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The perception of effort during muscular fatigue and recovery

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THE PERCEPTION OF EFFORT DURING MUSCULAR FATIGUE AND RECOVERY

BY

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USE OF THESIS

DECLARATION

"I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any institution of higher education; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text".

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Abstract

This study investigated how sense of effort is altered during fatigue in nine normal subjects. A contralateral limb matching paradigm was used in which the subjects non-dominant (reference) arm was held at 20% MVC with force production matched at one minute intervals by the dominant (marching arm). It was found that matching force increased in a linear fashion with fatigue. It was also observed that EMG amplitude increased in the reference and matching arm and remained elevated during a 15 minute recovery period. As in previous studies strong correlation (r = 0.85) between rmsEMG in the reference arm and matching force was recorded. It was found that a subject was able to estimate force accurately a short time (in 10 minutes) after the fatiguing influence was removed although strength had not fully recovered. As with previous studies it was concluded that judgements of force production were based on the subjects internally generated perception of effort and not on the absolute force being generated.

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CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Muscle fatigue is a common occurrence which results when skeletal muscles perform sustained or repeated contractions in order to complete a task. Muscle fatigue can be defined as "...any reduction in the force generating capacity of the total neuromuscular system regardless of the force required in any given situation" (Bigland-Ritchie & Woods, 1984, p. 691).

A contraction maintained at a low level for an extended duration (eg carrying a briefcase to work) will gradually cause a sensation of increasing heaviness to be experienced and a gradually increasing amount of effort being needed to support it. Studies concerning perceptions of weight and force date back to a text by Ernst Weber (1834) entitled *The Sense of Touch* (cited in Jones, 1986). In the same year Sir Charles Bell also published a text exploring muscular sense, especially that of the hand (cited in Jones, 1986). Muller (1840) cited in McCloskey (1981) is credited with first voicing the idea that sensations may result from central neural processes relating to motor commands.

Sensations of heaviness may be related to a centrifugal process known as corollary discharge. Corollary discharge is one of the central mechanisms involved in kinesthesia and was a term first used by Sperry (1950) to describe "...supposed internal signals that arise from centrifugal motor commands and that influence perception" (cited in McCloskey, 1981, p. 1415). Sense of effort refers to "... sensations said to arise directly

from the internal actions of motor commands" (McCloskey, Gandevia, Potter, and Colebatch, 1983, p.151) and may sometimes be used as a synonym for corollary discharge (McCloskey, 1981). Another process known as sense of tension or force is thought to be separate from, but closely related to a sense of effort, and is related to an individuals estimation of weight (Jones & Hunter, 1983b). McCloskey, Ebeling and Goodwin (1974) suggest that cutaneous mechanoreceptors, receptors in the contracting muscles, tendons or joints and centrifugal mechanisms all may contribute to sense of tension. It is however more likely that sense of tension is mediated by peripheral feedback mechanisms while sense of effort is mediated through central processes (Cafarelli, 1988).

Mechanisms that cause peripheral fatigue of the skeletal muscle system have been investigated quite thoroughly and are well known, however mechanisms responsible for central fatigue are not understood to the same degree. Alterations in metabolic processes within the fiber, failure of the motor neuron at the neuromuscular junction, changes in the motor nerve itself, and alteration in the central nervous system (Fox, Bowers & Foss, 1993) are all events that may cause muscular fatigue. While central fatigue is theorised to be psychologically related to a subjects motivation (Bigland-Ritchie & Woods, 1984) and biochemically to neurotransmitters serotonin and dopamine (Davis, 1995) it is most likely that peripheral fatigue occurs due to: altered sarcolemmal membrane depolarisation, neuromuscular junction failure, altered calcium absorption and release, and impaired cross-bridge interactions (Green, 1987).

How peripheral and central interactions of fatigue are processed by the central nervous system during fatigue and how this may affect a muscles perception of a weight is of great interest to the sports scientist. This is because many sports have actions (eg gripping a tennis racquet) that rely on prolonged contractions at a low level to achieve success. Altered perceptions of fatigue also has implications for research into individuals which suffer from effort related syndromes (eg chronic fatigue syndrome). During exercise these individuals have an increased sense of effort, in comparison to normal subjects, even though there is no differing physiological mechanisms present (McCluskey, 1993).

1.2 Purpose of the Study

The purpose of this study is to investigate how effort sensations change in skeletal muscle while it is being fatigued to exhaustion via a low level isometric contraction. This will be achieved by recording the progression of estimated tension production and rmsEMG amplitudes in the dominant arm (matching arm) and the non-dominant arm (reference arm). By doing this I will further clarify relationships between muscular fatigue and sense of effort already explored by other authors.

