insight into individual, environmental, and equipment factors affecting

a shooter's performance. However, standard protocols for testing rifles using these technologies have not been developed and these evaluation methods are not typically implemented during the rifle design process.

Many of the abovementioned studies have identified whole body stability and rifle steadiness as key contributors to shot accuracy. Given that muscle fatigue often results in tremor and instability, a better understanding of the fatigue process during shooting may provide details about stability of the shooter-rifle system not otherwise possible. Surface electromyography (EMG) can be used as a unique and minimally invasive tool to quantify muscular fatigue. During fatiguing isometric constant-force contractions the spectral power of the surface EMG signal shifts toward lower frequencies (Petrofsky and Lind, 1980; Stulen and DeLuca, 1981; Naeije and Zorn, 1982; Areddt-Nielsen et al, 1984; Merletti et al., 1990). A clear consensus on the physiological mechanism leading to this spectral shift has not been reached; however, characteristic frequency parameters, such as the median power frequency (MDF), have still proven to be useful in quantifying fatigue.

The purpose of this study was to explore the effect of weight and weight distribution on upper extremity muscular activity and fatigue during static rifle aiming. Testing rigs were designed that allowed the weight and center of mass (COM) of a C7A2 assault rifle to be altered using supplementary weights and an adjustable rail system. Three rifle COM positions and two additional weight conditions were assessed, each of which represented a potential future rifle design. The in-service rifle, with no added weight and no change in COM, was also included as a baseline. In total, seven rifle configurations were investigated. Soldiers performed static rifle holds with each of the

rifle configurations and fatigue was monitored using surface electromyography of the upper extremity and a subjective scale of perceived exertion. It was expected that there would be an increase in upper extremity muscular fatigue as weight increased and when the COM was shifted forward, towards the barrel. If this were true, additional weight and a more forward shifted COM would result in higher muscle activity levels, and in turn greater decreases in the median power frequency during the fatiguing task. Higher ratings of perceived exertion were also expected. It was hoped that this study would enhance the current weapon selection process and provide a starting point toward developing a standardized protocol for assessing muscular fatigue during rifle aiming.

CHAPTER 2: REVIEW OF LITERATURE

2.1 Objective Assessment of Rifles

Physiological and biomechanical studies investigating the weapon-shooter system are of great interest to weapon manufactures, participants and coaches involved in sport shooting, and the military community. The most common element in many shooting studies is the identification of determinants of successful shooting performance. This, however, is not straightforward as the firing of a rifle is a particularly intricate and multifaceted task, which is sensitive to individual, environmental, and equipment variations.

2.1.1 Individual Factors Affecting Performance

Many researchers have attempted to discern differences between shooters based on individual characteristics such as experience level, sex, and acquired technique. Era et al. (1996) compared postural control during aiming for national-level rifle shooters and amateur shooters. Deviations in center of pressure were quantified using a force plate, while aiming point fluctuations were captured with a bore-sighted laser and optical target. It was found that male expert shooters displayed greater postural stability than female expert shooters, who were in turn more stable than naive shooters. However, Kemnitz et al. (2001), using trained military personal, did not find a significant difference in marksmanship performance as a function of sex.

Zatsiorsky and Atov (1990) also found that as skill level increased rifle fluctuations decreased. They further asserted that highly qualified and successful shooters used a ‘fixation strategy’, whereby the shooter fixed the aiming line on target

just prior to firing. Conversely, less skillful shooters used an 'interception strategy', whereby the shooter attempted to correctly time the movement so that firing occurred at the moment when the aiming line intercepted the target center. Others, such as Larue et al. (1989), have attempted to compare the firing techniques used by different groups, such as biathletes and rifle shooters. These researchers compared weapon-shooter stability, not only using rifle oscillations and the center of pressure, but also using electromyography (EMG) to capture muscle activation patterns of the tibialis anterior, gastronemius and deltoid.

2.1.2 Environmental Factors Affecting Performance

Environmental factors, such as availability of visual performance feedback, simulated versus real environments, and weather conditions can all effect shooting performance. Within the last few decades, optoelectronic shooting training systems, operating on a dry fire basis and often using computer-simulated environments, have been used to describe rifle movement during shooting (Mason et al., 1990; Konttinen et al., 1998; Vitassalo et al., 1999; Momonen et al., 2003b). Most investigators who examined these systems have found them to be valid when compared to live-fire training and have found that the systems can actually improve training by providing instantaneous kinematic and shot accuracy feedback (Momonen et al., 2003b). Few investigators have focused on examining other environmental factors that may impact shooting performance. Reading et al. (1994) attempted to examine the impact of shivering, induced by acute cold exposure (4°C), on shooting accuracy. However, they were unable find significant effects despite the presence of mild shivering in the upper extremity.

2.2.3 Equipment Factors Affecting Performance

Equipment, in particular rifle design parameters, may have a great impact on a shooter's performance. Many experts have declared that weight reduction and shortening the length of the rifle are the most important design parameters to improve weapon handling (Miller, 1983; Hogg and Weeks, 1985; Bahniuk, 1989; Joyce, 1992; Chavee, 1993). However, published objective testing to affirm these beliefs appear to be sparse, and Obsorne and Smith (1986) found that many knowledgeable shooters preferred longer stocks and heavier weights.

Three investigative groups have objectively assessed the effects of weapon weight and weight distribution. Kemnitz et al. (2008) examined the effect of rifle stock length and rifle weight on military marksmanship performance and did, in fact, find that accuracy was significantly better with the shortest stock and lightest weight rifle. Yuan et al. (1997) also investigated the effects of rifle weight (3.3kg vs. 3.7kg) and stock length (28cm vs. 33cm) in an extensive study that quantified upper extremity kinematics, center of pressure fluctuations, aiming point fluctuations, muscular activity of the biceps brachii and deltoid, and subjective preferences during a simulated aiming exercise. They found that different upper extremity postures were assumed for varying rifle weights and handling lengths. Muscular activity levels of the left biceps brachii increased as weight was added. When the holding length of the rifle was increased, the activity of the right deltoid and left biceps brachii increased. Furthermore, center of pressure fluctuations in the transverse axis and aiming point fluctuations in the horizontal and transverse axis increased for the longer and heavier rifle condition. Subjective preferences also confirmed that aiming ability suffered with increased weight and lengthened rifles. Selinger et al. (2009) examined the effects of rifle weight and center of mass (COM)

during dynamic pivot and fire drills using a weapon-mounted accelerometer. A forward shift in rifle COM was found to increase the time it took soldiers to sight on target. However, additional weight was found to decrease the time to site on target and increase the amount of aiming point fluctuations. The investigators hypothesized that the additional weight caused the soldiers to rush the aiming portion of the shot to avoid muscular fatigue.

2.2.4 The Importance of Stability

A common thread in many of the aforementioned studies is the stressed importance of stability. Many researchers, simply working to understand the basic mechanisms underlying the skill of rifle shooting, have identified whole body postural stabilization (Era et al., 1996; Minvielle and Audiffern, 2000; Ball et al., 2003) and rifle steadiness (Konttinen et al., 1998; Ball et al., 2003; Pellegrini and Schena, 2005) as key determinants of accuracy. Although these findings may seem intuitive, the immense importance of weapon-shooter system stability is underscored when one considers the level of precision required during firing. When firing a standard assault rifle from a range of 100 meters, a deviation in the rifle barrel of only one cm from the aiming line (just over a half degree change in angle) can result in a missed target by approximately one meter.

Muscles of the body are the underlying supports that provide stability to the weapon-shooter system. Consequently, fatigue of the muscles decreases performance by causing tremor, wobble, or other instabilities. Muscle activity levels of the upper extremity, including the trapezius (Konttinen et al., 1998), deltoid (Larue et al., 1989; Wardrop and Roach, 1992; Yuan et al., 1997; Konttinen et al., 1998), biceps brachii

(Yuan et al., 1997), brachioradialis (Konttinen et al., 1998), flexor digitorum superficialis (Wardrop and Roach, 1992), and palmaris longus (Konttinen et al., 1998), as well as lower extremity muscles, including the tibialis anterior and gastronemius (Larue et al., 1989) have been investigated during shooting. Muscle activity patterns have allowed investigators to gain basic insight into the stabilizing mechanisms implemented during shooting (Wardrop and Roach, 1992; Larue et al., 1989), differentiate between skilled and naïve shooters (Konttinen et al., 1998), and better understand the impact of alterations in rifle design (Yuan et al., 1997). However, all of these studies have only quantified changes in muscle activity amplitude, either using an integrated EMG or root mean squared (RMS) technique. No studies have directly investigated muscle fatigue using an EMG spectral analysis, despite the fact that investigators have stated that they believe the ability to minimize fatigue would greatly enhance the performers' potential accuracy (Wardrop and Roach, 1992).

In summary, kinematics during rifle shooting have been successfully captured using optoelectronic motion capture systems, specialized shooter training systems, and goniometers. Force plates have also been used to capture whole body stability, while electromyography has been used to reveal muscle activity. All of these technologies have unveiled the impacts of individual, environmental, and equipment factors that may affect optimal performance. Furthermore, the importance of whole body stability and rifle steadiness are recurring themes in many of these studies. A fatigue specific EMG analysis has not been undertaken, even though it may provide details about stability of the shooter-rifle system that are not otherwise possible.

2.2 Measuring Muscle Fatigue

The concept of fatigue is often misunderstood and wrongly applied. Many may consider fatigue to occur at a discrete moment in time. For example, a 'failure point' is often identified when an individual can no longer complete or adequately maintain a given task. This identifiable deterioration in performance is frequently recognized as the onset of fatigue. However, given the physiological and biochemical changes occurring within a muscle, it is more appropriate to view fatigue as a continuous process throughout a task, which ultimately leads to the inability to maintain force and an observable mechanical failure (DeLuca, 1984).

2.2.1 Myoelectric Measures of Fatigue

During voluntary contraction, electrical signals, in the form of motor unit action potentials (MUAPs), can be recorded using EMG. Surface EMG, whereby the electrical signals are detected from the surface of the skin, can be used as a unique and minimally invasive tool to quantify the process of fatigue. The effects of fatigue are manifested in the surface EMG signal through two primary phenomena. Firstly, during a sustained static contraction, the frequency component of the EMG signal shifts toward the low end of the spectrum, and secondly, the amplitude of the EMG signal increases over time. In the following section the factors that result is these signal alterations will be discussed.

2.2.1.1 Spectral and Time Domain Myoelectric Manifestations of Fatigue

The power spectral density shift to lower frequencies and the increase in signal amplitude, during sustained contractions, has been documented extensively since the historic work of Piper (1912) and Cobes and Forbes (1923), respectively. Despite the myriad of work documenting the frequency shift (Petrofsky and Lind, 1980; Stulen and

DeLuca, 1981; Naeije and Zorn, 1982; Areddt-Nielsen et al., 1984; Merletti et al., 1990) and amplitude increase (Lippold et al., 1960; Stephens and Taylor, 1972; Arendt-Neilson and Mills, 1988), uncertainty still surrounds the underlying physiological mechanisms that lead to these changes. Four dominant explanations include: a decrease in the conduction velocity of the muscle fiber, a decrease in motor unit firing rates, an increase in motor unit recruitment, and motor unit synchronization.

Muscle fibre conduction velocity, the rate at which a MUAP propagates along a muscle fibre, has been highly correlated with a decrease in the surface EMG signal spectrum, both theoretically (Lindstrom et al., 1970; Lindstrom et al., 1977; Stulen and DeLuca, 1981) and experimentally (Naeije and Zorn, 1982; Sadoyama et al., 1983; Areddt-Nielsen et al., 1984; Zwarts et al., 1987; Merletti et al., 1990), during fatiguing isometric constant-force contractions. Throughout the process of muscle fatigue, the concentration of noxious metabolic biproducts, such as lactic acid and pyruvic acid, increase within the muscle fiber and interstitial fluid (Bezanilla et al, 1972). These biproducts result in a decline in pH that effects muscle enzyme behaviour, electrolytic balance, and ultimately leads to a decrease in membrane excitability and slowing of conduction velocity (Murphy, 1966; Mortimer et al, 1970, Edwards, 1981). A slower conduction velocity causes the time duration of the recorded waveforms to increase because the time for the MUAP to transverse the surface electrode sites increases (DeLuca, 1984). This change in shape of the MUAP waveform is reflected in the surface EMG power spectrum as a shift toward lower frequencies during fatigue.

The power spectral shift of the surface EMG signal also has an effect on the amplitude of the signal in the time domain. Tissues between the emanating signal and the

detection site, be it muscle or fat, act as low pass filters (Farina and Rainoldi, 1999). Because the frequencies of the signals being emanated from the muscle have shifted to the lower end of the spectrum, more signal energy is able to pass through the tissues and an increase in signal amplitude is recorded during fatigue (DeLuca, 1984).

Despite the clear correlation between conduction velocity reduction, power spectral shift, and amplitude increase, uncertainty still surrounds the underlying physiological mechanism. Linssen et al. (1990) studied muscle fatigue in a pathological population unable to produce lactic acid and they still recorded a decrease in the conduction velocity of the biceps brachii during sustained contractions, indicating that a modification in muscle pH is not the only determinate of conduction velocity. Furthermore, some investigators have noted that, even in a healthy population, the power spectral density was typically scaled by a factor greater than would be predicated based on changes in conduction velocity (Bigland-Ritchie et al., 1981; Naeije and Zorn, 1982).

Overall, it appears that the accumulation of acidic biproducts, resulting in a decrease in muscle fibre conduction velocity, contributes to the power spectral shift and amplitude increase. However, this phenomenon is not the only myoelectric manifestation of fatigue, and other physiological process may be occurring simultaneously to affect the surface EMG signal.

Motor unit firing rate, the frequency at which individual motor units discharge action potentials, has been proposed as additional fatigue adaptation. However, a clear consensus on the relationship between firing rate and fatigue has not been established. Many investigators have found that firing rates decrease during fatigue (Garland et al., 1994; Person and Kudina, 1972; Gatev et al., 1986; DeLuca et al., 1996; Calder et al.,

2008). Some investigators have hypothesized that fatigue induced metabolic build-up slows firing rates in much the same way as conduction velocity, particularly during early stages of contraction (DeLuca, 1997). When isolated, the affect of a decreased firing rate would theoretically result in a decrease in the amplitude of the surface EMG signal during early phases of contraction. In any case, the effect of firing rate on the power spectrum is hypothesized to be minimal and believed to be greatly overshadowed by the energy contributions of the MUAP waveforms (DeLuca, 1997).

Despite the physiological hypothesis for a decreased firing rate, other investigators have found that fatigue results in an increased firing rate (Bigland-Richie et al., 1986; Enoka et al., 1989; Miller et al., 1996). Still others have found that firing rates can increase, decrease, or remain stable, depending on the level of maintained force (Maton, 1981). Interestingly, Garland et al. (1994) found that the discharge rates of motor units active from beginning of contraction declined during fatigue, while the discharge rates of motor units that were newly recruited either remained constant or increased slightly. This finding may explain some of the discrepancies in earlier work, and indicates that the effects of firing rate are related to yet another physiological manifestation of fatigue- motor unit recruitment.

Motor unit recruitment, is another, physiological adaptation hypothesized to reflect the myoelectric manifestation of fatigue. Many researchers have proposed that as a muscle fatigues during an isometric contraction, the motor unit threshold decreases and additional motor units are recruited in order to maintain a constant-force (Bigland and Lippold, 1954; Lippold et al., 1957; Easton, 1960; Blank et al., 1979; Maton, 1981; Bigland-Richie et al., 1986; Maton and Gamet, 1989; Garland et al., 1994; Dolan et al.,

1995). This proposed adaptation would undoubtedly contribute to an increase in signal amplitude. However, the newly recruited, non-fatigued, motor units are frequently reported to have an increased conduction velocity, resulting in short signal duration (Gazzoni et al., 2001). Therefore, the time-dependent recruitment of motor units should result in a shift toward higher spectral frequencies. This contradicts the finding that during fatigue the power at lower frequencies increases. The level of motor unit recruitment has also been shown to be highly dependent on the level and length of contraction. Increased levels of motor unit recruitment tend to occur under lower levels of sustained contraction than higher levels of contraction and motor unit recruitment does not tend to occur immediately, but rather after prolonged contraction (Merletti et al., 1990; Gazzoni et al., 2001).

Motor unit synchronization, the tendency for multiple motor units to fire at nearly the same time, has been proposed as a fourth physiological mechanisms reflecting fatigue (Lippold et al., 1960; Person and Kudina, 1968; DeLuca, 1979; Basmajian, 1980). Synchronization, like recruitment, has also been found to become more evident as the contraction is sustained (Lippold et al., 1957; Lippold et al., 1960), although the relative levels of synchronization may differ greatly for various muscles, contraction levels, and contraction durations (Bremner et al., 1991; Semmler and Nordstrom, 1995; Huesler et al., 1998; Schmied et al., 1998). Motor unit synchronization has been found to cause an increase in the amplitude the surface EMG signal (Chaffin, 1973; Bigland-Richie et al., 1981; Yao et al., 2000). Yao et al. (2000) proposed that the effect can be explained by 'a reduction in the cancellation of the EMG signal that occurs when positive and negative phases of action potentials overlap'. Yet again, the effects of motor unit synchronization

on the power spectrum of the signal are unclear. Some researchers using mathematical models of the EMG signal have indicated that synchronization has little, if any, effect on the power spectrum (Blinowska et al., 1980; Jones and Lago, 1982), while others believe synchronization contributes to a shift toward lower spectral frequencies (Chaffin, 1973; Bigland-Richie et al., 1981).

Overall, changes in motor unit conduction velocity, firing rate, recruitment, and synchronization may jointly interact to alter the time and spectral characteristics of the surface EMG signal as fatigue progresses. Notably, the spectral shift is most dramatic near the onset of a sustained contraction, while the EMG amplitude tends to show the greatest increases near the end of a sustained contraction (DeLuca, 1984). This divergence in onset indicates that the myoelectric manifestation of fatigue is a multifaceted phenomenon; the spectral and amplitude changes are likely to have separate origins. If one is to assume that the four physiological mechanisms described above all contribute to the fatigue process, the discrepancy between spectral and amplitude onsets is reasonable. The decrease in conduction velocity is likely the primary contributor to the frequency shift and occurs early in the sustained contraction (DeLuca, 1984), resulting in the evident early drop to a lower spectral content. The slowed conduction velocity would also slightly increase the surface EMG amplitude, but this effect may be masked due to the decreased firing rate, which also occurs early in contraction and works to decrease the signal amplitude (DeLuca, 1984). As the contraction is sustained, the decreases in conduction velocity and firing rate tend to level off, while motor unit recruitment and synchronization may begin to occur. These two phenomena work to increase the

amplitude of the EMG signal, overcoming the effects of the decreased firing rate, and the overall amplitude of the signal rises in the later phases of contraction.

2.2.1.2 Confounding Factors Affecting the Myoelectric Signal

Many other factors can affect the myoelectric signal recorded from a muscle, including: muscle fiber type, muscle length, tissue filtering, electrode properties, and signal stationarity. Muscle fiber composition effects the rate at which a muscle fatigues. Researchers have determined that larger diameter muscle fibers display faster conduction velocities than smaller diameter fibers (Katz, 1947; Hakansson, 1957; Kossev et al., 1991). Muscle fibers can broadly be characterized as slow-twitch (Type I) and fast-twitch (Type II) (Scott et al., 2001). Type I muscle fibers are smaller in diameter and, therefore, have a slower conduction velocity. However, these fibers use aerobic metabolism, making them resistant to fatigue. Type II muscle fibers are larger in diameter and, therefore, have a faster conduction velocity, but these fibers use anaerobic metabolism thus making them more susceptible to fatigue. As a result, muscles with a greater percentage of fast-twitch fibers display greater initial conduction velocities, and therefore more power in the high end of the frequency spectrum (Hakkinen and Komi, 1986; Gerdle et al., 1991; Lissen et al., 1991). Additionally, these muscles display a greater reduction in conduction velocity, and therefore greater leftward shift in the spectrum over the course of a contraction (Kupa et al., 1995). Overall, the myoelectric manifestations of fatigue are related to the percentage of type II fibers per cross sectional unit area (Sadoyama et al., 1988; Linssen et al., 1991). However, it should be noted that fiber type ratios are highly variable between individuals and across muscles.