1.3 Aim of Study

The aim of this study is to record alterations in a subjects sense of effort during a low level isometric contraction to maximal endurance. This will be achieved by:

- Recording and comparing force production in the matching arm and reference arm during the exercise protocol and recovery period;
- Recording and comparing EMG profiles of the reference and matching arms;
- Recording perceived exertion of the subjects reference arm, via a Borg Scale rating, once per minute during the course of the exercise protocol; and
- Recording and comparing maximal voluntary contraction (MVC) of the reference and matching arm before and after the exercise protocol.

1.4 Hypothesis

- There will be increased force production during the endurance task and recovery in the matching limb;
- An increase in EMG amplitudes in both limbs during the endurance task which will remain elevated during recovery;
- There will be increased perceived effort during the endurance task and recovery in the reference limb; and
- There will be a decrease in MVC and maximal EMG of the reference arm and matching arm during recovery, compared to pre exercise values.

1.5 Theoretical Framework

It has been observed that fatiguing a muscle will result in a decrease in the force able to be produced. The peripheral, and to a lesser extent central mechanisms of fatigue have been well documented. The role of sense of effort during fatigue and recovery has not been as extensively studied. The mechanisms behind sense of effort will be explored in subjects by utilising EMG and tension measures in contralateral arms. The importance of these findings will lie in being able to relate force and myoelectrical relationships to sense of effort and muscle fatigue in normal subjects.

CHAPTER TWO

LITERATURE REVIEW

2.1 Fatigue

Muscle fatigue is activity dependant and results in an impairment of motor performance (Enoka & Stuart, 1992). As fatigue increases the perceived effort required to maintain the same degree of force will also increase (Enoka & Stuart, 1992). Not only is fatigue demonstrated by a decrease in force production but also with a shift in the EMG frequency range spectrum and the accumulation of intra-muscular metabolites (Bigland-Ritchie & Woods, 1984). The causes of fatigue are often divided into two areas, peripheral and central. Peripheral fatigue refers to mechanisms that affect the muscle directly while central fatigue is associated with events occurring only in the CNS (Davis, 1995).

2.1.1 Peripheral Mechanisms

The proposed mechanisms of peripheral fatigue have been extensively studied and as such are generally accepted. Asmussen (1979) states that there are two areas in which peripheral fatigue can occur divided into "transmission mechanisms" and "contractile mechanisms". Possible mechanisms of peripheral fatigue stated by Green (1987) are: pre-synaptic failure, failure of sarcolemma to sustain an action potential, depressed calcium release from sarcoplasmic reticulum, reduced binding affinity of troponin for calcium, a failure in the cross bridge cycle and, depressed calcium re-accumulation by sarcoplasmic reticulum.

2.1.2 Central Mechanisms

There are however several theories as to how muscle fatigue can affect the CNS and its perception. Gandevia, Allen, & McKenzie (1995, p. 281) suggest some possible mechanisms of central fatigue. These include: decline in motor cortical neuron discharge during sustained contractions, decline in muscle spindle afferent discharge over the course of strong isometric contractions, and "...inhibitory feedback from Golgi tendon organs and group III and IV afferents". Also suggested are psychological factors such as a lack of motivation in the subject (Bigland-Ritchie & Woods, 1984; Secher, 1992; Stokes, Cooper, & Edwards, 1988). There also "...may be a physical limitation to the CNS capacity" (Bigland-Ritchie & Woods, 1984, p. 693). Davis (1995) hypothesised that the neurotransmitters 5-hydroxytryptamine and dopamine might play a fatiguing role within the CNS during prolonged exercise.

2.2 Kinesthetic Sensibility

Proprioception is the perception of limb position and movement achieved through the activity of sensory neurons in the skin, muscles and joint tissue (Grigg, 1994). Information from the proprioceptors can be interpreted by the consciousness. This is known as kinesthetic sensibility and involves "...perceived sensations about the static position or velocity of movement....and perceived sensations about the forces generated during muscular contractions" (McCloskey, 1978, p. 763). Perceived sensations may be mediated by peripheral proprioceptive mechanisms and also by central input from the motor centres, the latter has been termed "corollary discharge".

2.2.1 Peripheral Mechanisms

Peripheral contributions to kinesthetic sensibility occur through muscle spindles, tendon organ receptors, joint receptors, and cutaneous mechanoreceptors (Jones, 1994). Muscle spindles react to muscle length and are involved in signalling joint movement (Grigg, 1994). Vibration is known to be a powerful stimulus for muscle spindles. Experiments involving vibration of the biceps brachii muscle tendon of one arm have shown either an increased force output estimation in the vibrated limb (Jones & Hunter, 1985) or a decreased force output estimation (McCloskey, 1978) when compared to the arm not exposed to vibration. This provides conflicting evidence as to whether muscle spindles are able to signal the force of a contraction. Golgi tendon organs are present in skeletal muscle tendons and relay information to the CNS concerning tendon tension. Overestimations of tension may be a result of Golgi tendon organ discharges (McCloskey, 1978).