The thickness of subcutaneous tissue can also affect the surface EMG signal. Tissues including muscle and fat at act low pass filters (Farina and Rainoldi, 1999). A thicker tissue layer, resulting in a greater distance between the emanating signal and the electrode detection site on the skin's surface, will result in a shift toward the low end of the frequency spectrum and a decrease in signal amplitude. Therefore, comparison of spectral parameters detected from similar locations among subjects or different locations within subjects necessitates concern (DeLuca, 1997).

The length of a muscle during a sustained isometric contraction is also hypothesized to affect the myoelectric parameters of fatigue. Arendt-Neilsen et al. (1992) found that muscle length can affect the propagation velocity of action potentials during the development of muscle fatigue. They believed that when the muscle length changed, the diameter and length of the muscle sarcomeres were altered, affecting the conduction velocity of the action potential, which then impacted the amplitude and frequency components of the EMG signal. Morimoto (1986) indicated that when muscle length is shortened, the conduction velocity increased. This is supported by Rosenburg and Seidel (1989) and Mannion and Dolan's (1996) findings that shortened muscles exhibit a shift in the power spectrum to higher frequencies.

The myoelectric signal is not only affected by muscle characteristics, but also by electrode properties. The configuration of the electrode site, including the inter-electrode distance, electrode shape and electrode size, will affect the bandwidth of the differential electrode filtering characteristics (DeLuca, 1997). Therefore, if spectral parameters are to be compared across contractions, the same electrode configuration must be maintained. Electrode location will also affect the signal characteristics, and particular care must be

taken if the spectral properties of a signal are to be examined. Deluca (1997) recommends locating the electrodes between the myotendinous junction and the nearest intervention zone (motor point). If an electrode is located too near to a motor point, the action potentials travelling in both directions may be detected. This will result in a superposition of positive and negative phases, with relatively short time delays between them. The differential electrodes will record this as a high frequency signal, shifting the spectral properties to the right.

The orientation of the bipolar electrodes with respect to the muscle fibers will also affect the spectral properties of the surface EMG signal. Deluca (1997) recommends that the detection surfaces of the electrodes be oriented perpendicular to the length of the underlying muscle fibers because the length of the fibers that transverse the bipolar electrodes will affect the time it takes for the signal to travel from one detection site to another. If the electrode is not perpendicular to the muscle fibers, the fiber length between detection sites will increase, lengthening the time it takes for the signal to transverse the electrodes. This will be interpreted as a decrease in conduction velocity and will shift the spectral properties of the signal to the left.

Signal stationarity is imperative if the spectral properties of a signal are to be examined. Collecting the EMG during isometric contraction, as opposed to dynamic contractions, best allows for this assumption to be met (DeLuca, 1997; DeLuca, 1984). Dynamic contractions are typically non-stationary, which results in alterations in the spectral properties of the signal, making it inappropriate to calculate a power spectrum. During a dynamic contraction, the length and orientation of the muscle fibers with respect to the electrode site can be greatly altered either by changes in muscle position relative to

the skin or by slight shifts in electrode placement along the skin (DeLuca, 1984; DeLuca, 1997). Additionally, as body segments change position during a dynamic contraction, the moment arm, torque, and relative force contributions of the involved muscles are altered. The resultant recruitment and de-recruitment of motor units also contributes to non-stationarity. Recently, some investigators are using Cohen class time-frequency transforms (Bonato et al., 2001) or wavelets (Karlsson et al., 2000) to quantify fatigue during cyclic dynamic contractions. These methods constrain and isolate the non-stationary components of the signal by assuming that the effects are constant for identical phases of each cycle.

It is important to note that even during sustained isometric contractions, various neuromuscular control strategies may be employed to minimize fatigue. It is possible to vary the force contribution among synergistic and antagonists muscles, while leaving the net torque or force unchanged. Along with these global muscle tradeoffs, local motor unit substitution and rotation may also be used as strategies to minimize fatigue and optimize endurance. McLean and Goudy (2004) and Westgaard and DeLuca (1999) have found that during sustained low level contraction, substitution between motor units occurs, where by fatigued motor units are replaced with newly recruited non-fatigued motor units. Other investigators, such as Fallentin et al. (1993) have asserted that motor unit rotation may occur, where by motor units engage in cyclic phases of activation and deactivation.

Overall, in order to guarantee strong EMG signal quality, care must be taken to ensure that electrodes are properly located and oriented on the muscle of interest. To make comparisons across subjects, the electrode characteristics, including inter-electrode

distance, shape and size, must be consistent. To best ensure the spectral characteristics of the signal are not contaminated, muscle fatigue should be assessed during sustained isometric contractions and great care must be taken to ensure that static postures are maintained.

2.2.1.3 Myoelectric Parameters Used to Quantify Fatigue

Various spectral descriptors have been used to quantify the changes in frequency content of the surface EMG signal as a consequence of fatigue. Measures have included various high to low frequency ratios (Kaiser and Petersen, 1965; Sato, 1965), counts of zero crossings (Lynn, 1979, Hagg, 1981), and characteristic frequencies such as the mean and median power frequencies (Lindstrom, 1970; Stulen and DeLuca, 1981). Although all measures assess spectral shifts, the mean power frequency (MNF) and median power frequency (MDF) have emerged as the most common descriptors. Other parameters, although widely used in the past, suffer from drawbacks. Frequency ratios are: not linearly-related to conduction velocity; are dependent on the initial value chosen as a divisor; and, are sensitive to the shape of the EMG signal spectrum, which may vary due to motor recruitment (Kaiser and Petersen, 1965; Sato, 1965). Counting zero crossings in the time domain, despite being simple to implement, are severely affected by noise (Hagg, 1981). Both the MNF and MDF are reliable, consistent and relatively unbiased spectral parameters that are linearly-related to conduction velocity. However, each present with distinct advantages. The MNF tends to have a lower standard deviation than the MDF, while the MDF is less affected by high frequency noise and more affected by fatigue (Potvin, 1992). Additionally, the MDF is the preferred measure if the signal to

noise ratio is low. For these reasons, many investigators deem the MDF the preferred measure when quantifying fatigue (Potvin, 1992).

To quantify the progression of fatigue over time, the MDF is typically calculated over multiple time epochs and the slope of the regression line is calculated as the final outcome measure. The MDF regression line presents with a negative slope as the MDF decreases as a function of time during a sustained contraction. Linear relationships between the MDF and time have been found by Petrofsky and Lind (1980), Mannion et al. (1997), and Kankaanpaa et al. (1998), while near linear relationships, with a somewhat exponential decreases have been found by Dolan et al. (1995) and Stulen and DeLuca (1978). Discrepancies may be due to different choices of muscles, different processing schemes, or differing underlying fatigue processes. Overall, the rate of decrease is a function of contraction force, with higher forces resulting in greater rates. The absolute change in MDF from the beginning of contraction to end of contraction can decrease by more than 50%, depending on the muscle under investigation.

After cessation of a sustained contraction, the MDF has been observed to recover to its initial value following a recovery period of approximately 4-5 minutes (Sabbahi et al., 1979; Petrofsky and Lind, 1980; Mills, 1982). This is consistent with the time it takes for lactic acid and other biproducts to be removed from fatigued muscles (Harris et al., 1981) and the time required for conduction velocity to return to a non-fatigued state (Broman, 1977). However, some investigators have indicated that recovery times could be much longer when systemic exhaustion occurs (Sahlin et al., 1978).

When using the increase in signal amplitude as a fatigue index, the integrated EMG or RMS of the signal in the time domain are also calculated for set epochs and the

slope of the regression line is used as on outcome measure. However, most investigators have found that the slopes of the frequency parameters are better indicators of muscle fatigue (Lindstrom, 1970; Stulen and DeLuca, 1981; DeLuca, 1984; Potvin, 1992).

In summary, fatigue is a process which involves both physiological and biochemical changes within the muscle. Surface EMG can be used to quantify the myoelectric manifestations of fatigue, despite the fact that the exact physiological mechanisms are not entirely understood. To allow comparisons across subjects, muscles, and trials, and to ensure high signal quality, electrode properties and positioning must be kept consistent. The slope of the MDF appears to be one of the strongest myoelectric measures of muscle fatigue and should be assessed during sustained isometric contractions in order to ensure signal stationarity.

2.2.2 Subjective Measures of Fatigue

Psychophysics is a branch of psychology dealing with the relationship between physical stimuli and the sensation perceived by a subject. Scaling, that is developing methods to quantify a subject's perceived sensation, has become a prominent subfield of psychophysics. The use of the human sensory system as an instrument for measuring somatic symptoms first gained ground in the early 1950s (Steven, 1951). By the late 1950s, the concept of perceived exertion was developed further by Borg and Dahlstrom (Borg, 1998). Perceived exertion is somewhat of an umbrella term, encompassing experiences such as: fatigue, effort, breathlessness, muscle ache, feelings of warmth, weight and heaviness, force, arousal, and exercise intensity. Many factors can influence a subject's perceived exertion including physiological cues from the pulmonary system, the cardiovascular system, peripheral muscles, and other bodily organs. Additionally,

psychological cues, including cognitive demands, emotions, motivation, past experiences, and personality traits may all factor into a subject's perceived exertion.

A key concept in psychophysics is that perception does not grow linearly with physical stimulation; rather the relationship can be modeled using either positive or negative power functions (Borg, 1998). For example, if a subject undergoes a physical increase of 100%, they may perceive their exertion levels to increases by 200% or only 50%. The theory behind this distorted growth function is that 'people do not directly perceive a decline in working capacity, but rather an increase in exertion' (Borg, 1998); therefore, one cannot presuppose a linear relationship between changes in physical exertion and changes in work capacity.

Based on many psychophysical and physiological experiments, Borg developed two scales that can be used to quantify perceived exertion. The Borg Ratings of Perceived Exertion (RPE) scale and the Borg CR10 scale both use a graded scale and verbal anchors, yet differ in underlying principle. The RPE scale is an ordinal scale with values ranging from 6 ('no exertion at all') to 20 ('maximal exertion'). The RPE scale was designed recognizing an underlying power function and is intended to linearize the scale of the response. That is, the ratings are linearly-related to physiological measures such as workload, heart rate, and oxygen consumption. Although the RPE scale has the advantage of being easy to use because of this linear relationship, the statistical analyses that can be performed on the data are limited by the scale's ordinal nature.

The Borg CR10 scale uses a ratio-scaling method and begins at 0 ('nothing at all'), but has no upper maximal limit. Subjects are able to use any value above 10 to indicate maximal experienced exertion and can use fractions to describe any level of

exertion. The CR10 scale is not linearly-related to any physiological measures of exercise intensity, but the statistical procedures that can be carried out with this scale are far greater because the scale is a ratio scale. That is, if a subject reports a rating twice as great as a previous rating, then the subject perceives that they are working twice as hard. This allows investigators to examine relative growth functions and absolute values. Although the RPE scale is more widely used, consistent measures of perceived exertion can be attained using both scales and similar reliability coefficients have been obtained (Borg, 1998).

In summary, investigators have objectively quantified kinematic and kinetic properties of the shooter-rife system and have provided valuable insight into the importance of whole body stability and rifle steadiness. Despite the fact that muscles provide the foundation on which stability can be achieved, no known studies have attempted to quantify muscle fatigue using an electromyographic spectral analysis during rifle shooting. Although the physiological mechanisms underlying fatigue are not entirely understood and great care must be taken to ensure high signal quality, the MDF parameter is a reliable and widely accepted EMG measure of muscle fatigue. Subjective rating of perceived exertion may also provide insight into subjects' experienced levels of muscular fatigue and allow for comparison between objective and subjective findings.

CHAPTER 3: MEHODOLOGY

4.1 Subjects

Fourteen (thirteen male, one female) healthy Canadian Forces Reserve soldiers, who had completed Personal Weapons Training, participated in this study. Additional subjects were desired, but could not be tested due to soldier availability and logistical constraints. Subjects were briefed on the aims of the investigation and, thereafter, read and signed an information and consent form (Appendix A) approved by the Queen's University Research Ethics Board (Appendix B) and the Defence Research and Development Human Ethics Committee. The subjects had a mean height of 181cm ± 4cm and weight of 82.2kg ± 15.5kg. Individual subject anthropometric data are presented in Appendix C. All subjects wore the standard issue military combat boots, fatigue pants, a cotton T-shirt, fragmentation vest, tactical assault vest and combat helmet. Subjects were asked not to wear their long sleeve fatigue shirt. This allowed the investigators to attach electrodes easily and, whenever needed, check and replace electrodes without asking the subject to remove any clothing or equipment.

4.2 Rifle Configurations

Testing rigs were designed by Colt Canada Inc. (ON, Canada) that allowed the weight and center of mass (COM) of a 5.56mm C7A2 assault rifle to be altered using supplementary weights and an adjustable rail system. Three rifle COM positions were assessed, including: current rifle COM (0cm), current rifle COM shifted forward 7cm (+7cm), and current rifle COM shifted backward 7cm (-7cm). For each of these three COM positions, two weight conditions were assessed: 3kg and 4kg of additional weight

beyond the current rifle's weight. A standard rifle with no added weight and no change in COM was also included as a baseline. The standard rifle weighed 4kg (including a 30 round magazine and the rail system) and the COM was located at the junction of the magazine and forestock (Figure 1). In total, seven rifle configurations, each of which represented the weight and COM of a potential future design, were investigated (Table 1).

Figure 1: Standard C7A2 assault rifle instrumented with adjustable rail system. The three investigated COM positions have been indicated.

Table 1: Rifle configurations

Rifle Configuration	Weight Condition (kg)	COM Positions (cm)
0	0	0
4	3	-7
5	3	0
6	3	+7
7	4	-7
8	4	0
9	4	+7

4.3 Instrumentation

Data were collected simultaneously on five subjects; therefore, five sets of all instrumentation described below were used. Data collection was performed in a field setting on-site at a military base in Farnham, Quebec over the course of four days.

4.3.1 Electromyography

Surface electromyography (EMG) data were recorded using five eight-channel Bluemyo Bluetooth® EMG Telemetry systems (Invenium Technologies, ON, Canada) at a sampling rate of 1000Hz. The EMG telemetry systems had a quantization resolution of 12bits, an A/D input range of $\pm$1.65V, a Bluetooth Class II wireless interface, an operating range of 20m, and were powered using a 7.2 NiMH battery power supply. Two differential AE-100 silver/silver chloride EMG electrodes with a constant 1 cm spacing were mounted onto an on-board digital conversion chip that had a constant gain of 300V/V, and a bandpass filter of 25-500Hz. EMG signals were recorded bilaterally from three different upper extremity muscles, namely: anterior deltoid (AD), one finger width distal and anterior to the acromion (SENIAM, 2005); biceps brachii (BB), on the line between the medial acromion and the fossa cubit at 1/3rd the distance from the fossa cubit (SENIAM, 2009); and brachioradialis (BR), one finger width distal to the fossa cubit (NORAXON, 2009) (Figure 2). The supporting arm (SA), was defined as the arm that extended forward and braced the barrel of the rifle during aiming, and the trigger arm (TA) was defined as the arm that was flexed inward and grasped the rifle's trigger. A common reference electrode was placed on the SA olecranon process. The muscle locations were based on the required actions while shooting. Due to time constraints during testing and to ensure strong signal quality, only muscles that could be easily

accessed, without requiring the removal of the subjects' chest armour and tactical assault vest, were chosen. Therefore, the pectoralis major and all back and truck muscles were not chosen.

Figure 2: Instrumentation of upper extremity electromyography.

To improve electrode adhesion to the skin, a small patch of hair was removed using shaving foam and a hand-held razor. Rubbing alcohol and a cotton pad were used to abrade the skin and remove oil and dead skin cells. After the area was dry, the surface electrodes were placed onto the skin and secured using a fabric-based adhesive tape. As a precaution against electrode failure due to profuse sweating, outlines of electrode locations were made on the skin.

The shielded electrode cables were run up the subject's arms, over the shoulders

and attached to the Bluemyo system, which was housed in a carrying case strapped to the back of the soldier's tactical vest. All data were wirelessly transmitted from the telemetry systems to PC laptops, located approximately four meters from the subjects, using Aircable Host XR long-range industrial Bluetooth USB-dongles (Wireless Cables Inc., CA, USA).

4.3.2 Ratings of Perceived Exertion

The Borg CR10 Scale (Appendix D) was used to collect data on the subjects' perceived level of exertion following each rifle static hold. Prior to data collection, an investigator read the Borg's CR10 Scale Basic Instructions (Borg, 1998) to all subjects to ensure that they understood the scale. A poster displaying the scale was mounted to the desk of the data collection station, within plain view of the subjects. Prior to providing a rating, subjects were provided with the following instructions from their individual data collectors: 'I want you to rate your perception of exertion, that is, how heavy and strenuous the task feels to you. This depends mainly on the strain and fatigue you feel in your muscles and on your feeling of breathlessness. How heavy and strenuous does the task feel to you?' (Borg, 1998).

4.4 Testing Protocol

Five subjects completed the protocol described below simultaneously under the guidance of five data collectors.

4.4.1 Orientation Session

One day prior to testing, all subjects completed over six hours of familiarization and training with the weighted rifles. Subjects were meticulously instructed on proper aiming form and technique by senior military personnel. This training helped ensure that

all subjects assumed the same standard posture throughout the static aiming task. The posture required that subjects stand with their body square to the target, feet shoulder width apart, and knees slightly flexed. The stock of the rifle was positioned against the lateral aspect of the pectoralis muscle on the TA side. The subject's neck was slightly flexed and protruded to allow the subject to see through the rifle scope. The SA hand grasped the magazine and the TA grasped the pistol grip, both using a wrap grasp. Therefore, both wrists were in slight ulnar deviation and both elbows and shoulders were flexed, with the TA elbow being more flexed than the SA elbow and the SA shoulder being more flexed than the TA shoulder. Neither shoulder was abducted; both arms were kept tight to the body. The back was to be kept straight and was angled slightly forward by flexing at the hip (Figure 3).

Figure 3: Subjects assuming static rifle hold while instrumented with electromyography.

4.4.1 Testing Session

Subjects were suited with the EMG instrumentation described in section 4.3.1. Data collectors asked subjects to perform a series of muscle flexions to ensure that all channels were being properly collected. Once proper collection was ensured, subjects were asked to stand in a relaxed posture without the rifle in hand for ten seconds while a baseline trial was collected. This resting EMG trial was later used to remove baseline noise from other trials.

Subjects completed two repetitions of the static aiming task for each of the seven rifle configurations. Subjects assumed the static aiming posture (described in section 4.4.1) for one minute while aimed at a mock target. The target was aligned at eye level, approximately two meters in front of the subjects. The order of rifle configurations was

block randomized, that is, the rifles were tested in random order, but the two repeats for each rifle were completed sequentially. Subjects were not blinded to the rifle configurations. A minimum of five minutes rest was provided between trials. After the completion of each trial, subjects were asked to subjectively rate their perceived exertion as described in section 4.3.2. Upon completion of all trials for all rifle configurations, subjects were asked to stand in a relaxed posture, without the rifle in hand, for ten seconds while a final baseline trial was collected. Subjects then completed a body map exit survey to indicate the regions where they felt the most muscular strain during testing (Appendix E).

4.4 Data Processing

Custom software developed using Matlab 7.4.0 (The Math Works, MA, USA) was used for all data processing. Gains were applied to each trial, the DC-offset was removed, and all trials were band-pass filtered (20-450Hz) using a zero phase shift 3rd order Butterworth digital filter.

4.4.1 Error and Equipment Checking

Prior to further data processing, all raw EMG files for each subject, muscle and trial were visually inspected in the time domain as a rectified signal and in frequency domain as a power density function profile. Unfortunately, the data presented with a great deal of fault, which resulted in considerable data loss.

In the frequency domain, powerful noise spikes were present in some trials, as well as lesser spikes at preceding and subsequent harmonics. Due to the capacious nature of these spikes, and the importance of maintaining a high signal quality for spectral fatigue analysis, notch filtering was not implemented. Rather, trials were discarded if

noise spikes were visible. Noise contamination was either substantial or unapparent within the spectral profile, making identification of good and poor trials possible using only visual inspection. Refer to Appendix F for examples of good spectral profiles, which were kept, and poor spectral profiles, which were discarded.

In the time domain, dropped signals were evident, possibly due to electrode shorting or other internal electrical malfunctions within the BlueMyo system. These 'flat-lined' trials were easily detectable using visual inspection and also presented with contaminated power density function profiles. Signal clipping was rare, but was evident in some trials. Trials displaying any clipping were discarded. Appendix F also contains examples of good time domain trials, which were kept, and poor time domain trials, which were discarded.

Overall, if only one of the two trials for a given rifle was problematic, it was discarded and the other trial was kept for further data processing. If both of the trials were problematic, then the data for that rifle were lost. Certain Bluemyo systems and data channels appeared to present with greater noise contamination than others; therefore, data loss tended to be concentrated within certain muscle sites of certain subjects. If, for any given muscle, a subject did not have useable data for at least five of the seven rifle configurations, all data for that subject's muscle were discarded.

In total, approximately 40% of the data were lost. A breakdown of the percentage of retained (non-contaminated) data and the number of subjects contributing data for each muscle can be found in Table 2. Of the lost data, approximately 60% were discarded due to noise contamination, 35% due to dropped signals, and less than 5% due to signal clipping.

Table 2: Summary of data loss

Muscle Site	Retained Data (%)	Number of Subjects Contributing Data
AD-SA	66	10
AD-TA	72	11
BB-SA	59	9
BB-TA	46	7
BR-SA	64	9
BR-TA	49	7

The large amount of noise contamination called into question the quality of the spectral signal collected by the Bluemyo system. In an attempt to determine if the errors were due solely to equipment, a check of signal quality was performed and can be found in Appendix G. The frequency and amplitude content of generated sine waves, recorded using the BlueMyo system, were examined. Although some low level noise was present, the Bluemyo system appeared to accurately quantify the frequency of signals within the 20-400Hz range. The prominent noise spikes, that were evident in the field data, were not evident in the signal quality check. It was noted, however, that the amplitudes of recorded signals may have varied between electrodes. In most cases during testing, the same electrode was used on the same muscle site for all rifle configurations. Therefore, the electrode discrepancies should have had minimal impact on the findings of the study.

4.4.2 Electromyography

Each muscle's total integrated EMG was used as a parameter to indicate the amount of muscular activity required throughout the entire aiming task for a given rifle configuration. The EMG signals were full wave rectified and the mean EMG amplitudes recorded during the baseline trials were removed. The EMG signals were then smoothed using a zero phase shift 3rd order Butterworth digital filter with a low pass cut-off

frequency of 3Hz. As the subjects may have been moving slightly when they settled into the static hold or just before they completed the hold, data from the initial and final two seconds of the sixty second static hold were discarded. The signal within the remaining fifty-six second window was then integrated to provide a measure of muscular activity during each static hold. When two repeats existed, an average was calculated.

The slope of the median power frequency (MDF) for each muscle was used to quantify the progression of fatigue throughout the aiming task for a given rifle configuration. The signal within each one second epoch was zero-padded and converted to a single-sided power spectrum using the Fast Fourier Transform defined in Equation (1). The MDF for each one second epoch was then determined. Once again, the first and last two seconds of data were discarded due to the possibility of movement. Using the remaining fifty-six data points the slope of the time vs. MDF regression line was calculated as an outcome measure. When two repeats existed, an average was calculated.

(1) $$X(k) = \sum_{j=1}^{N} x(j)\omega_N^{(j-1)(k-1)}$$

For vector of length *N* where: $\omega_N = e^{(-2\pi i)/N}$

(The Math Works, MA, USA)

A summary of all EMG data processing steps, including sample plots, can be found in Appendix H.

4.4.3 Ratings of Perceived Exertion

The Borg CR10 ratings of perceived exertion were used to quantify subjects' overall perceived level of exertion for each rifle configuration. The first and second repeat ratings were averaged to produce a final subjective outcome measure.

4.5 Statistical Analysis

All statistical analyses were performed using SPSS Statistics 17.0 software (SPSS Corporation, IL, USA). Two-way repeated measures analyses of variance (ANOVA) were applied in this study to make comparisons among the rifle configurations. The independent variables included rifle COM (+7 cm, 0 cm, -7 cm shifts from standard position) and rifle weight (3kg and 4kg of additional weight). The dependent variables included: integrated EMG (iEMG), slope of the MDF (sMDF), and Borg CR10 rating of perceived exertion (cRPE) for each muscle. For each omnibus F, an alpha level of 0.05 was selected as the minimum level of significance. The effect size (η_p^2) and observed power were also reported. One-way paired contrasts were used for post hoc comparisons and the corresponding p values were reported.

A one-way ANOVA was used to compare the standard rifle configuration, which had no additional weight (0kg) and no shift in COM (0cm), with other COM (0cm) configurations (5^{th} and 8^{th} rifle configurations), in order to compare 0kg, 3kg, and 4kg of added weight. In an attempt to control family-wise error rate, an alpha level of 0.01 was selected as the minimum level of significance.

CHAPTER 4: RESULTS

The effects of design alterations to the C7A2 assault rifle were assessed. Two novel weight conditions (3kg and 4kg of additional mass) and three center of mass (COM) positions (-7cm, 0cm and +7cm shift) were investigated and compared to the current C7A2 design. Dependent measures included muscular activity level (iEMG), rate of muscular fatigue (sMDF), and subjective ratings of perceived exertion (cRPE). The body areas exhibiting the most muscular strain throughout testing were also assessed subjectively. Individual subject outcomes for each dependent measure and rifle configuration can be found in Appendix I.

5.1 Objective Parameters

5.1.1 Muscle Activity Level

For the biceps brachii of the supporting arm (BB-SA), there was a significant COM effect ($p<0.05$, $\eta_p^2= 0.518$) with an observed power of 0.709. To perform post hoc analyses, and because a weight effect was not evident, the iEMG measures were averaged across weight condition for each COM position (Figure 4). Paired comparisons revealed that muscle activity level for the 0cm COM position was significantly less than the activity level for the +7cm position ($p=0.010$).

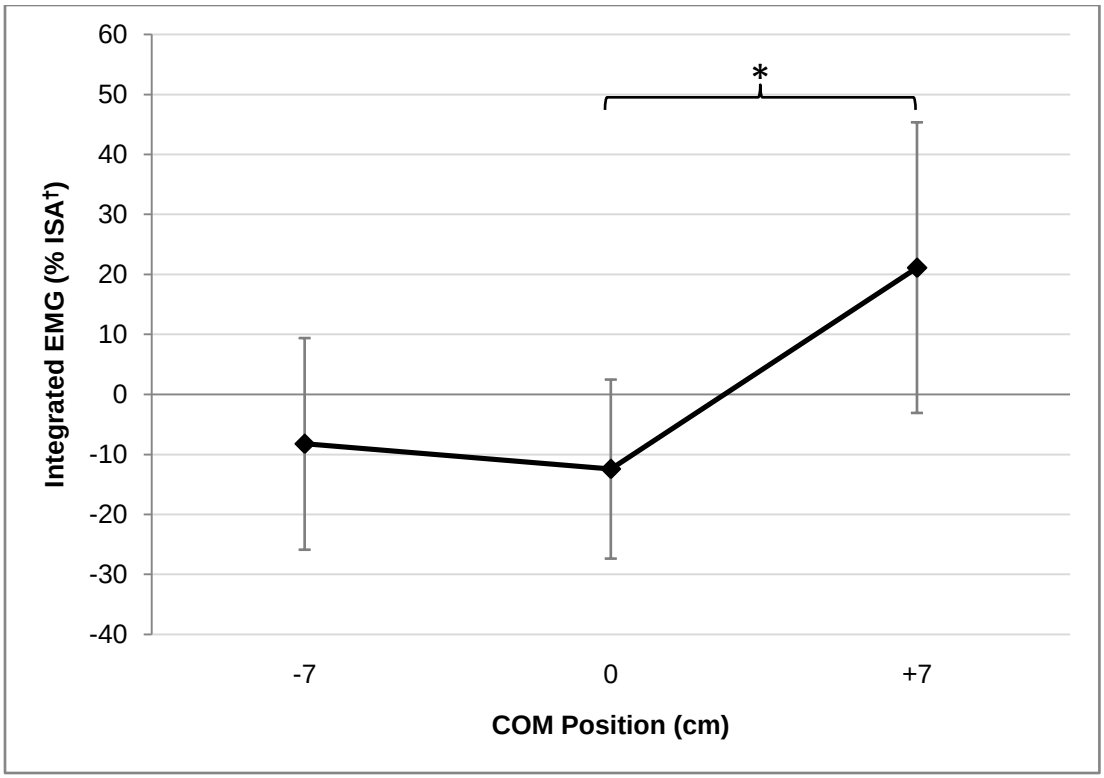

Figure 4: Integrated EMG of the BB-SA for each COM position. Significant differences were found between the 0cm and +7cm COM positions. *(†Prior to averaging across subjects, individual values were normalized to the respective intra-subject average (ISA), which was the subject's average across all rifle configurations. This removed much of the inter-subject variability and was applied for graphical purposes only.)*

The brachioradialis of the supporting arm (BR-SA) also exhibited a significant effect due to COM ($p<0.05$, $\eta_p^2= 0.369$) with an observed power of 0.702. Once again, a weight effect was not present, allowing the iEMG measures to be averaged across weight condition for post hoc analysis purposes (Figure 5). The +7cm COM position was found to induce higher activity levels than the -7cm COM position in the BR-SA ($p=0.050$).

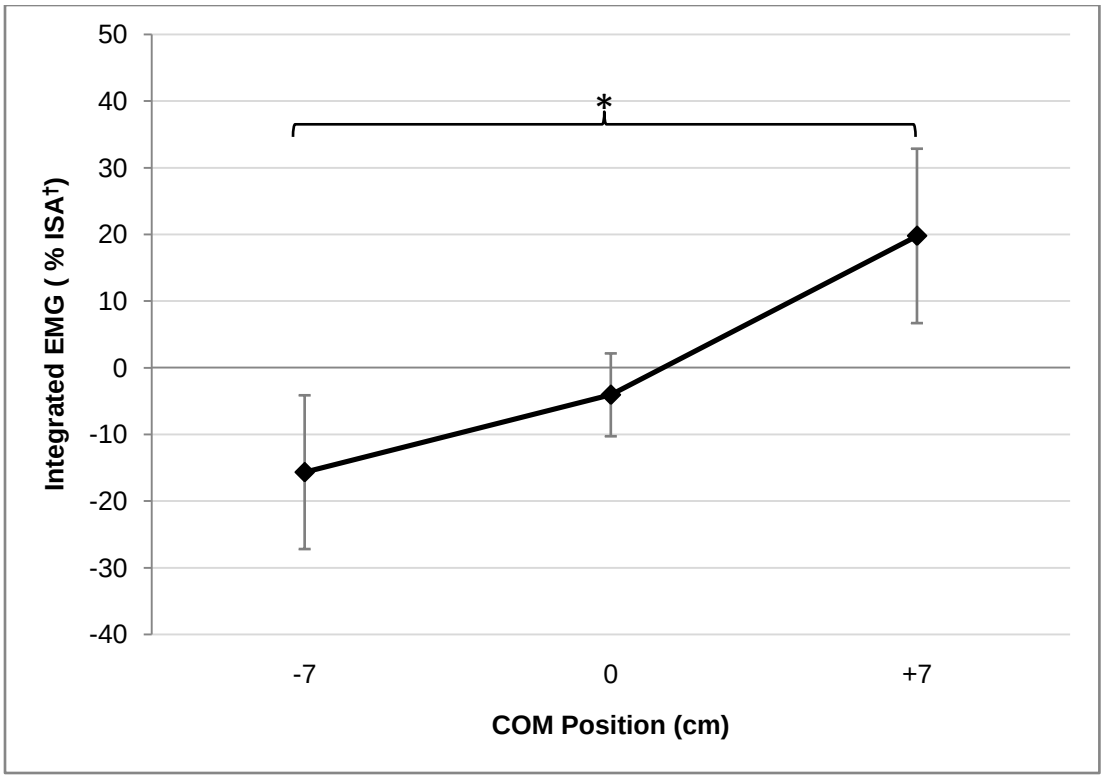

Figure 5: Integrated EMG of the BR-SA for each COM position. A significant difference was found between the -7cm and +7cm COM positions. *(†Prior to averaging across subjects, individual values were normalized to the respective intra-subject average (ISA), which was the subject's average across all rifle configurations. This removed much of the inter-subject variability and was applied for graphical purposes only.)*

The weight by COM interaction was significant for the brachioradialis of the trigger arm (BR-TA) ($p<0.05$, $\eta_p^2= 0.504$), with an observed power of 0.685 (Figure 6). Based on visual inspection of the means, post hoc paired comparisons were made. At the 0cm COM position, the activity level was greater for the 4kg weight condition than the 3kg weight condition (p=0.030). However, a significant difference was not found at the +7cm COM position (p=0.170). The muscle activity level for the 3kg weight condition was found to be greater at the +7cm COM position than the -7cm (p=0.032) and 0cm position (p=0.021), while at the 4kg weight condition the muscle activity at +7cm position was not found to be greater than the -7cm position (p=0.839).

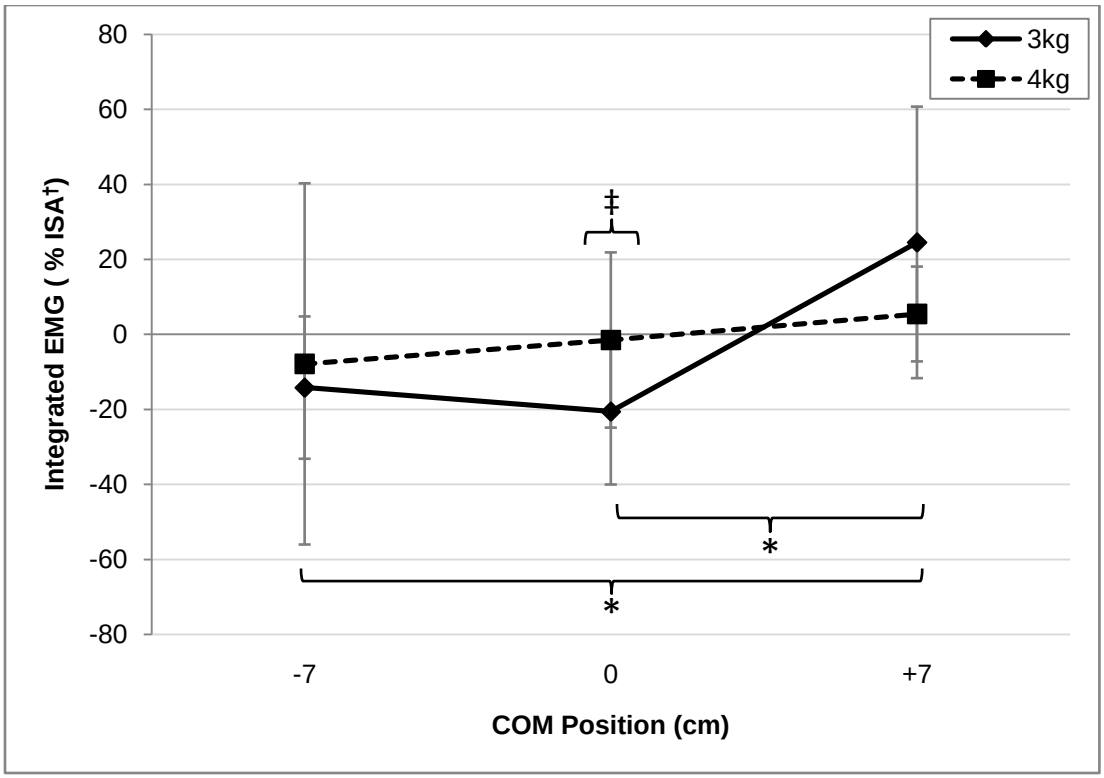

Figure 6: Integrated EMG of the BR-TA for each weight condition and COM position. A weight by COM interaction effect was evident. * represents significant differences within the 3kg condition. ‡ represents significant differences within COM position. *(†Prior to averaging across subjects, individual values were normalized to the respective intra-subject average (ISA), which was the subject's average across all rifle configurations. This removed much of the inter-subject variability and was applied for graphical purposes only.)*

Finally, a contrast of the baseline condition, which had no additional weight (0kg) and no shift in COM (0cm), with 5th and 8th rifle configurations, in order to compare 0kg, 3kg, and 4kg of added weight, did not reveal a significant effect for any of the investigated muscles ($p>0.01$).

5.1.2 Rate of Muscular Fatigue

The sMDF was used to assess the rate of muscular fatigue. Initial MDF values, at the onset of the hold, ranged between 100Hz to 150Hz. The average initial MDF values for each muscle can be found in Table 3.

Table 3: Initial MDP values for each muscle

Muscle Site	Average Initial MDF (Hz)	Standard Deviation (Hz)
AD-SA	123	18
AD-TA	130	32
BB-SA	120	29
BB-TA	120	18
BR-SA	125	28
BR-TA	120	33

For the biceps brachii of the trigger arm (BB-TA), there was a significant weight effect ($p<0.05$, $\eta_p^2= 0.798$) with an observed power of 0.639. Visual inspection of the means showed that the 3kg weight condition resulted in a greater rate of fatigue; meaning steeper negative MDF slopes (-0.076±0.085 ΔMDF/sec) than the 4kg weight condition (-0.072±0.056 ΔMDF/sec) for the BB-TA. High standard deviations are largely due to high inter-subject variability.

The sMDF did not reveal any other weight effects or any weight by COM interaction effects. However, a COM effect was evident for the BR-TA ($p<0.05$, $\eta_p^2= 0.536$), with an observed power of 0.742 (Figure 7). Based on visual inspection of the means, a post-hoc paired comparison between the -7cm and +7cm positions was made. The slope of the MDF at the +7cm position was significantly less than the -7cm position ($p=.015$), indicating that greater rates of fatigue occurred in the BR-TA when the weight was shifted forward on the weapon.

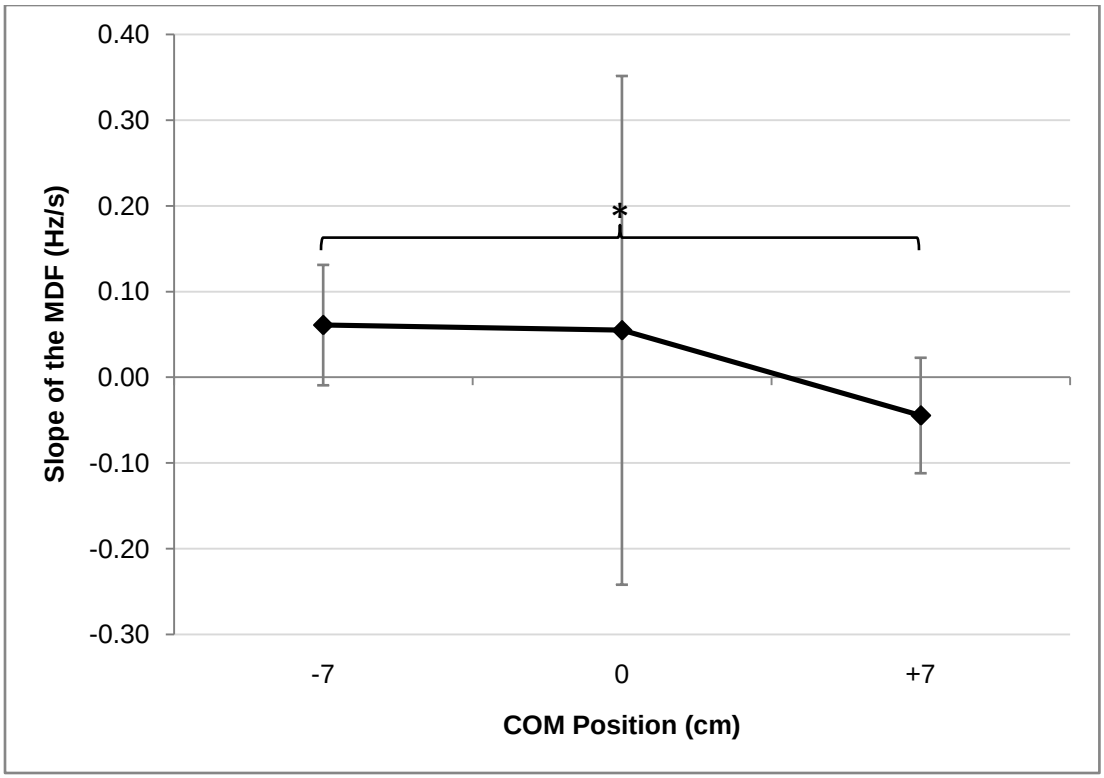

Figure 7: Slope of the MDF for the BR-TA for each COM position. A significant difference was found between the -7cm and +7cm COM positions.