The remaining two peripheral contributors are joint receptors which only transmit information when the joint is moved to its outer limit of range of motion and cutaneous mechanoreceptors whose role is thought to be almost negligible with notable functions being recorded mainly in the human hand (Grigg, 1994).

2.2.2 Corollary Discharge

The term corollary discharge can be associated with high level neural processes and internal actions (Enoka & Stuart, 1992)..."which arise from motor signals and which influence perception" (McCloskey, et al., 1983, p. 151). McCloskey (1981) is of the opinion that static contractions are extremely likely to be perceived by corollary discharge; much more so than sensations of movement. McCloskey and Torda (1975) concluded from their experiments that corollary discharge may interact with muscle afferent signals before accessing the consciousness and that weight and tension estimation could be mediated through corollary discharge. The evidence for the role of corollary discharge in the perception of effort is discussed by Enoka and Stuart (1992) and McCloskey, et al. (1983). This includes:

- An experimentally induced decrease in muscle force leads to an increased perceived exertion in association with an increase in the generation of motor commands;
- Attempted movement of a paralysed limb is not perceived, even though there is awareness of the attempt and input from peripheral sensory sources indicating movement;
- Excitation of a motor neuron pool leads to a decrease in motor commands and perceived exertion; and
- Lesions following motor strokes increase perceived effort.

2.2.3 Sense of Effort

A major kinesthetic function is the judgement of force experienced while the muscle is exerting an isometric contraction. This judgement is normally thought of as a centrally generated sense of effort (ie. corollary discharge) but could also possibly arise from a peripheral sense of force (Jones, 1995).

Ekblom and Goldberg (1971) are credited with first raising the issue of central and peripheral factors contributing to an effort sense. Since then many authors have investigated this sense of effort (Cafarelli & Bigland-Ritchie, 1979; Jones & Hunter, 1983a; and McCloskey, et al., 1974). They have generally used the arm and involved either the biceps brachii, triceps surae or forearm muscles. Jones and Hunter (1983a) conducted experiments similar to the current study involving the contralateral muscles of the upper arm. Tension and myoelectrical relationships were established relating contralateral arms and they concluded that sense of tension was not distinguishable from a sense of effort. McCloskey, et al., (1974) found evidence during the course of their experiments for a general overestimation of tension in fatigued muscles via central processes. The phenomenon of altered estimation in fatigue has since being studied by other investigators (Aniss, Gandevia, & Milne, 1988; Cafarelli & Bigland-Ritchie, 1979; Jones & Hunter, 1983a) who have also concluded that it is mediated by central mechanisms. It has also been established that the degree to which sense of effort alters, depends largely on the size of load rather than the length of time the contraction is held.

2.3 Electromyography (EMG) and Muscle Fatigue

Electromyography is used to detect myoelectrical signals and is an important tool when studying localised muscle fatigue (Beliveau, Van Hoecke, Garapon-Bar, Gaillard, Herry, Atlan, & Bouissou, 1992; Linssen, Stegeman, Joosten, van't Hoff, Binkhorst, & Notermans, 1993). Analysis of surface EMG amplitude, power density frequency spectrum, and muscle fiber conduction velocity can provide important information in fatigue profiles of muscles (Linssen, et al., 1993). Possibly the most commonly measured EMG variable used to observe myoelectrical fatigue is amplitude. Bigland-Ritchie (1981) states that EMG magnitude depends on the amount of active fibers, the fibers mean activation rate, and each fibers average action potential. Jones and Hunter (1982; 1983a; & 1983b) have carried out several experiments concerning the relationships between myoelectric activity and force perception. Their findings suggested that during the course of a fatiguing contraction overestimation of forces was most likely to result from efferent signals of similar magnitude being dispatched to fatigued and unfatigued muscles. Several authors have described myoelectrical and metabolic patterns evident in the muscle during fatiguing exercise and the following recovery period. These include:

- A progressively increasing elevation in EMG amplitude as fatigue develops and immediately postexercise when compared to resting EMG (Bigland-Ritchie, 1981; Kirsch and Rymer, 1987; and Maton, 1981);
- A recovery of the EMG power spectrum that occurs within 10 minutes postexercise and which is faster than that of intramuscular metabolites (Beliveau, et al., 1992; Kirsch & Rymer, 1987);

- Changes in phosphate, phosphocreatine and phosphoric acid concentration which appear to parallel those in the EMG power spectrum during exercise (Beliveau, et al., 1992);
- A decrease in the low frequency EMG content coupled with an increase in high frequency EMG content (van der Hoeven, van Weerden, & Zwarts, 1993); and
- A decrease in myoelectrical activity during the course of a fatiguing MVC (Bigland-Ritchie, 1981).