Once again, a contrast of the baseline condition, which had no additional weight (0kg) and no shift in COM (0cm), 5th rifle configuration (3kg weight, 0cm COM) and 8th rifle configuration (4kg weight, 0cm COM) did not reveal a significant effect for any of the investigated muscles ($p>0.01$).

Although the BR-TA and BB-TA were the only muscles to display significant sMDF differences across weight and COM conditions, it should be noted that these muscles did not display the greatest overall rates of fatigue. The average percent change in MDF, over the 60s hold, for each muscle is presented in Figure 8. To calculate percentage change for each muscle, the average slope for each subject across all rifle configurations and the average initial MDF value for each muscle were used.

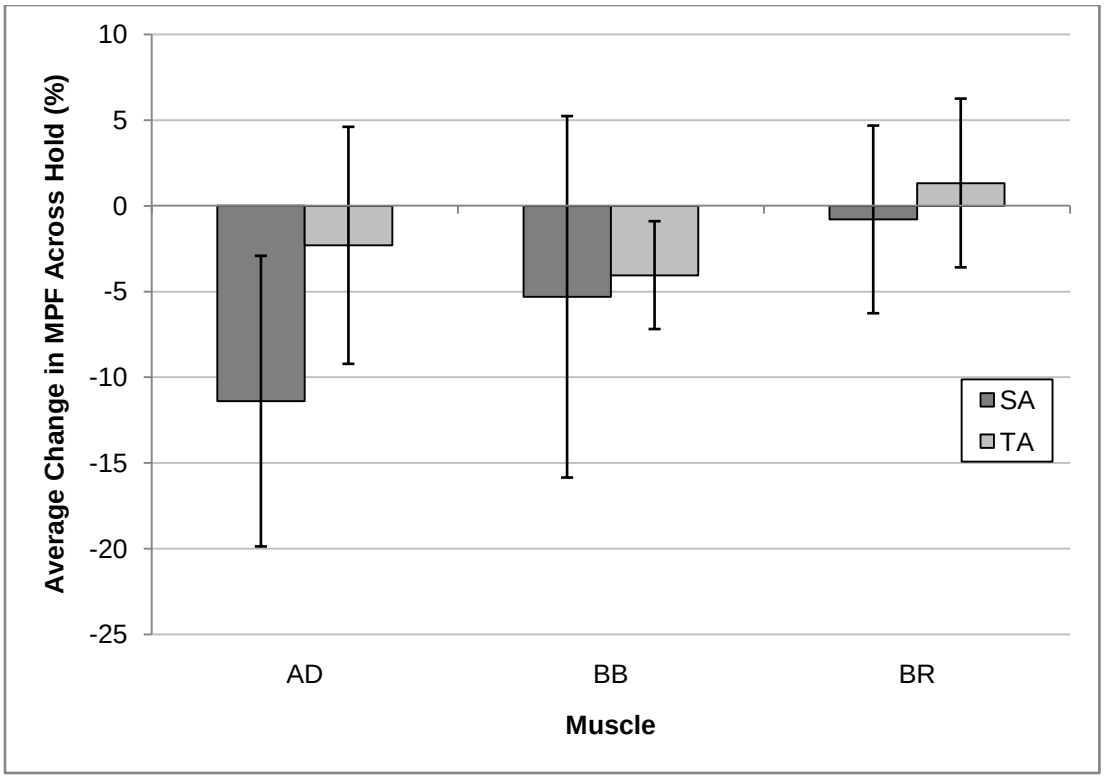

Figure 8: Percent change in MDF for each muscle over the course of the static hold.

Over the course of the static hold, the SA appeared to displayed greater percent decreases in MDF than the TA. Additionally, the AD of the SA appeared to be the only muscle that presented with a decrease in the MDF over 10%.

5.2 Subjective Parameters

5.2.1 Borg CR10 Ratings of Perceived Exertion

For Borg CR10 ratings of perceived exertion, significant weight ($p<0.05$, $\eta_p^2= 0.514$), COM ($p<0.05$, $\eta_p^2= 0.597$), and weight by COM interaction ($p<0.05$, $\eta_p^2= 0.372$) effects were evident, with observed powers of 0.947, 1 and 0.942, respectively. Visual inspection of the means indicated that the 3kg and 4kg weight condition were perceived to be equally strenuous at the +7cm position (Figure 9). Through post hoc comparisons, it was found that the perceived exertion was lower for the 3kg weight condition than the

4kg weight condition under the -7cm (p=0.027) and 0cm (p=0.001) COM positions. For the 3kg weight condition, the +7cm position was deemed more strenuous than the -7cm (p=0.001) and 0cm (p=0.001) positions. For the 4kg weight condition, the -7cm position was felt to be less strenuous than the 0cm (p=0.027) and +7cm (p=0.080) positions.

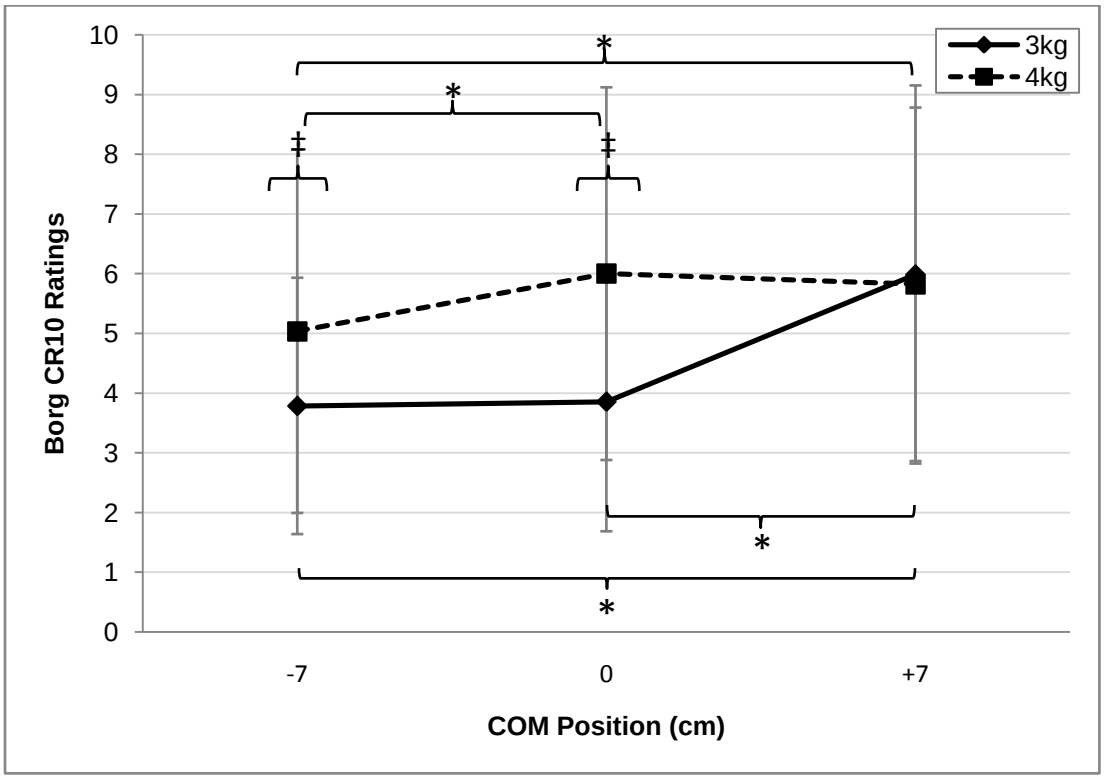

Figure 9: Borg CR10 Ratings of perceived exertion for each weight condition and COM position. A weight by COM interaction effect was evident. Upper and lower * represent significant differences within the 4kg and 3kg conditions, respectively. ‡ represents significant differences within COM position.

A contrast of the baseline condition with heavier balanced weights (5^{th} and 8^{th} rifle configurations) produced a clearly statistically significant effect ($p<0.01$) (Figure 10). This corresponded to an effect size of $\eta_p^2 = 0.743$ and observed power of 1. Paired comparisons indicated that the perceived exertion levels were less for the baseline condition than the 3kg ($p<0.01$) or 4kg ($p<0.01$) weight condition. Additionally, the 4kg

condition resulted in significantly greater perceived exertion levels than the 3kg condition ($p<0.01$).

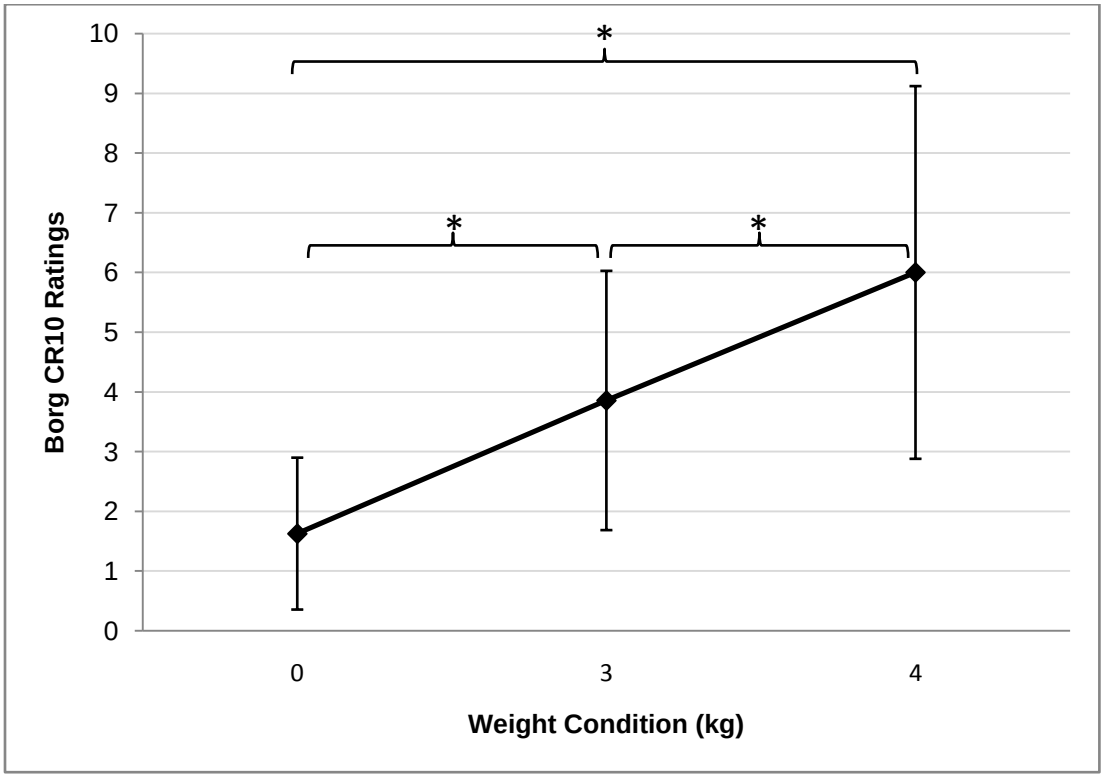

Figure 10: Borg CR10 ratings of perceived exertion for each weight condition under a 0cm COM position. The ratings for the 4 kg weight condition were significantly greater than that for the 0kg and 3kg conditions and the ratings for the 3kg condition were significantly greater than that for the 0kg condition.

5.2.2 Body Map Exit Survey

Eighty-six percent (12 of 14) of subjects indicated that the lower back region experienced significant muscular strain during testing. This percentage was well above the percentage for any other identified body region. However, the SA appeared to experience greater muscular strain than the TA. The anterior portion of the upper arm (biceps region) for the SA side was the next most frequently indicated region at 64%. Forty-three percent of subjects also identified the SA forearm, while 36% of subjects identified the SA anterior shoulder region and wrist. Thirty-six percent of subjects

identified the anterior shoulder region of the TA. All other body regions were indicated by less than 25% percent of the subjects.

CHAPTER 5: DISCUSSION

The main goal of this study was to evaluate the effects of weight and weight distribution on upper extremity muscular fatigue during static rifle aiming. Seven different rifle configurations, varying in weight and COM, were assessed. Myoelectric data were collected while subjects performed static rifle holds for a duration of sixty seconds. Subjective ratings of perceived exertion were also attained at the conclusion of each static hold. For the purposes of this study, fatigue was viewed as a continuous process throughout the task, as opposed to occurring at a discrete moment in time.

6.1 Weight Effect

It was expected that rifles with greater weights would result in greater upper extremity muscular demands, and in turn, greater levels of fatigue. This was not substantiated by the muscle activity level (iEMG) findings or the fatigue rate (sMDF) findings. Across all six muscles investigated, no differences in EMG amplitude were evident when 3kg and 4kg of additional weight were compared. Even more surprising was the fact that the baseline rifle condition, which had no additional weight, did not result in lower activity levels than either of the weighted conditions.

The expectation that added weight would result in quantifiable increases in muscular demand was also unsupported by the spectral analyses. Five of the six investigated muscles showed no differences in rates of fatigue across the weight conditions. A significant weight effect for the BB-TA was found, but the trend was quite unanticipated. The rate of fatigue was found to be greater under the 3kg condition than the 4kg condition. Although this finding was statistically significant, the practical

significance must be questioned, particularly given that the finding is counterintuitive. Each subjects' average percent decrease in MDF over the course of the holds was under 10% for the BB-TA, indicating that the muscle was not overly fatigued. Additionally, given that data from only seven subjects were available for use in the statistical test, the representativeness of the sample to the overall population is questionable.

Overall, objective myoelectric measures did not discriminate between weight conditions; however, that is not to say that a difference does not exist. Subjective CR10 ratings of exertion clearly indicated that, as weight was added, perceived muscle strain increased. The baseline condition (0kg of added weight) resulted in 'very weak to weak' muscular strain (a rating of 1.5/10) while the 3kg condition resulted in 'somewhat strong' muscular strain (a rating of 4/10) and the 4kg condition resulted in 'strong to very strong' muscular strain (a rating of 6/10).

The discrepancies between subjective and objective findings are not easily explained. However, given that the heaviest weight condition was double the weight of the standard rifle and that almost all subjects perceived some increase in exertion as weight was added, it is likely that increased muscular strain and fatigue occurred but were not properly captured by the myoelectric measures. Theories to explain this phenomenon will be discussed in greater detail in sections to follow.

6.2 Center of Mass Effect

Contrary to the unanticipated weight findings, objective myoelectric measures confirmed the theory that shifting the rifle COM forward would result in greater upper extremity muscular strain. The effects of alterations in COM were predominantly evident in the musculature of the supporting arm (SA). The muscle activity levels of the BB-SA

rose nearly 40% when the COM was shifted from the 0cm position to the +7cm position, while the BR-SA activity level was 35% greater when the rifle COM was in the forward position (+7cm) as compared to the backward position (-7cm). The supporting arm bears the weight of the rifle barrel and is the most forward contact point. Therefore, when the weight of the rifle is redistributed to a more forward position, the effects are largely felt by the supporting arm. In keeping with this notion, the trigger arm did not reveal any muscle activity differences across COM positions.

However, rates of muscular fatigue were once again difficult to explain. Although activity levels increased under the forward-shifted COM for the BB-SA and BR-SA, the corresponding rates of fatigue did not show increases. No differences in rates of fatigue were evident for any supporting arm muscles. One trigger arm muscle, the BR, presented with greater rates of fatigue under the +7cm position than the -7cm position. Although this finding also supports the notion that a forward-shifted COM results in greater rates of muscular fatigue, the practical significance must once again be considered carefully given the low overall rates of fatigue observed. The average decreases in MDF for the BR-TA were under 5% for all subjects. In fact, half the subjects presented with average slopes that were slightly positive.

For the COM effect, subjective ratings of exertion appeared to corroborate the objective finding that a forward-shifted COM was more strenuous than a more backward COM position. However, a weight by COM interaction effect was also evident and will be discussed below.

6.3 Weight by Center of Mass Interaction Effect

Although muscle activity levels were not strictly affected by weight, a weight by COM interaction was evident for the BR-TA. At the 0cm position the 4kg weight condition resulted in nearly 20% greater activity levels than the 3kg condition. However, when the COM was positioned at -7cm and +7cm, differences in activity level for the two weights were not apparent. Additionally, muscle activity levels of the BR-TA showed differences due to COM for only the 3kg weight condition; the forward-shifted COM was once again found to result in activity levels 30% greater than that observed for the more backward COM positions.

These findings were somewhat paralleled by the ratings of perceived exertion, which also presented with an interesting interaction effect between weight and COM. Subjects were able to perceive an increase in muscle strain as the weight was shifted from the -7cm to +7cm position. Additionally, subjects perceived the 4kg weight to be more strenuous than the 3kg weight at the -7cm and 0cm positions. Much like the BR-TA interaction effect, weight differences were not perceivable when the weight shifted forward to the +7cm.

6.4 Areas of Muscular Strain

Overall, the subjective ratings of muscular strain presented very clear tends. Although muscle activity levels did reveal some COM effects, results were not consistent across muscles and were not substantiated by rates of fatigue. A possible explanation for this divergence is that the body region experiencing the greatest muscular strain was not captured. The lower back was the body area most frequently cited as experiencing muscular strain. The subjective ratings of exertion may have been largely driven by the

perceived exertion of the low back and, therefore, did not correspond well with objective measures of upper extremity muscular strain. During pilot testing, attempts were made to instrument the low back with EMG. However, the low back was not chosen for several reasons including: the need to remove clothing and armour during instrumentation, difficultly with electrode adhesion due to movement of the overlaying armour system, and frequent shorting out of electrodes due to excessive sweat.

Prior to this study, it was expected that the effects of weight would be clearly evident and that the effects of COM would be much more difficult to isolate. Therefore, it was particularly surprising that myoelectric measures were not able to differentiate between 4kg and 8kg of total weapon weight, yet were able to provide some insight into the effects of a forward shift in COM of only 7cm. This paradox could be explained if one considers the areas likely to be experiencing muscular strain. When additional weight was added, without variations in COM, the musculature of the core, lower extremities and upper extremities may all have been used to compensate for the added weight. As a result, whole body fatigue may have increased, driving up the ratings of perceived exertion, while the effects on isolated muscles of the upper extremity may have been too minimal to be quantified using myoelectric measures. In contrast, when the COM of the rifle was shifted forward, without variations in weight, it may not have been possible for added strain to be shared by a range of muscles. The burden of the effect may have been placed on the supporting arm musculature, which was instrumented with EMG. However, the proposal that weight increases result in whole-body muscular strain, while alterations in COM largely affect the musculature of the supporting arm, is only a hypothesis and needs to be investigated further.

6.5 The Difficulty of Quantifying Rates of Muscular Fatigue

A primary objective of this study was to quantify the rate of muscular fatigue using a spectral analysis of the surface EMG signal. Given the importance of stability and rifle steadiness, it was hoped that quantifying upper extremity muscular fatigue would provide insight into the effects of weight and COM alterations on static rifle aiming. Unfortunately, the spectral analysis did not prove to be fruitful. Many confounding factors, previously identified in Chapter 2, may have affecting the surface EMG signal, masking the myoelectric manifestations of fatigue.

It is expected that four primary factors affected the spectral properties of the EMG signal, including: i) non-stationary dynamic contractions, due to minor postural shifts throughout the hold; ii) motor unit substitution and/or rotation, even when sustained static postures where assumed throughout the hold; iii) alterations in muscle length, due to differing assumed postures for various rifle configurations; and iv) electrode position and orientation. Each of these will be discussed further.