2.4 Perceived Exertion

For quite some time now scientists have endeavoured to find a ratio-based relationship between the subjective occurrence of perceived exertion and an objective, quantifiable physiological mechanism. Mihevic (1981) suggests that the degree to which a physiological response is interpreted as a perceptual cue depends on the responses availability to the conscious. The psychophysical perceptions of a subject to physical effort is known as perceived effort with Borg (1982, p. 377) stating that a subject rating of "...perceived exertion is the single best indicator of the degree of physical strain".

There are two physiological factors, local and central, thought to contribute to exertion perceptions. Local factors which involve feelings of strain from the exercising muscles and may include input from blood lactate, Golgi tendon organs and general muscle sensations (Mihevic, 1981; Pandolf, 1982). Central factors are associated with heart rate, ventilation and respiration rates (Mihevic, 1981). Ekblom and Goldbarg (1971) published experimental findings relating oxygen consumption, heart rate and blood

lactate concentrations to ratings of perceived exertion (RPE). They concluded that subject RPE was based on both, central and peripheral factors, with RPE in heavy exercise relating to the amount of muscle mass used. Cafarelli (1982) theorised that sensory responses to brief static and dynamic exertion are a function of the neuromuscular system.

In 1970 Borg (1982) proposed a 15-grade scale which has been widely accepted by the scientific community to best objectify subjective perceptual feelings (Table 2.1). The ratio values in this table have been found to correlate strongly to heart rates of between 60 and 200 beats per minute for adults aged 30 to 50 years, with heart rate thought to reflect exercise strain (Borg, 1982; Mihevic, 1981). The following equation may allow heart rate to be predicted from RPE:

Heart Rate = RPE X 10 (Borg & Noble, 1974)

Table 2.1 The 15 point scale for perceived exertion.

6	
7	Very, very light
8	
9	Very light
10	
11	Fairly light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very, hard
18	
19	Very, very hard
20	

Source: Borg, G. (1982). Psychological bases of percived exertion. Medicine and Science in Sports and Exercise, 14 (5), 377-381.

As well as Borg's 15-grade RPE scale there has been a scale developed based on ratio-scaling principles, used to grade the subjects effort magnitude. This scale can be applied to rate subjective increases experienced during activities involving an increasing stimulus intensity. A possible disadvantage of theses scales may be a tendency for the subject to "conserve numbers" (eg 20 or 10 must equal the maximal effort) in order to fit in with the scale (Cafarelli, 1988).

CHAPTER THREE

METHODOLOGY

3.1 Design

This study involved comparisons of muscle force and EMG measures in contralateral arms. Subjects were seated in a strength-testing chair and held their non-dominant (reference) biceps brachii at 90° at a force equating to 20% of their MVC, until they were unable to maintain the required force. At regular intervals, of one minute, a replication of force production in the reference arm was attempted by the dominant (matching) arm. Immediately following this matching contraction, RPE in the reference arm was recorded. EMG profiles of both limbs monitored through surface electrodes mounted on the biceps brachii were recorded throughout the entire procedure. Figures 3.1 and 3.2 illustrate a subject positioned in the force chair ready to begin the exercise protocol.

3.2 Pilot Study

Preceding the main project a pilot study was conducted. The main purpose of this study was to measure reproducibility of force and EMG data obtained using the experimental setup. This study was also used to familiarise the author with all equipment operation prior to commencement of the main project. Five male subjects participated in this study mean age 23.6 (± 2.1) years and mean weight 76.6 (± 5.6) kilograms, with data being collected from between 4 and 11 limbs. Contractions were performed, in random order, with non-dominant and dominant biceps brachii equal to 10, 20, 30, 40, 50, 60, 80

percent of subject MVC, as measured at the beginning of the session. The protocol was performed for each subject during two separate occasions with all data being sampled at a rate of 500 Hz. Method error (ME) of MVC and maximal rmsEMG data was 2.9 and 10.3, respectively. The coefficient of variation was 2.2% for MVC and 14.5% for the rmsEMG. Force and rmsEMG data for the first test and the retest have been graphed against one another and are displayed in Figure 3.3. Figure 3.4 contains typical force and rmsEMG traces recorded during the contractions made at various MVC percentages.

3.3 Instruments

- Force Chair and restraining straps;
- Padded Board with C-Clamps;
- Tensiometer-strain gauge;
- 5 Volt Power Supply;
- IBM microprocessor;
- Amlab Software;
- 15 Point Borg Scale (Borg, 1982);
- RPE Data Collection Sheet;
- Alcohol swabs (Medi-Swab);
- Electrode leads; and
- Surface EMG electrodes (Ag/AgCl, Meditrace).