In order to properly quantify muscle fatigue using spectral parameters, it was essential that soldiers maintain a static posture throughout aiming. Although subjects were closely monitored and the importance of maintaining a static posture was stressed, dynamic motions may have altered the relative force contribution of involved muscles and inevitably affected the stationarity of the EMG signal (DeLuca, 1997; DeLuca, 1984). Pellegrini and Schena (2005) characterized arm-gun movement during air pistol aiming and, like many others (Konttinen et al., 1998; Ball et al., 2003; Pellegrini and Schena, 2005), were able to quantify high frequency movements associated with muscle tremor. However, they were also able to quantify low frequency movements, which they

asserted to be a direct result of postural adaptations. As subjects experienced fatigue, they may have naturally altered their posture to rest fatigued muscle sites, while activating less fatigued muscle sites. As the motor unit activity levels changed, along with muscle length and/or tension during dynamic movements, characteristic frequency measurements, such as the MDF, were likely influenced by factors other than fatigue.

Even if kinematic data had been collected and static postures were found to occur, motor unit substitution and rotation may have affected the power spectral density profile. Fallentin et al. (1993), Westgaard and DeLuca (1999), and McLean and Goudy (2004) have postulated that, activity levels of motor units alternate even during a sustained static contraction, be it through rotation or substitution, as a means of offsetting fatigue. Although uncertainty still surrounds these theories, the redistribution of motor unit activity may have partially reduced muscle fatigue.

Moreover, even if static postures were assumed and motor unit substitution and rotation did not occur, the soldiers' postures may have varied for each rifle configuration. Yuan et al. (1997) found that different upper extremity postures were assumed for varying rifle weights and handling lengths. This makes spectral comparisons across rifles problematic because changes in the length of the underlying muscle fibers (Rosenburg and Seidel, 1989; Mannion and Dolan, 1996) and the orientation of the electrode with respect to the emanating signal (DeLuca, 1997) affect the power spectrum of the myoelectric signal.

Lastly, minor changes in electrode position and orientation may have affected the power density spectrum of the surface EMG signal (DeLuca, 1997). A consequence of implementing a strenuous task was that subjects often perspired, which affected the

electrode adherence to the skin and signal quality. All possible measures were taken to ensure that electrodes did not move during testing. Well-ventilated muscle sites, which were the least likely to perspire, were chosen. However, when electrodes shorted out due to sweat or slid out of position, they had to be replaced or repositioned. An outline of the electrode location was made on the skin in an attempt to ensure consistent location and orientation. However, very minor changes in position may have affected the spectral properties of the surface EMG signal.

6.6 Study Limitations

The aforementioned difficulties in quantifying rates of fatigue must certainly be considered limitations of the study. Additionally, the sample population of this study was relatively small and was made even smaller due to substantial data loss. The large amount of noise contamination and the relatively low rates of muscular fatigue called into question the quality of the spectral signal collected by the Bluemyo system. However, the check of signal quality (Appendix G) indicated that the system accurately quantifies the frequency of signals within the 20-400Hz range. It was noted, however, that the amplitudes of recorded signals may have varied between electrodes. This may have introduced some error in the iEMG outcome measure for the rare cases in which electrodes had to be replaced.

Furthermore, this study was limited to an indoor mock-setting and may not be easily adaptable to a field scenario. Testing was initially scheduled to take place on an outdoor-live fire range, where soldiers could take aim at automated targets situated 100m from the firing line. At the conclusion of the hold, soldiers were to fire two live rounds and accuracy was to be tracked. Unfortunately, due to weather constraints, this was not

possible. The importance of maintaining a steady aim on the mock target was stressed during indoor testing; however, soldiers' motivation to maintain the proper posture may have lessened in comparison to a field scenario.

6.7 Conclusions and Future Directions

It was hoped that the findings of this study would enhance the current weapon selection process. Unfortunately, objective myoelectric parameters did not provide sufficient insight into the effects of added weapon weight. However, subjective findings clearly indicated that added weight came at a cost to the soldiers. Given that the perceived exertion due to the 4kg weight condition was rated 'strong to very strong' (a rating of 6/10) by many soldiers, it is likely this much additional weight should be avoided.

Although objective measures provided little insight into the effects of weight, objective measures supported the subjective implications that a forward-shift in COM, regardless of weight, resulted in increased muscular strain. Increases in muscular activity of 30-40% were evident in the supporting arm musculature when the COM was shifted forward 7cm. This increase in muscular activity corresponded to a significant increase in perceived exertion from 'somewhat strong' (a rating of 4/10) to 'strong/ very strong' (a rating of 6/10). Slight shifts in COM may seem relatively inconsequential compared to large alterations in weight; however, objective findings indicated that the added strain due to a forward-shift in COM is heavily felt in the supporting arm. Given the importance of the supporting arm during rifle stabilization and aiming, it seems the forward-shift in COM should be avoided for future weapon designs.

Future studies should be conducted to verify the findings of this study and improve on the methodological approach. This study has provided a starting point toward developing a standardized protocol for assessing muscular fatigue during rifle aiming; however, many improvements could be made. Future work of this nature should investigate a means of quantifying fatigue of the low back. Armour systems were worn during this study in an attempt to make the tasks comparable to combat situations. However, given the overwhelming feedback that the back was the body region experiencing the greatest fatigue, it may be more appropriate for future work to be conducted without an armour system and have the back instrumented. It was also found that the supporting arm musculature experienced the greatest strain. As a result, it is recommended that the trigger arm muscle sites be transferred to the lower back during future studies.

During future studies, maximum voluntary contractions (MVCs) should be collected for each muscle site. Oberg et al. (1994) have indicated that fatigue related changes in the myoelectric signal begin to manifest at working levels above 15% MVC, while others have found the levels to be approximately 7% MVC (Jorgensen et al., 1998). A clear consensus as to what working level fatigue related changes occur at does not exist, and values likely differ between muscles, individuals, and lengths of contraction. However, if the level of exertion had been know for each muscle, it would have been possible to know whether greater rates of muscular fatigue should have been expected.

It is also recommend that future investigations take place in a more controlled laboratory setting. If the lab-based studies provide valuable insight into the effects of weapon weight and weight distribution, then future investigations should take place on

live fire ranges, as this study was intended to. A comparison of myoelectric measures of muscle strain and shot accuracy may prove to be quite insightful.

In conclusion, the muscle activity levels during sustained rifle holds indicated that forward shifts in COM place added strain on the supporting arm musculature, which is imperative in maintaining rifle steadiness during aiming. Myoelectric measures did not reveal the effects of added weight, although this may have been largely due to the fact that muscle activity of the lower back was not captured. Differentiation between weight conditions and COM positions was not possible using spectral analysis, specifically the slope of the MDF. Subjects may have naturally engaged in minor postural adjustments to substitute and rotate fatigued motor units. Taking this limitation into consideration, accurate spectral measures of fatigue may be difficult to quantify in subsequent studies.

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APPENDICES

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B: Ethics Approval

C: Subject Anthropometrics

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APPENDIX A: Consent Form

August 11th, 2008

Informed Consent Form

Field Trial to Evaluate Rifle Weight and Horizontal Centre of Mass Properties

Purpose of the Study

The purpose of this research study is to objectively and subjectively evaluate new weapon mounted technologies and their compatibility with future solider headwear systems. Specifically, the effect of weight and center of mass alterations will be evaluated. This research project is being conducted by Human Systems Inc. and Queen's University Ergonomics Research Group under the auspices of Defense Research and Development Canada (DRDC-Toronto). Human Systems Inc. is responsible for the research design, project management, equipment setup, and evaluation of your subjective opinions about the various rifle configurations. Queen's is responsible for collecting and analyzing the objective biomechanical components of the study (e.g., postural adaptations and muscular fatigue.). This letter is an invitation for experienced marksman soldiers to participate in a project.

Procedures during Testing

Preparations: The testing schedule and availability of measurement systems limit our ability to invite every soldier to participate in this study. However, all soldiers will be briefed by DRDC and Human Systems Inc, prior to testing and specific soldiers will be asked to read this ethics consent form before signing. At the Queen's research station, we will place an accelerometer on your tactical vest (or wrist) and muscle sensors (EMG) on your trunk and upper limbs so we can track movements of your trunk (or wrist) and muscular effort. This step will require that you remove your fatigues briefly. Preparations will require about 20 minutes.

Rifle Range Tests: The rifle range tasks will be conducted under the supervision of the Range Safety Officer (RTO) and all safety procedures must be followed. The live-rifle tasks we will ask you to complete include: known distance drill (target hold), and pivot drill (short distance. You will be suited with the EMG system and/or an accelerometer during these tasks. None of these measurements systems should interfere with your ability to perform the tasks.

Risks and Benefits

The addition on the accelerometer and EMG system does not create any serious added risk. However, it is possible that skin sensitivity, soreness, or pain will occur when we remove the tape after the tasks. Some individuals may be allergic to the tape itself. The main risks inherent to completing any of the tasks include: shoulder soreness from weapon kickback, pulling a muscle, becoming over-heated or becoming physically tired. If any of these injuries occur, we will have a first aid kit available for you to access ice and first aid supplies. If a more serious injury occurs, we will first seek help from the officer in charge of the range and then, if needed, use our portable cell phone to call for a military ambulance, city ambulance, taxi or we will drive you to the nearest medical facility.

In terms of benefits, you will have helped in the development and selections of new weapon-mounted technologies for soldiers involved in combat and defense missions. In addition, you will be able to understand how biomechanical data are collected and view your performance on the computer as the data are collected. However, you will not receive any reimbursement as your military supervisors have agreed to allow this evaluation of weapon mounted technologies as part of your regularly-assigned duties.

Confidentiality

All information obtained during the course of this study is strictly confidential and will not be released in a form traceable to you. Your name will be omitted from all records containing objective or subjective data and it will be placed in a password coded and locked file that is available to only the investigators, project manager and students who are processing the data. Any videotaping of the tasks will be used for data analyses only and will not be shown to anyone outside the research team. As soon as the data processing and report writing are completed, these tapes will be erased. These study results will be used as anonymous data for scientific publications and presentations and for educational purposes.

Freedom to Withdraw from the Study

Your participation in the study is voluntary. No one within the military will be given your results and knowledge of participation. However, you may request a written letter directed to your supervisor for your file (and copied to you) that will acknowledge and thank you for your participation in this study. If this letter is requested, then the military will become aware of your participation.

You are free to withdraw at any time. There will be no coercion and no military reasons to continue with the study if you choose to withdraw.

If you are dissatisfied with any aspect of the study, we encourage you to talk to a Principal Investigator, Dr. Joan Stevenson (1-613-533-6288) or (joan.stevenson@queensu.ca). You may also discuss concerns with any of the following people: Major Linda Bossi, military scientific authority at DRDC (1-416-635-2197); or Dr. Pat Costigan, Director of the School of Kinesiology and Health Studies at Queen's University (1-613-533-6603). If you have any questions about research subject's rights, you can contact Dr. Albert Clark, Chair of the Research Ethics Board for the Health Sciences (1-613-533-6081).

The Meaning of your Signature

By signing two copies of these Informed Consent Forms, you are acknowledging that:

1) you have been given a verbal briefing,

2) you have read this information

3) you have been given an opportunity to ask additional questions

4) you feel informed of the tasks and measurements requested of you

5) you are aware of the risks and benefits of participation

6) you will receive a copy of this form for your files

7) you are participating is voluntary

8) you may withdraw from the study at any time without penalty

Yours Truly,

Joan M. Stevenson, PhD

Professor & Principal Investigator

August 11th, 2008

Soldier's Copy

Ethics Consent

Field Trial to Evaluate Rifle Weight and Horizontal Centre of Mass Properties

This page is for the researchers to verify that you are willing to participate in the above study. By signing this page you are declaring the following:

- You were given a verbal presentation about the above-mentioned research study
- You were given an Ethics Consent letter of information to read and keep
- You are aware that the purpose of the study is to asses new weapon mounted technologies based on your subjective opinion and objective signals from accelerometers and muscle sensors
- You realize that you can withdraw at any time without penalty or coercion
- You know that you can contact any of the people identified in the Ethics Consent letter if you have questions, concerns, or complaints
- You realize that your data will be kept confidential
- By signing this consent form, you realize that you do not waive your legal rights nor release the investigator(s) and sponsors from their legal and professional responsibilities.

(Please sign and keep this page for your personal records)

_____ _____

Print your Name Date

_____

Signature of Participant

_____ _____

Witness Date

Do you wish to have a letter added to your personal file indicating your participation in this study?

Yes _____ No _____

Are you willing to be photographed or videotaped for research purposes only?

Yes _____ No _____

August 11th, 2008

Researcher's Copy

Ethics Consent

Field Trial to Evaluate Rifle Weight and Horizontal Centre of Mass Properties

This page is for the researchers to verify that you are willing to participate in the above study. By signing this page you are declaring the following:

- You were given a verbal presentation about the above-mentioned research study
- You were given an Ethics Consent letter of information to read and keep
- You are aware that the purpose of the study is to asses new weapon mounted technologies based on your subjective opinion and objective signals from accelerometers and muscle sensors
- You realize that you can withdraw at any time without penalty or coercion
- You know that you can contact any of the people identified in the Ethics Consent letter if you have questions, concerns, or complaints
- You realize that your data will be kept confidential
- By signing this consent form, you realize that you do not waive your legal rights nor release the investigator(s) and sponsors from their legal and professional responsibilities.

(Please sign and return this page and return to a Queen's researcher or military person in charge of the study)

_____ _____

Print your Name Date

_____

Signature of Participant

_____ _____

Witness Date

Do you wish to have a letter added to your personal file indicating your participation in this study?

Yes _____ No _____

Are you willing to be photographed or videotaped for research purposes only?

Yes _____ No _____

APPENDIX B: Ethics Approval

QUEEN'S UNIVERSITY HEALTH SCIENCES & AFFILIATED TEACHING HOSPITALS RESEARCH ETHICS BOARD

June 23, 2008

This Ethics Application was subject to:

☐ Full Board Review
Meeting Date:
☒ Expedited Review

Dr. Joan Stevenson
School of Kinesiology and Health Studies
Room 148, Physical Education Centre
Queen's University

Dear Dr. Stevenson,

Study Title: **Field Trial to Evaluate Rifle Weight and Horizontal Centre of Mass Properties**
Co-Investigators: **Ms. Jessica Selinger, Ms. Susan Reid, Dr. Pat Costigan, Mr. David Tack**

I am writing to acknowledge receipt of your recent ethics submission. We have examined the protocol and consent form for your project (as stated above) and consider it to be ethically acceptable. This approval is valid for one year from the date of the Chair's signature below. This approval will be reported to the Research Ethics Board. Please attend carefully to the following list of ethics requirements you must fulfill over the course of your study:

- **Reporting of Amendments**: If there are any changes to your study (e.g. consent, protocol, study procedures, etc.), you must submit an amendment to the Research Ethics Board for approval. (see http://www.queensu.ca/vpr/reb.htm).
- **Reporting of Serious Adverse Events**: Any unexpected serious adverse event occurring locally must be reported within 2 working days or earlier if required by the study sponsor. All other serious adverse events must be reported within 15 days after becoming aware of the information.
- **Reporting of Complaints**: Any complaints made by participants or persons acting on behalf of participants must be reported to the Research Ethics Board within 7 days of becoming aware of the complaint. Note: All documents supplied to participants must have the contact information for the Research Ethics Board.
- **Annual Renewal**: Prior to the expiration of your approval (which is one year from the date of the Chair's signature below), you will be reminded to submit your renewal form along with any new changes or amendments you wish to make to your study. If there have been no major changes to your protocol, your approval may be renewed for another year.

Yours sincerely,

Albert Clark
Chair, Research Ethics Board

June 24, 2008
Date

ORIGINAL TO INVESTIGATOR - COPY TO DEPARTMENT HEAD- COPY TO HOSPITAL(S) /P&T (If appropriate) - FILE COPY

Study Code: PHE-082-08

- **Investigators please note that if your trial is registered by the sponsor, you must take responsibility to ensure that the registration information is accurate and complete**

APPENDIX C: Subject Anthropometrics

Table 4: Subject anthropometrics

Subject Code	Sex (M/F)	Support Arm (R/L)	Height (cm)	Weight (lbs)
01	M	L	178	79.4
02	M	L	178	70.3
03	M	L	178	61.2
04	M	L	183	94.3
05	M	L	185	98.9
06	M	L	190	106.6
07	M	L	180	70.3
08	M	L	180	93.0
09	M	L	175	79.4
10	F	L	175	68.0
11	M	L	183	113.4
12	M	L	185	72.6
13	M	L	180	75.7
14	M	L	178	68.0
Average ± Standard Deviation:			181 ± 4	82.2 ± 15.5

APPENDIX D: Borg CR10 Scale

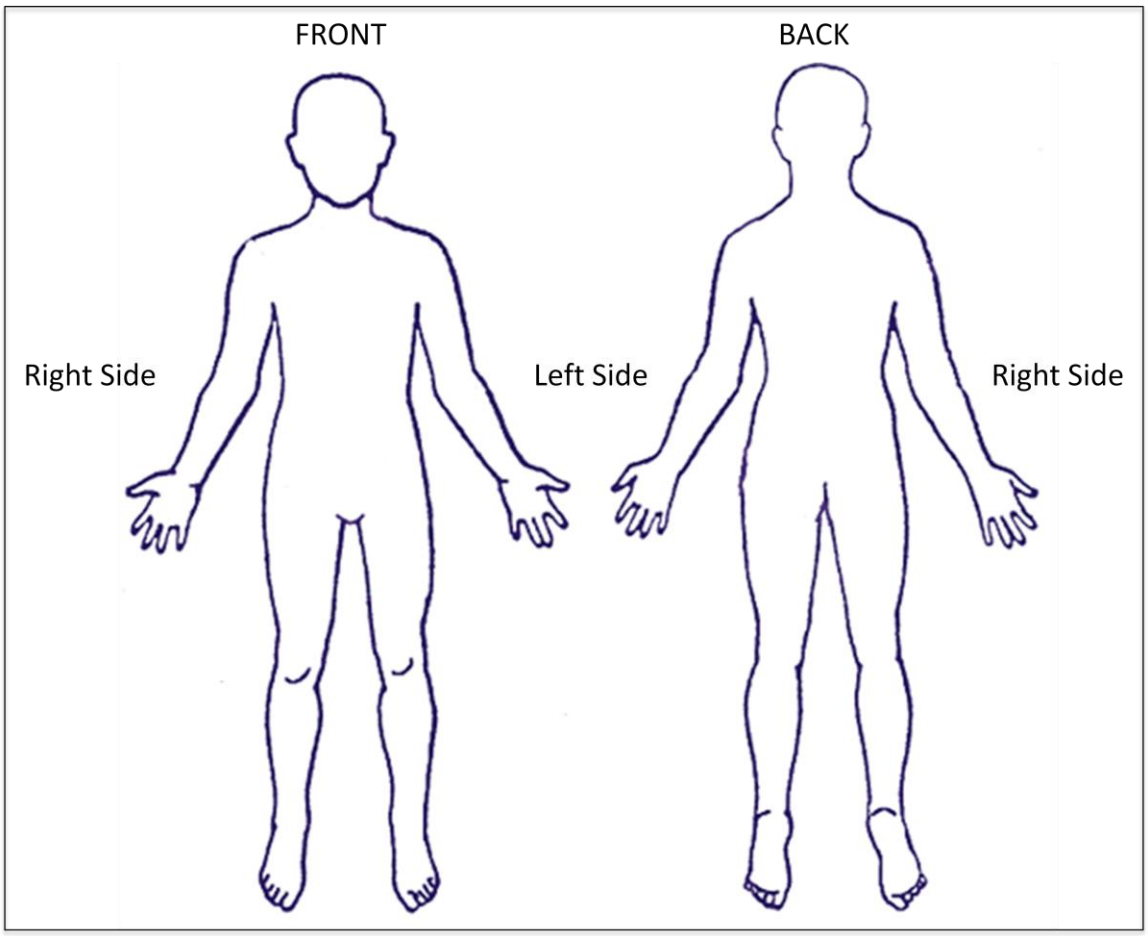
0	Nothing at all
0.5	Extremely weak (just noticeable)
1	Very weak
2	Weak (light)
3	Moderate
4	Somewhat strong
5	Strong (heavy)
6	
7	Very strong
8	
9	
10	Extremely strong (almost maximal)
•	Maximal

APPENDIX E: Muscular Strain Exit Survey

Subject: _____

Muscular Strain Exit Survey

Please indicate the body region (s) where you felt the most muscular strain during testing?