3.4 Subjects

Nine subjects composed of university staff and students participated in this study (7 male and 2 female). Ages ranged from 20 to 37 years, mean 27.6 (s.d. û6.9) and weight ranged from 53 to 110 kilograms, mean 79.6 (s.d. û17.2). Subject exercise activity level ranged from 2-3 days of aerobic exercise a week to 6-7 days mixed aerobic and light resistance training. Physical characteristics are described in Appendix A. Eight of the nine subjects were right hand dominant with one male subject being left hand dominant. Each subject was familiarised with test protocols and expectations previous to the commencement of testing and informed as to the potential side effects they may experience post-exercise. To this effect all subjects signed an informed consent form prior to any testing (Appendix, B). This study received approval form the Edith Cowan University Committee For The Conduct of Ethical Research before any testing was performed. To protect subjects anonymity names were not used with all subjects assigned numbers.

3.4.1 Subject Limitations

Subjects varied in age and sex and also in strength, susceptibility to fatigue and dominant arm. Subjects also varied on subjective ratings of perceived exertion. Subjects were required to be non participatory in intensive weight training.

3.4.2 Subject Delimitations

Delimitations included subjects perception of effort, threshold of pain and time to fatigue. In order to decrease impact of these areas when subjects neared maximal

endurance they were verbally encouraged to give 100%, insuring th?' a true maximal endurance was reached.

3.5 Procedures

3.5.1 Apparatus

Subjects were seated in the force chair and secured with the restraining straps across the midriff. Elbows were then positioned at shoulder width on an adjustable padded brace which was secured in place with c-clamps. The brace was secured in the optimum height position to produce a 90 angle between the upper arm and the forearm. Height was adjusted via a series of holes drilled into the force chair frame. The strain-gauge force transducers mounted on the force chair frame were then attached to the subjects wrist via a padded, non-elastic strap. Both hands were placed in a pronated position. Once per week the strain-gauge force transducers were calibrated using fixed weight calibration plates (Appendix C). Nine volt batteries were used to run a regulated 5 volt power supply and were discarded once they dropped a half volt in order maintain calibration accuracy. Throughout the testing session force and EMG measures for both limbs were continually recorded and stored, via the Amlab program, on the computer hard drive at a rate of 500 Hz.

3.5.2 Determination of MVC

Preceding each testing session subjects MVC (measured in N) was determined at 90° of flexion using both the non-dominant (reference) arm and the dominant (matching) arm. The subject was instructed to bring the wrist to the shoulder with the largest amount of

effort possible and to avoid all other body movements. When a MVC was being performed the subject was instructed to keep the opposing arm also at 90° of flexion. Each contraction was held until a visually judged peak force had been obtained on the computer monitor. Two minutes rest was allocated between trials. From the contraction with the highest force production for the non-dominant arm, a 20% MVC was determined. This was then displayed on the computer monitor using a yellow trace to provide the subject with a marker of the required target contraction. A blue trace was positioned at 10 N below the yellow and subjects experiencing difficulties keeping the force on the yellow trace were informed that they could keep it between the two, giving them a larger target area.

3.5.3 Electromyography

The subjects biceps brachii and lateral epicondyle were thoroughly cleaned with alcohol swabs. Surface (Ag/AgCl) electromyograph electrodes were then placed over the biceps brachii muscle of both limbs. The active electrode was positioned over the mid-point of the muscle belly and the inactive electrode 20 mm distal. The mid-point was determined visually by having the subject flex their biceps brachii at 90° of flexion. The earth electrodes was placed over the lateral epicondyle of the humerus. Electrode leads were attached after the surface electrodes were secured and plugged into a preamplifier controlled by an IBM computer.

3.5.4 Borg Scale RPE

A 15 point Borg Scale was employed to record subject RPE in the reference arm. Prior to commencement of any testing subjects who were unfamiliar with the use of a Borg

Scale were instructed as to its usage. Subjects were informed in a very clear manner that given RPE values were to correspond to the amount of effort they felt they were exerting at the wrist and not the force. RPE values were sampled from the reference arm once per minute during the endurance task and at 1, 3, 5, 10, and 15 minutes of the recovery. Values were recorded in a data sheet (Appendix D) along with any comments the subject cared to make.

3.5.5 Endurance Task

The endurance task was commenced after the subject performed the isometric contraction of the reference arm at the predetermined 20% MVC level. From this time once per minute the subject was verbally instructed to match the force being exerted in the reference arm, with the matching arm, for a period of 10 seconds. Immediately following this contraction a rating of perceived exertion in the reference arm was recorded using a Borg Scale (Borg , 1982). Maximal endurance was considered to of been achieved when the subject could no longer sustain the target force of 20% MVC.

3.5.6 Post-Exercise Procedure

For a period of 15 minutes after maximal endurance the subject remained seated in the force chair and a recovery protocol was performed. During this period subjects continued to attempt to match force produced in the reference arm with the matching arm at time intervals of 1, 3, 5, 10, and 15 minutes post maximal endurance. At the above appointed times a 20% contraction of the reference arm was performed. After the contraction had been held for 5 seconds a RPE value was given by the subject.

Following this the matching arm attempted to exert a similar force for 10 seconds. Both arms were then relaxed and an MVC of the reference was performed immediately followed by an MVC of the matching arm. As in the pre exercise MVC procedure the opposing arm remained at 90° of flexion.

3.6 Data Analysis

All data was analysed using the either the statistical program SPSS (version 6.0) for windows or Microsoft Excel (version 5.0). Data recorded during the endurance task and recovery period for force and EMG variables varied widely in magnitude between subjects. Due to this fact, data was normalised, for comparison purposes to percentages of pre exercise maximal measures. To take into account the fact that subjects also varied in endurance time all data were standardised to produce an equivalent time series for each subject. Standardisation was achieved though the use of percentages to segment endurance times into equivalent portions with values being taken from corresponding times. MVC and maximal EMG were determined by taking the average of a 0.25 second period before and after the strongest recorded force. Paired t-tests were performed between initial values and values recorded during the endurance task and recovery to obtain statistically significant values ($P<0.05/P<0.01$). A Pearson r product moment correlation was performed between average values for reference arm rmsEMG and matching force.

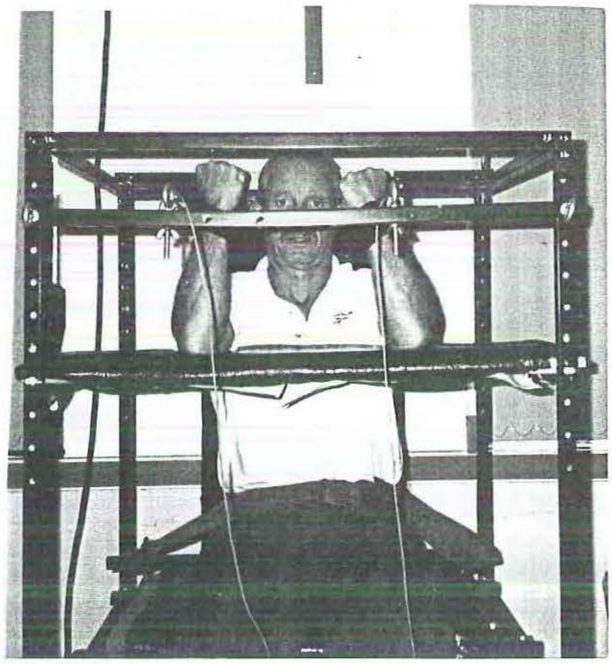

Figure 3.1 A front-on illustration displaying a subject correctly positioned to commence the endurance task.

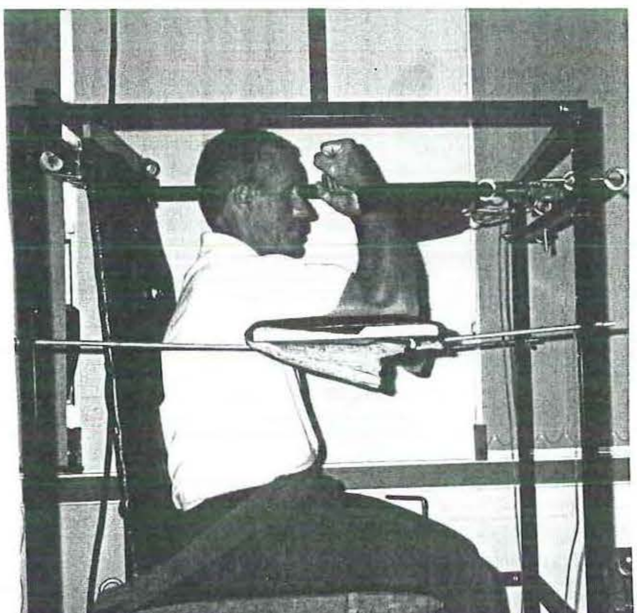

Figure 3.2 Side on illustration showing the positioning of wrist straps and angle of the subjects arms.