APPENDIX F: Selected Raw Data Plots

Plots of raw data in both the time and frequency domain can be found below. Sample plots of trials that were kept, as well as trials that were discarded, due to abnormalities in the frequency and time domain, have been provided.

Below are two sample plots of trials that appeared normal in the time and frequency domain; therefore, they were kept for further data processing.

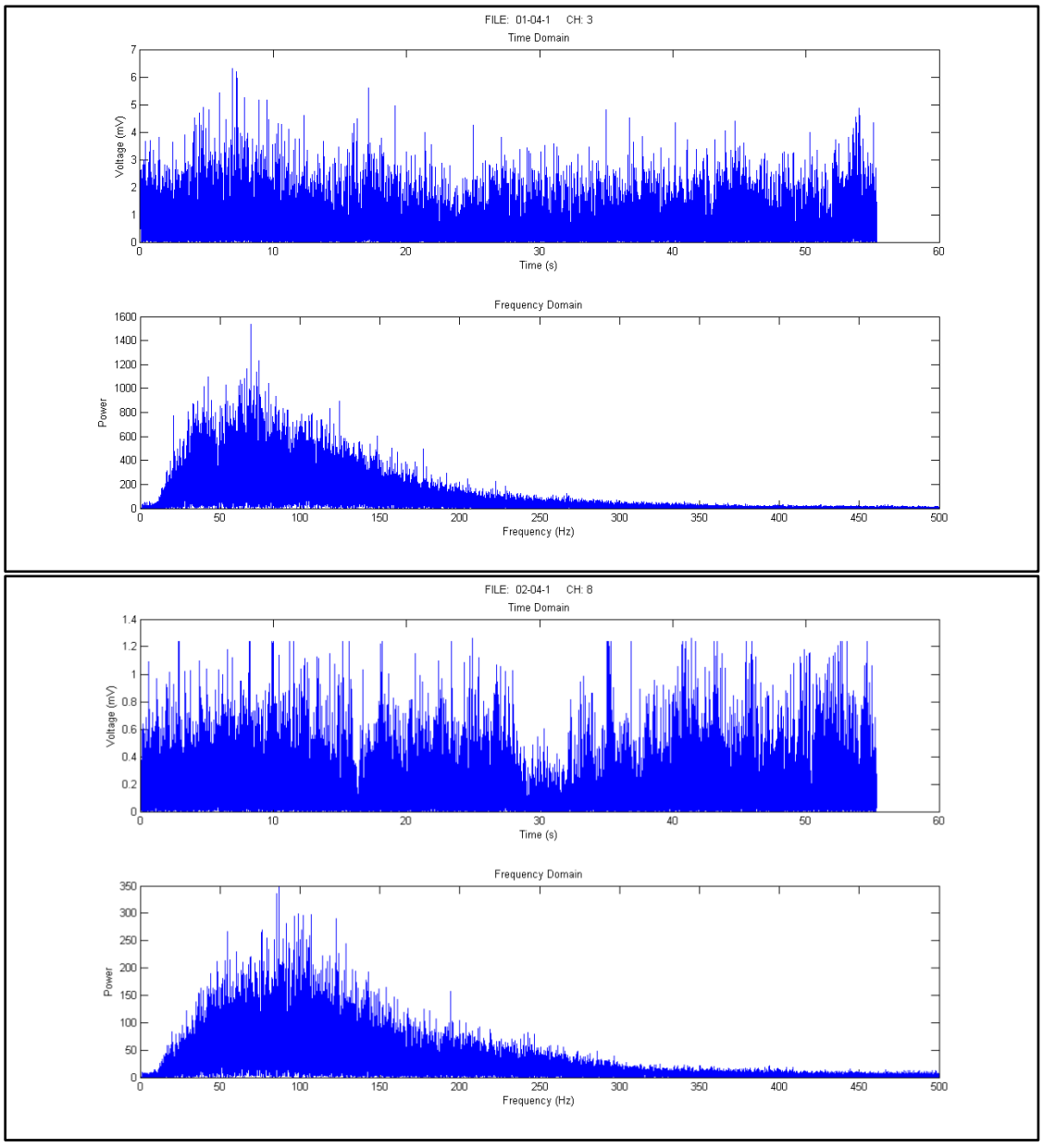


Figure 11: Sample plots of retained trials

Below are two sample plots of trials that contained noise contamination in the frequency domain and where therefore discarded.

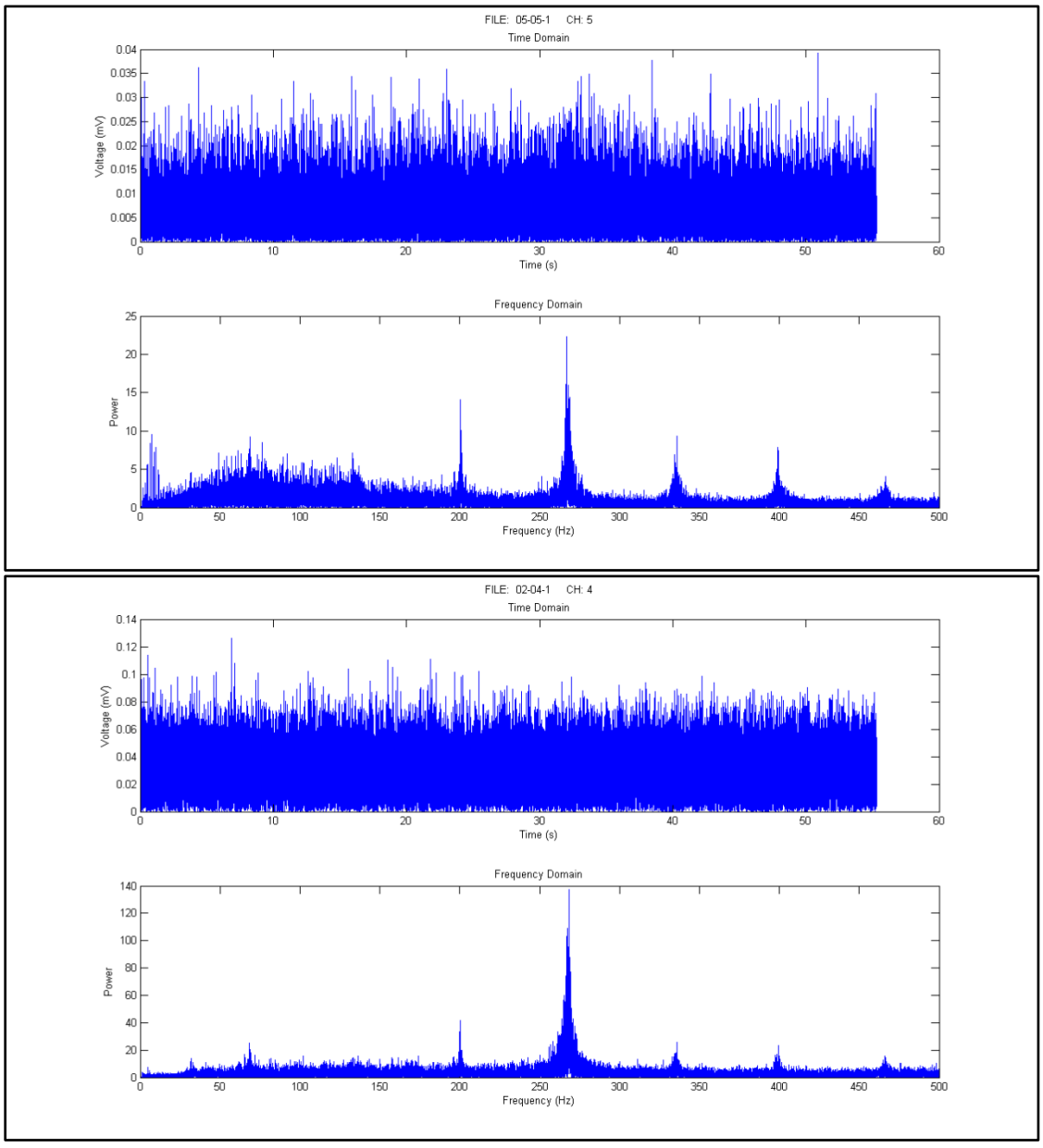


Figure 12: Sample plots of discarded trials due to noise contamination

Two sample plots of trials that presented with abnormalities in the time and frequency domain, and were therefore discarded.

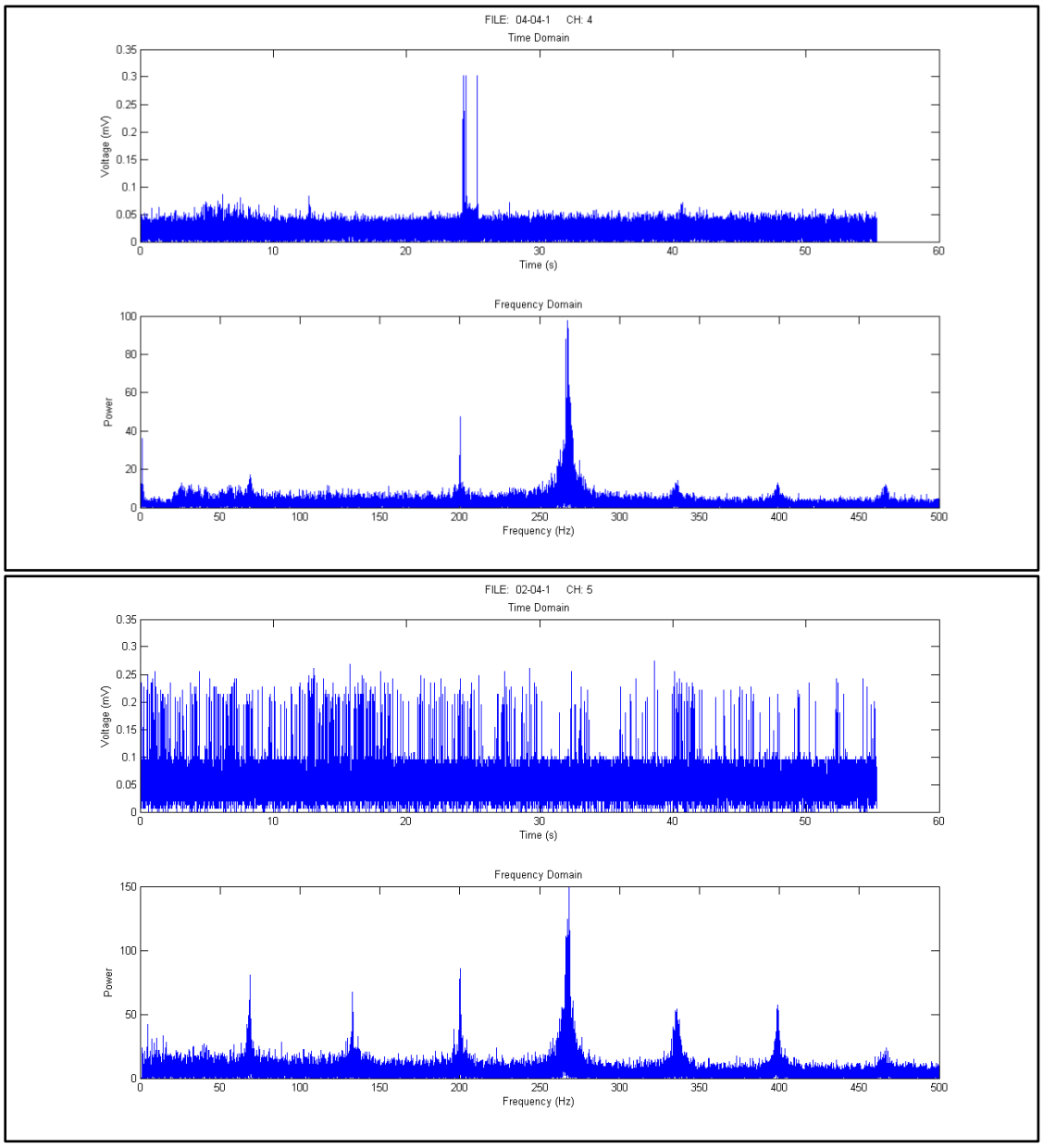


Figure 13: Sample plots of discarded trials due to frequency and time domain abnormalities

Below are two sample plots of trials that suffered from clipping in the time domain and were therefore discarded. Note: Data loss due to clipping was minimal in comparison to other data abnormalities.

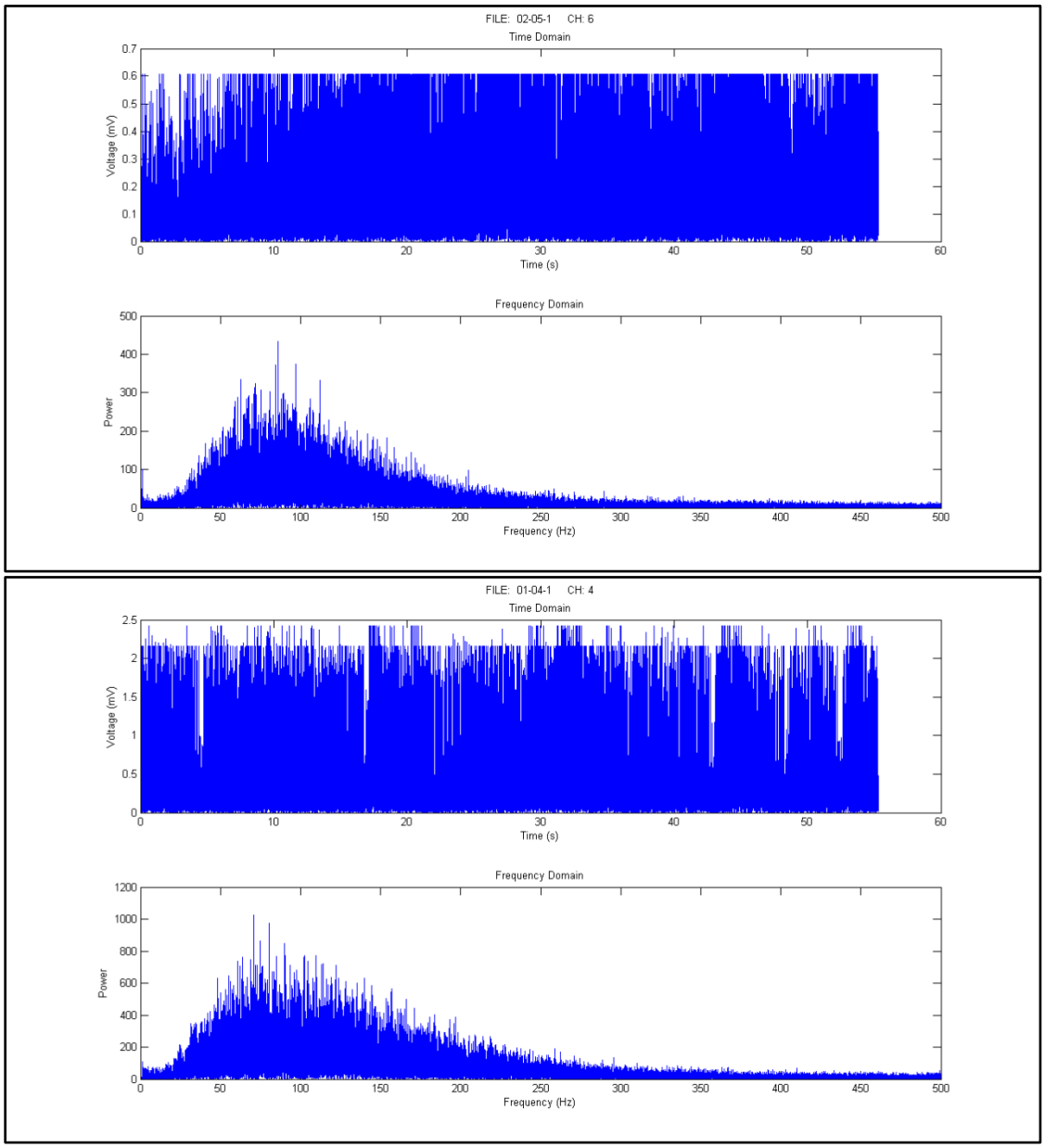


Figure 14: Sample plots of discarded trials due to clipping

APPENDIX G: Signal Quality Check

A large amount of data was lost due to noise contamination. Additionally, relatively low rates of muscle fatigue were evident, despite the strenuous nature of the task. Given these concerns, a check of the EMG signal quality was performed.

One Bluemyo Bluetooth® EMG Telemetry system, which presented with the greatest amount of noise contamination during testing, was selected. Two differential AE-100 silver/silver chloride EMG electrodes were also tested (E1 and E2). Using a sine wave generator, signals of varying frequency, including 20, 50, 100, 300, and 400 Hz, were generated. All signals had peak to peak amplitudes of 0.15V. The signals were visually confirmed using an oscilloscope. A custom resistor circuit was then used to decrease the amplitude of the signals to $1/100^{th}$ of the initial voltage. Therefore, a final voltage input of 1.5mV was attained. This signal was also visually confirmed using the oscilloscope. Finally, the signal was run through an electrode, using alligator clips. A ground signal was also run through the reference electrode.

Frequency Domain Check

A comparison of the frequency input, from the sine wave generator, and the frequency output, from the Bluemyo system, showed a relatively strong correlation. However, when a 100Hz signal was input, a peak frequency of approximately 88 Hz was registered by the Bluemyo system. Unfortunately, it was not possible to tell whether the sine wave generator or the Bluemyo system produced this error. For all other input signal frequencies, the peak output frequency was within 1 Hz. Both electrodes (E1 and E2) recorded nearly identical frequencies.

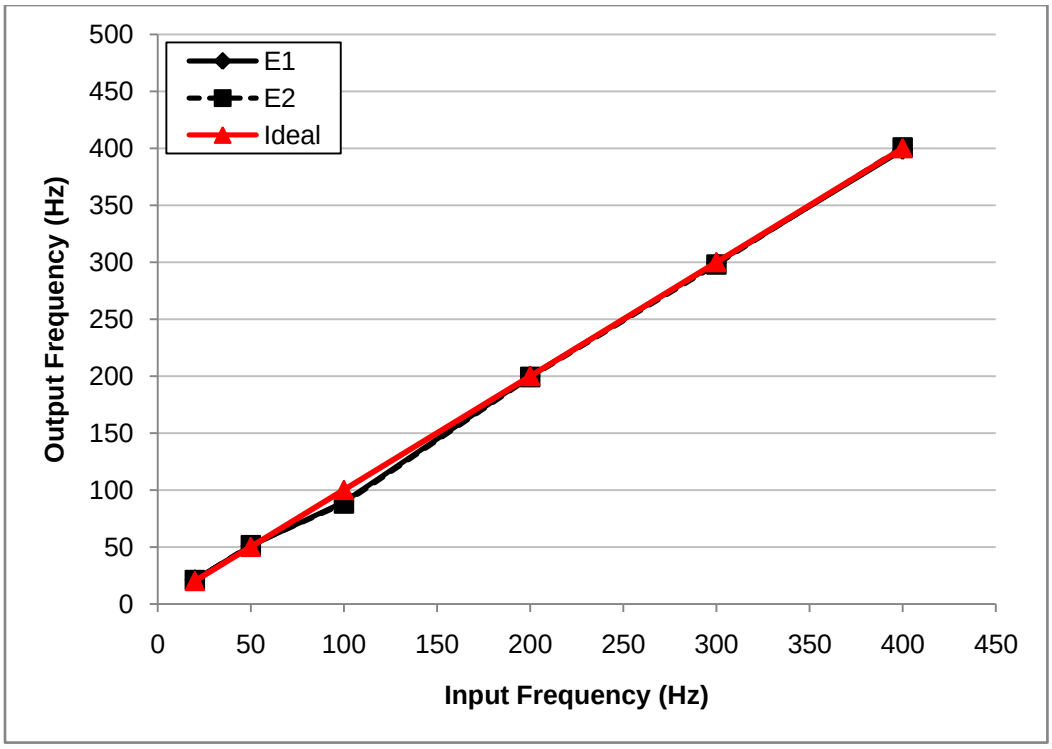


Figure 15: Check of Bluemyo frequency output

Below is a sample plot of a 100Hz signal collected with E1. The peak signal appeared very clear (upper plot). The y-axis scale has been altered in the lower plot to allow for viewing of noise contamination.