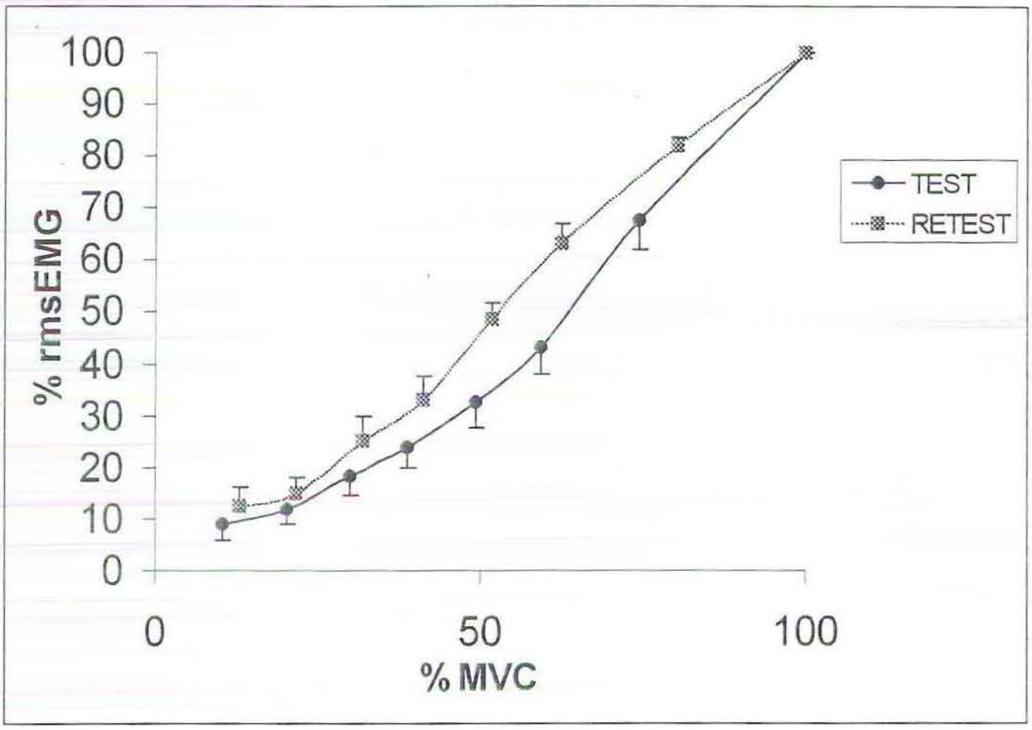

Figure 3.3 This represents the relationship found between force and rmsEMG values recorded during contractions of various strength.