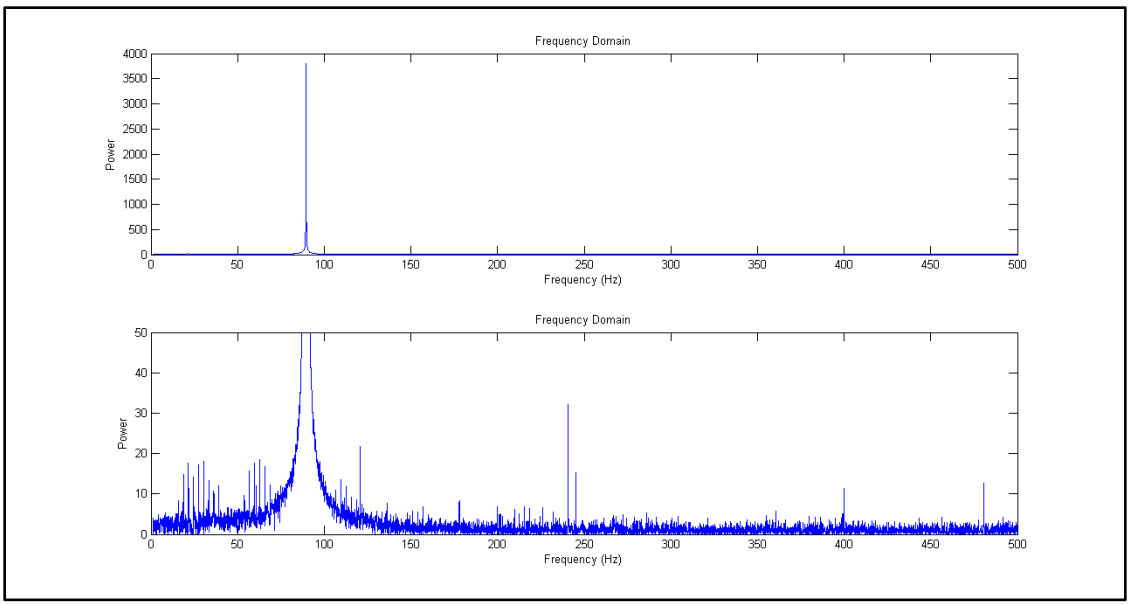


Figure 16: Bluemyo frequency output for 100Hz signal

Overall, signal frequencies were reasonably well quantified using the Bluemyo system and noise contamination was evident, but minimal.

Time Domain Check

A comparison of the peak to peak amplitude input, from the sine wave generator, and the amplitude output, from the Bluemyo system, did not show a strong correlation. All input signals had a peak to peak amplitude of approximately 1.5mV, while output signals tended to have much greater peak to peak amplitudes. Additionally, signals were registered differently by the two electrodes, with E2 recording lower amplitudes than E1, except at 20Hz. Both electrodes displayed maximum amplitudes at around 100 Hz and then began to trail off.

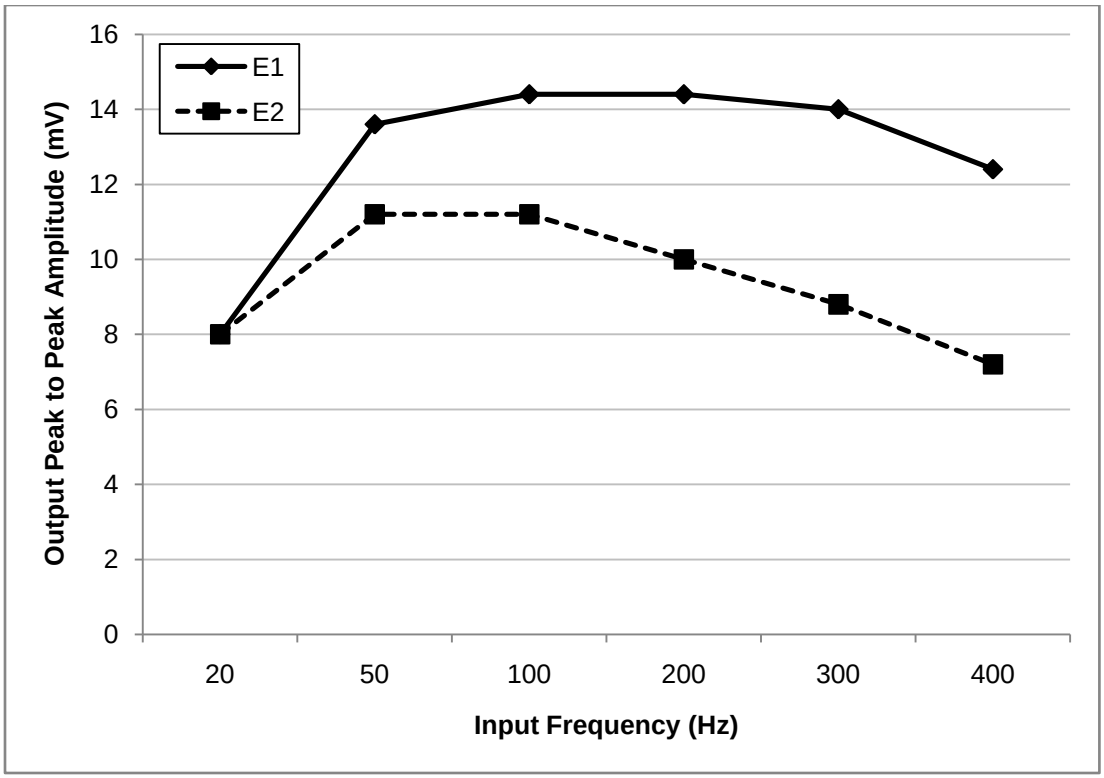


Figure 17: Check of Bluemyo amplitude output

In most cases during testing, the same electrode was used on the same muscle site for all rifle configurations. Therefore, the electrode discrepancies should have had minimal impact on the findings of the study. However, in cases where data collectors were forced to change a faulty electrode, error may have been introduced.

Fatiguing Static Hold

As a final system check, a static fatiguing hold was performed. The right biceps brachii of one subject was instrumented with both electrodes. E1 was placed on the line between the medial acromion and the fossa cubit at 1/3rd the distance from the fossa cubit (SENIAM, 2005) and E2 was placed just laterally of E1. The subject stood with her back against a wall and the right elbow was flexed at 90°. The arm was kept tight to the body and in line with the wall. The subject was asked to concentrate on maintaining a static

posture while holding an 8kg weight for 60s. The data were processed in an identical fashion to that described in the section 4.4.1.

As can be seen from the plots below, the MDF decreased over the course of the contraction, as expected. The slope of the MDF was -0.745Hz/s 44%for E1 and -0.389Hz/s for E2. This corresponded to a percent decline in MDF of 44% for E1 and 20% for E2. When the electrode was properly placed (E1) greater rates of fatigue were observed and the MPF values were less dispersed. This highlights the importance of proper electrode placement.

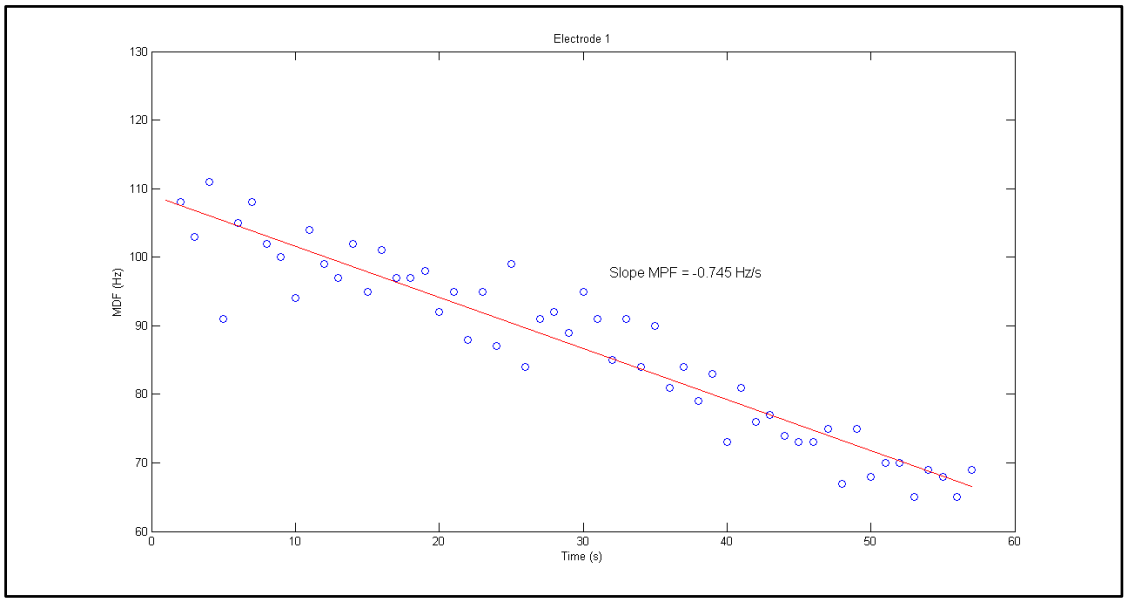


Figure 18: Electrode one change in MDF during a static hold

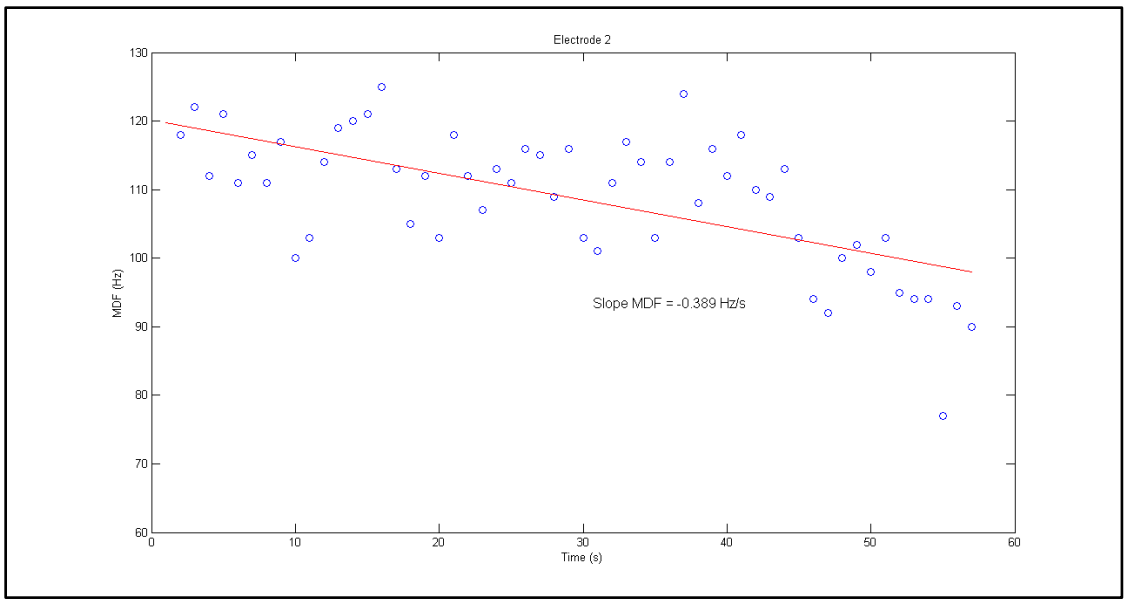


Figure 19: Electrode two change in MDF during a static hold

Overall, the Bluemyo system appeared to accurately record the spectral properties of an electrical signal. This was confirmed using a sine wave generator and myoelectric signals. However, the signal amplitudes recorded using different electrodes are inconsistent. It is expected that this problem introduced minimal errors to the analyses since electrodes were only replaced when absolutely necessary due to failure.

APPENDIX H: Electromyography Data Processing Summary

Initial Processing

Gains were applied to each trial and the DC-offset was removed. Trials were then band-pass filtered (20-450Hz) using a zero phase shift 3rd order Butterworth digital filter.

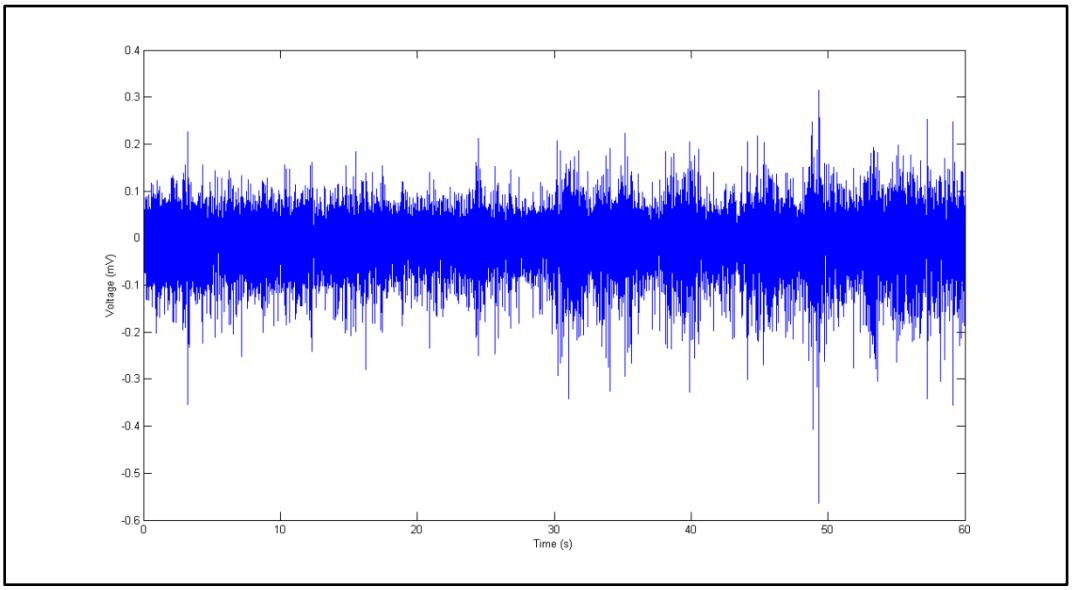


Figure 20: Sample plot of static hold EMG data following DC-offset removal and band-pass filtering

Integrated EMG Processing (Time Domain)

Trials were full wave rectified and the mean EMG amplitudes recorded during the baseline trials were removed.

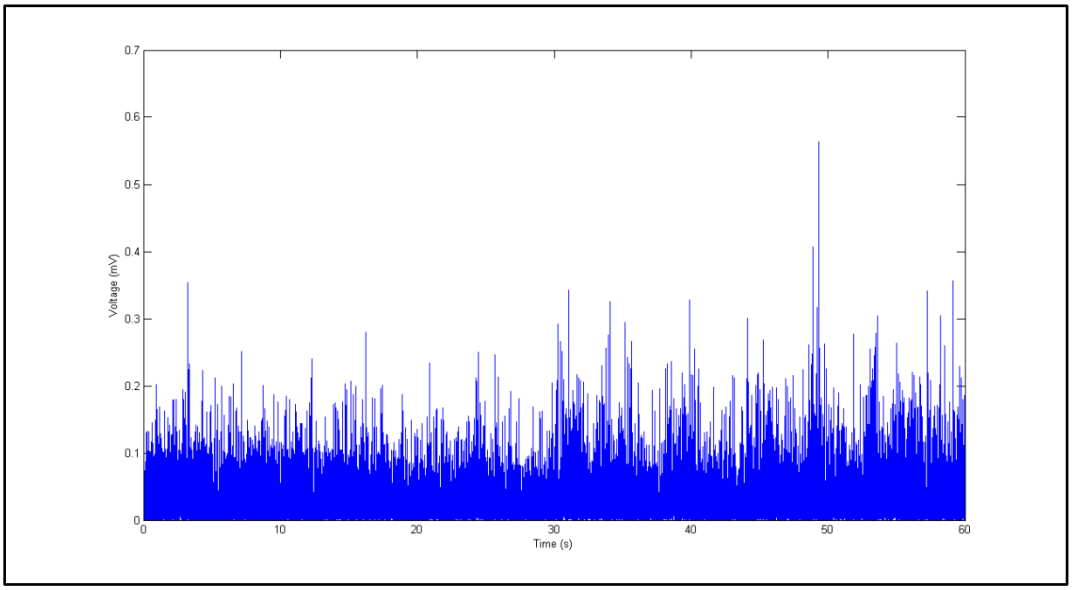


Figure 21: Sample plot of static hold EMG data following rectification

Trials were then smoothed to produce a linear envelope using a zero phase shift 3rd order Butterworth digital filter with a low pass cut-off frequency of 3Hz.

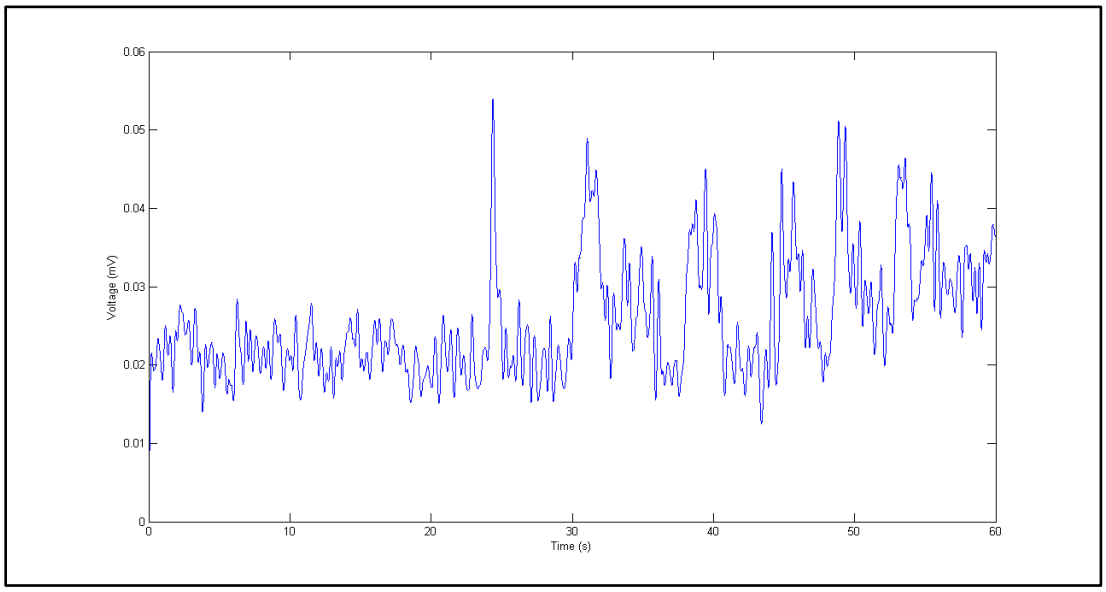


Figure 22: Sample plot of static hold EMG data following low pass filter (3Hz)

The area under the linear envelope, within the central fifty-six second window, was then calculated to provide a measure of muscular activity.

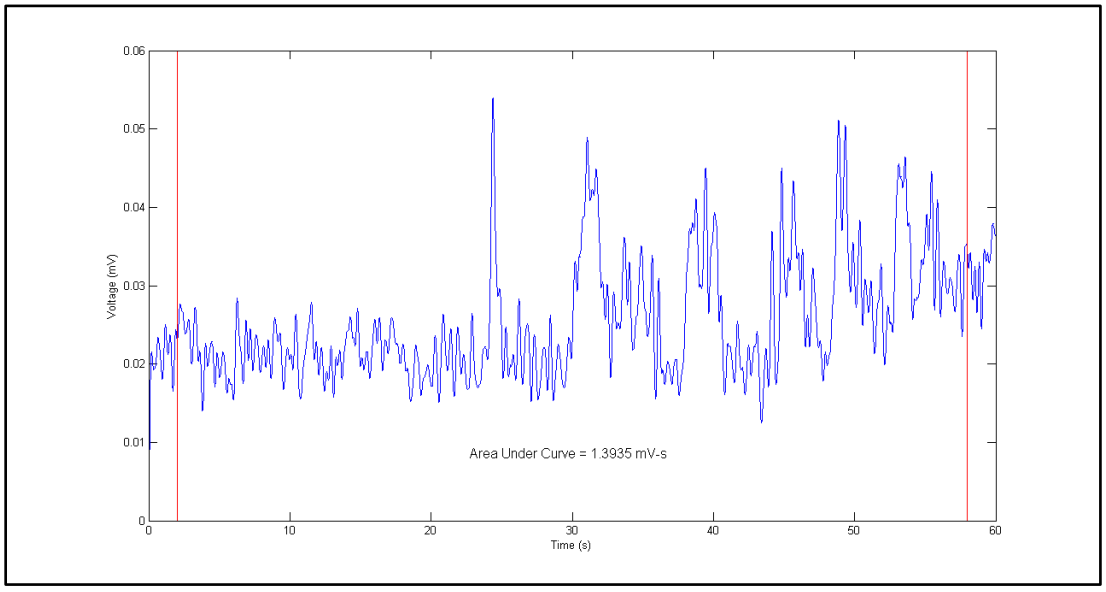


Figure 23: Sample plot of integrated EMG outcome measure

MDF Processing (Frequency Domain)

The signal within each one second epoch was converted to a single-sided power spectrum using a Fast Fourier Transform.

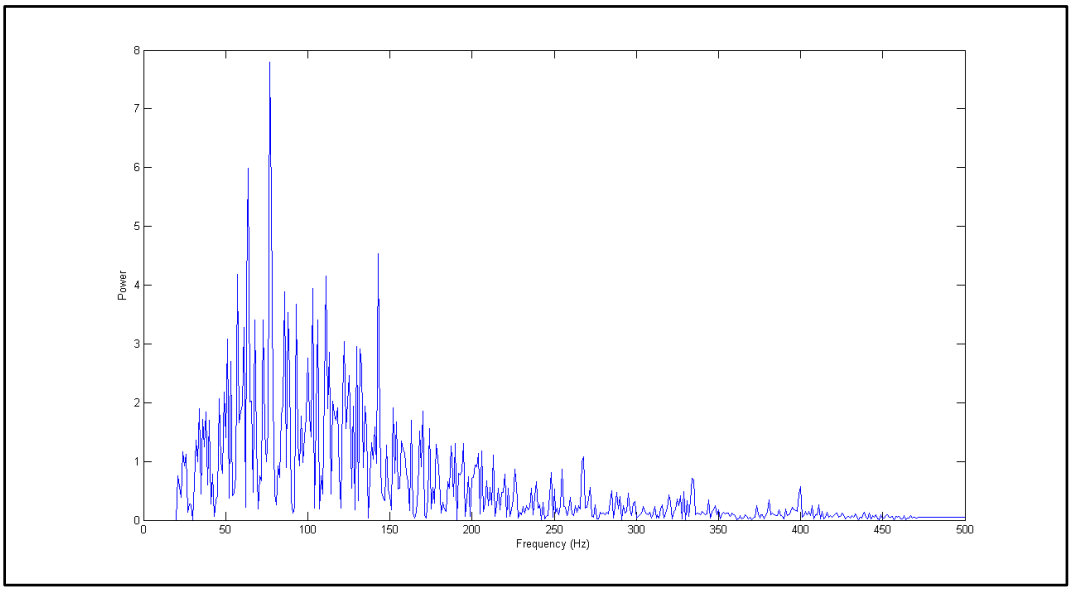


Figure 24: Sample plot of single-sided power spectrum following FFT

The MDF for each one second epoch was determined

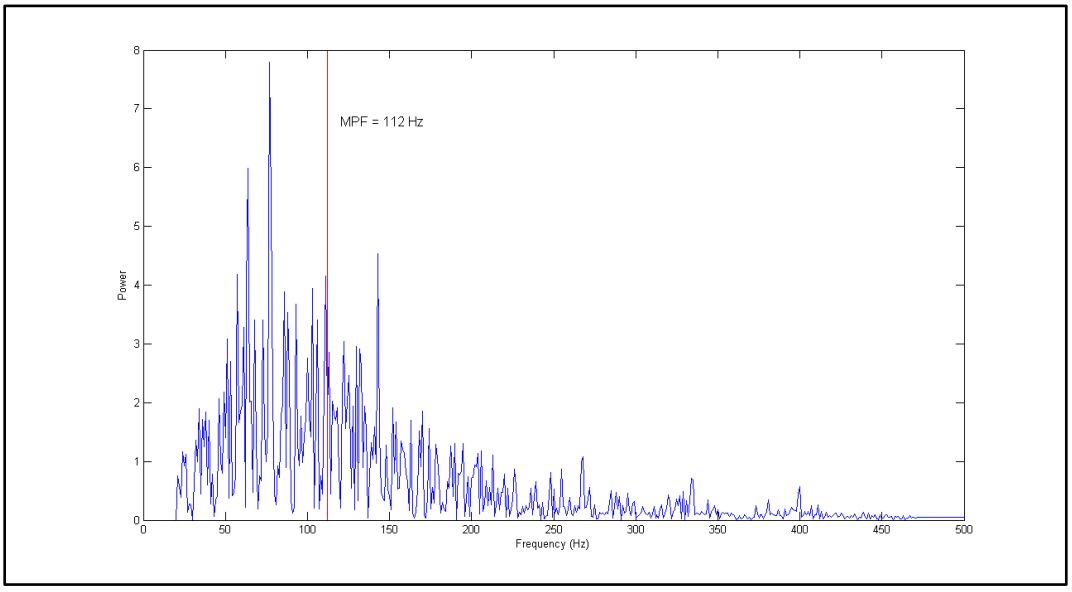


Figure 25: Sample plot of MDF for a one second epoch

Using the central fifty-six MDF data points, the slope of the time vs. MDF regression line was calculated to provide a measure of the rate of muscular fatigue.

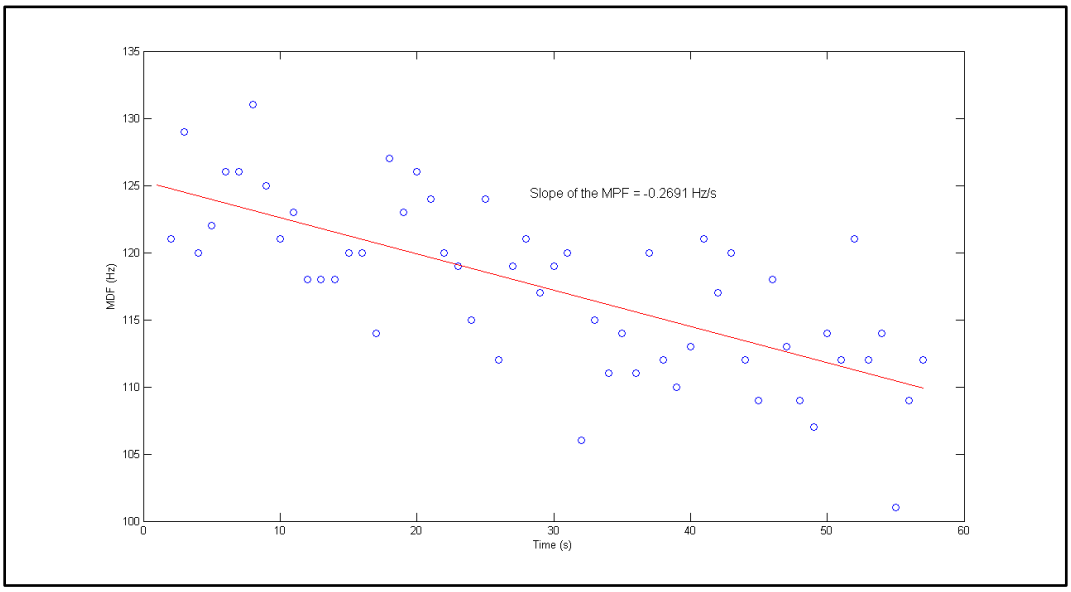


Figure 26: Change in MDF during a static hold

APPENDIX I: Individual Subject Parameters for Each Rifle Configuration

Integrated EMG (iEMG)

Table 5: iEMG for the Anterior Deltoid of the Supporting Arm (AD-SA)

Subject Code	Rifle Configurations						
	0	4	5	6	7	8	9
01	20.18	25.18	30.99	17.49	25.49	29.00	36.30
05	6.00	5.09	6.04	5.07	4.53	5.86	12.08
06	9.38	10.71	9.20	9.71	12.20	10.13	6.10
08	5.82	3.47	0.28		4.03	4.24	1.06
09	18.58	9.79	11.42	6.90	24.68	7.31	15.32
10	0.72	0.73	0.62	0.77	1.58	1.64	1.92
11	1.25	2.64	0.33	0.84	0.18	1.21	0.34
12	22.56	9.83		20.61	11.65	21.30	
13	4.15	4.86	22.20	61.84	54.00	54.98	29.30
14	16.34	18.79		21.47	31.30	18.99	

All values in mV·s

Table 6: iEMG for the Anterior Deltoid of the Trigger Arm (AD-TA)

Subject Code	Rifle Configurations						
	0	4	5	6	7	8	9
01	8.46	9.45	13.82	4.26	10.21	8.62	12.76
02	4.25	8.83	5.02	8.47	9.00	6.85	1.57
05	2.36	2.40	1.55	0.82	1.88	2.09	4.26
06	11.90	11.79	13.28	15.26		8.08	15.27
08	0.73	0.50	0.46	0.91	1.28	1.05	1.05
09	4.18	3.23	7.87	5.84	6.37	9.40	7.22
10	8.43	9.86	17.39	10.22	13.80	12.27	14.55
11	1.93	2.34	1.12	1.61	2.46	2.52	1.01
12	7.88	3.62	9.64			7.42	13.45
13	2.34	2.29	8.37		4.20	4.35	6.08
14		6.14	17.86	8.94	16.06		16.92

All values in mV·s

Table 7: iEMG for the Biceps Brachii of the Supporting Arm (BB-SA)

Subject Code	Rifle Configurations						
	0	4	5	6	7	8	9
01	28.11	33.19	26.33	41.12	42.47	44.79	32.26
05	0.93	2.53	3.79	4.54	3.47	3.17	3.39
06	7.62	7.92	7.23	15.59	11.15	11.50	6.23
08	1.65	2.11	1.13	2.98	3.16	2.38	1.97
09	7.69	8.11	6.17	16.78	12.25		5.67
10	0.44	0.44	0.48	1.26	1.45	1.98	4.76
11	1.07	1.82		1.39	0.99	1.48	
12	5.12	6.69	11.19		9.68	9.96	14.85
14		3.88	4.66	5.49	5.11	3.44	7.54

All values in mV·s

Table 8: iEMG for the Biceps Brachii of the Trigger Arm (BB-TA)

Subject Code	Rifle Configurations						
	0	4	5	6	7	8	9
01	44.38	38.82	35.53		36.20	30.92	41.09
02	1.15	1.41	2.31	2.76	2.66	2.85	3.06
06	1.41	1.44	2.54	2.62	2.88	2.50	2.84
09	0.35	0.31	0.31	0.27	0.48	0.33	0.67
10	0.41	0.43	0.75	0.51	0.47	0.64	0.53
11	0.23	0.45		0.83	1.03	0.46	
14	0.47	0.67		1.12	0.78	1.03	1.09

All values in mV·s

Table 9: iEMG for the Brachioradialis of the Supporting Arm (BR-SA)

Subject Code	Rifle Configurations						
	0	4	5	6	7	8	9
01	0.79	0.94	1.50	1.63	1.71	1.62	1.87
02	3.03	2.97	2.87	8.05	5.24	7.97	4.04
03	15.20	50.95	44.17	44.09	34.95	43.20	49.79
04	0.05	0.07	0.11	0.13	0.12	0.12	0.23
05	0.05	0.03	0.04	0.08	0.07	0.11	0.13
06	1.00	1.32	1.35	1.31	1.18	1.48	1.92
09	0.70	0.84	1.52	1.39	1.34	1.06	2.18
11	0.25	0.34	0.27	0.24	0.28	0.32	0.38
12	1.90	4.36	4.48	5.69	4.21	3.45	5.91

All values in mV·s

Table 10: iEMG for the Brachioradialis of the Trigger Arm (BR-TA)

Subject Code	Rifle Configurations						
	0	4	5	6	7	8	9
05	2.52	4.50	2.26	9.45		2.70	4.66
06	7.64	9.16	9.54	14.20	12.91	12.51	13.85
08	3.96	4.89	4.09	6.54	4.39	4.31	4.15
09	4.62	3.94	3.33	4.92	7.78	4.29	4.44
10	0.16	0.15	0.32	0.28	0.25	0.37	0.35
11	2.03	3.12	2.11	2.91	2.55	3.46	3.09
14	8.16	12.05	12.82	16.56	15.53	14.33	16.67

All values in mV·s

Slope of the MDF (sMDF)

Table 11: sMDF for the Anterior Deltoid of the Supporting Arm (AD-SA)

Subject Code	Rifle Configurations						
	0	4	5	6	7	8	9
01	-0.002	-0.114	-0.199	-0.248	-0.161	-0.090	-0.181
05	-0.186	-0.515	-0.464	-0.303	-0.693	-0.665	-0.428
06	-0.312	-0.484	-0.541	-0.240	-0.464	-0.325	-0.461
08	-0.107	-0.095	0.640		-0.082	-0.073	-0.159
09	-0.182	-0.175	0.088	-0.088	-0.118	-0.186	0.037
10	-0.150	0.289	0.092	-0.069	0.010	-0.860	-0.048
11	-0.058	-0.167	-0.649	-0.500	0.038	-0.262	-0.087
12	-0.259	-0.196		-0.433	-0.322	-0.422	
13	-0.487	-0.488	-0.342	-0.635	-0.818	-0.940	-0.257
14	0.093	-0.013		-0.253	-0.555	-0.198	

All values in ΔHz/second

Table 12: sMDF for the Anterior Deltoid of the Trigger Arm (AD-TA)

Subject Code	Rifle Configurations						
	0	4	5	6	7	8	9
01	-0.020	0.019	-0.002	0.249	-0.035	0.232	-0.058
02	-0.075	-0.159	1.608	-0.184	-0.524	0.036	1.171
05	0.126	-0.256	-0.055	-0.223		-0.178	0.070
06	-0.074	-0.130	-0.199	-0.078	-0.106	0.011	-0.249
08	-0.070	-0.270	-0.624	-0.220	-0.090	-0.145	-0.705
09	-0.127	1.687	-0.084	-0.104	-0.091	-0.175	0.057
10	-0.150	-0.088	0.094	-0.507	0.052	-0.135	-0.183
11	-0.018	0.153	-0.188	0.024	0.032	-0.073	-0.296
12	-0.059	-0.053	-0.224			-0.184	-0.050
13	-0.103	-0.368	-0.092		-0.270	-0.070	-0.159
14		0.265	-0.592	0.416	-0.383		-0.189

All values in ΔHz/second

Table 13: sMDF for the Biceps Brachii of the Supporting Arm (BB-SA)

Subject Code	Rifle Configurations						
	0	4	5	6	7	8	9
01	-0.067	0.014	-0.037	-0.321	0.111	0.039	0.000
05	-0.274	-0.138	-0.015	-0.133	-0.056	-0.095	0.047
06	-0.425	-0.624	-0.470	-1.947	-0.539	-0.698	-0.117
08	-0.126	-0.139	-0.053	-0.122	-0.005	-0.077	-0.014
09	0.093	0.098	0.130	-0.030	0.190		-0.417
10	-0.019	-0.107	-0.008	0.356	0.272	0.229	-0.007
11	-0.092	-0.087		0.003	-0.080	-0.087	
12	0.174	-0.268	-0.187		-0.514	0.030	-0.041
14		-0.237	0.290	-0.276	0.135	-0.184	0.048

All values in ΔHz/second

Table 14: sMDF for the Biceps Brachii of the Trigger Arm (BB-TA)

Subject Code	Rifle Configurations						
	0	4	5	6	7	8	9
01	0.047	0.079	-0.047		-0.360	0.188	-0.298
02	-0.676	-0.299	-0.071	-0.202	-0.121	-0.236	0.127
06	-0.007	-0.037	-0.294	-0.145	0.019	-0.113	-0.278
09	-0.016	-0.216	-0.002	-0.181	0.075	-0.166	0.008
10	0.107	0.069	-0.079	-0.079	-0.111	-0.087	0.225
11	-0.172	0.125		-0.088	0.003	-0.134	
14	-0.244	-0.082		-0.033	-0.272	-0.186	0.273

All values in ΔHz/second

Table 15: sMDF for the Brachioradialis of the Supporting Arm (BB-SA)

Subject Code	Rifle Configurations						
	0	4	5	6	7	8	9
01	0.038	-0.019	-0.067	0.069	0.102	0.006	0.046
02	-0.038	-0.117	0.063	-0.092	-0.070	-0.050	0.096
03	-0.352	0.354	0.094	0.331	-0.291	0.127	0.611
04	-0.118	-0.120	0.089	-0.058	0.058	0.087	-0.011
05	-0.533	-0.257	-0.305	-0.312	-0.182	-0.077	-0.419
06	0.051	-0.122	-0.107	-0.116	-0.105	-0.137	-0.157
09	0.090	0.000	0.154	-0.117	0.123	-0.031	-0.019
11	0.119	-0.009	0.060	0.006	-0.061	0.082	-0.002
12	0.110	-0.357	0.118	-0.311	0.633	0.268	0.034

All values in ΔHz/second

Table 16: sMDF for the Brachioradialis of the Trigger Arm (BB-TA)

Subject Code	Rifle Configurations						
	0	4	5	6	7	8	9
05	-0.046	0.100	-0.196	-0.162		1.573	0.108
06	0.091	0.147	-0.057	0.049	0.156	0.143	-0.108
08	0.024	-0.030	-0.017	0.022	0.077	0.048	-0.085
09	0.104	0.038	0.068	-0.001	0.179	0.067	0.122
10	0.098	0.142	-0.208	0.051	0.037	-0.196	-0.297
11	-0.056	-0.117	-0.083	-0.003	0.024	-0.097	-0.044
14	0.053	0.048	-0.220	-0.237	-0.051	-0.061	-0.040

All values in ΔHz/second

Borg CR10 Ratings of Perceived Exertion (cRPE)

Table 17: cRPE for each rifle configuration

Subject Code	Rifle Configurations						
	0	4	5	6	7	8	9
01	3.0	4.5	4.0	10.0	9.5	9.0	9.0
02	2.0	5.5	4.5	8.5	7.5	7.0	5.0
03	4.5	6.5	5.5	9.0	7.0	8.5	7.5
04	0.5	1.0	1.0	1.0	1.5	2.5	2.0
05	1.0	2.5	2.0	2.5	2.5	3.0	3.0
06	0.5	1.0	1.5	4.0	3.0	3.0	2.5
07	1.0	5.0	3.5	6.0	2.5	7.0	6.0
08	0.8	2.5	3.0	4.5	3.0	3.5	7.0
09	3.0	3.0	4.0	5.5	5.5	5.0	6.0
10	2.5	4.0	5.5	6.5	8.0	9.5	9.0
11	0.0	0.0	0.0	0.3	0.0	0.0	0.0
12	0.5	6.0	5.5	8.5	4.5	7.5	6.5
13	2.0	6.5	7.0	8.0	9.5	9.0	9.5
14	1.5	5.0	7.0	9.5	6.5	9.5	8.5

Muscular Strain Exit Survey

Table 18: Identified areas of muscular strain

Subject Code	Anterior				Posterior									
	Shoulder		Upper Arm		Shoulder		Upper Arm		Forearm		Wrist		Back	
	TA	SA	TA	SA	TA	SA	TA	SA	TA	SA	TA	SA	Upper	Lower
01				✓						✓			✓	
02	✓	✓	✓	✓							✓			✓
03		✓	✓	✓			✓	✓						✓
04	✓	✓								✓				✓
* 05			✓	✓			✓	✓						✓
** 06		✓												✓
07										✓		✓		✓
08									✓	✓				✓
09		✓		✓								✓		✓
10				✓						✓	✓	✓		✓
11											✓	✓		
12			✓	✓										✓
13			✓	✓									✓	✓
14				✓						✓		✓		✓
% of Subjects	14	36	36	64	0	0	14	14	7	43	21	36	7	86

TA: Trigger Arm, SA: Supporting Arm
**Subject 05 also indentified the anterior and posterior thigh*
***Subject 06 also identified the posterior thigh*