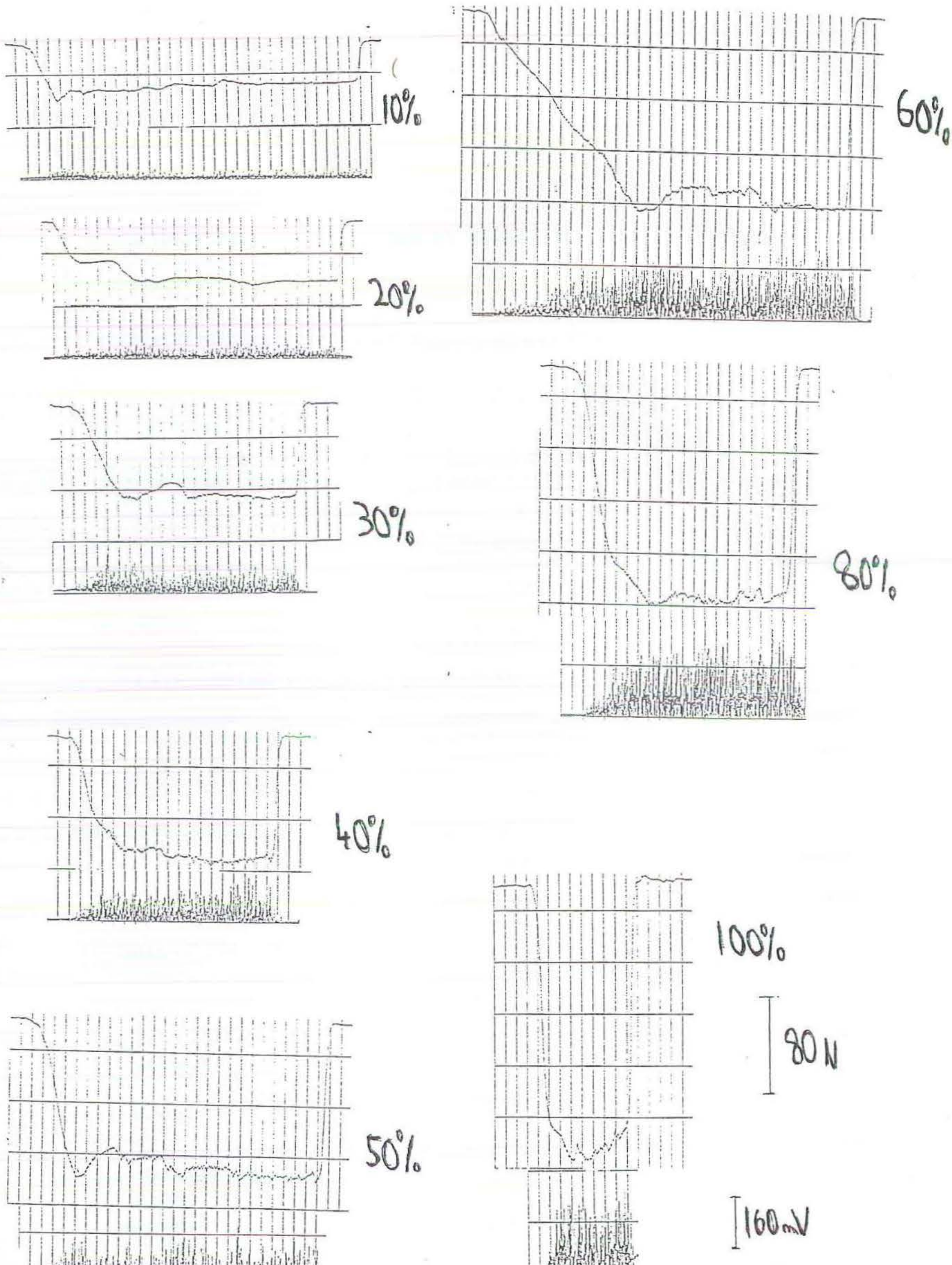

Figure 3.4 This displays typical rmsEMG and force traces recorded during contractions of varying force (one divison equals 0.5 seconds).

CHAPTER FOUR

RESULTS

All force and EMG subject data for the endurance task and recovery protocols were normalised with respect to pre-exercise maximal measures as outlined in the methods section. Values are expressed as mean ± the standard error of the mean (sem). Measures corresponding to 0% of maximal endurance are those values recorded during the first matching contraction. Subject raw data can be found Appendix E. Standardised values for normalised subject data can be found in Appendix F.

4.1 Pre-Exercise MVC and Maximal EMG

Data representing the mean MVC and maximal EMG for the reference and matching arm are displayed graphically in Figure 4.1 and Figure 4.2 respectively. The reference arm produced a mean force of 315.1 (±22.3) N with a range of 209 - 427 N. This compared to the matching arm which produced a mean force of 343.6 (±22.5) N with a range of 216 - 508 N. The matching arm produced a mean force which was 8.3 % greater than the reference arm. This difference in means was found not to be statistically significant. The reference arm produced a mean voltage of 185.4 (±12.7) mV with a range of 78 - 278 mV. This was very closely replicated by the matching arm which produced a mean voltage of 184.6 (±20.0) mV with a range of 85 - 268 mV. There was very little variation between the maximal EMG of both arms with the reference arm producing a rmsEMG signal 0.4 % greater than the matching arm.

4.2 Force Production During the Endurance Task

Normalised data representing the relationship between force production in the reference and matching arm can be found graphically in Figure 4.3. There was great variability in the endurance times of each subject, with times ranging from 7 to 34 minutes. Mean endurance time was 12.9 (±1.6) mins. Throughout the endurance task subjects were found to be very accurate at maintaining the required reference contraction, with the force being maintained at a mean of 20.4 (±0.3) % of the reference MVC. Force exerted by the matching arm was less accurate with contractions exerted by the matching arm found to gradually increase in strength as the endurance task progressed. Normalised force in the matching arm ranged from 21.8 (±1.0) % of the subjects matching arm MVC, during the first matching contraction to 41.8 (±2.5) % during the subjects final contraction. The fact that the first matching contraction was only approximately 2% greater than the reference arm force demonstrated that the subjects were able to accurately judge the required force during a low level contraction. However at maximal endurance this was far from the fact with force production of the matching arm during the final measure being 104.5% of the reference arm. Differences between the first matching contraction and those made at 40%, 60%, 80% and 100% of the endurance time were significantly greater ($P<0.05$).

4.3 EMG Production During the Endurance Task

Values for rmsEMG production in the reference and matching arm are displayed graphically in Figure 4.4. The mean EMG value of the reference arm was 28.1 (±0.7) % of the pre-exercise maximal value. There was very little variation in rmsEMG values for the reference arm with measures only ranging over 7.7%. Reference arm rmsEMG corresponding to the first matching contraction was 24.0 (±3.5) % and increased to 31.7 (±2.8) % at the point equivalent to 80% of the subjects maximal endurance. rmsEMG during the contraction corresponding to maximal endurance had decreased to 30.0%. Paired t-test's relating the first rmsEMG value to those at 20%, 40%, 60%, 80% and 100% found no changes of statistical significance ($P<0.05$). A Pearson test for correlation was performed between average values for reference arm rmsEMG and matching force with the relationship bearing a coefficient of 0.85 (Figure 4.5).

Values for the matching arm increased on average by 14.7% of maximum, almost twice that of the reference arm. A value of 26.0 (±3.8) % of the pre-exercise maximal measure was recorded during the first matching contraction and one of 40.7 (±4.4) % was recorded during the last. The mean rmsEMG measure for the matching arm was 31.5 (±1.24) %, which was only 3.4% greater than the mean of the reference arm. At the points corresponding to 0%, 20%, 40% ,60% and 80% of maximal endurance, both arms appeared to follow the same distribution pattern, with the largest difference being 3.5%.

It was only during the contraction corresponding to maximal endurance that a rmsEMG value in the matching arm increased to a greater extent (10.7%). The fact that rmsEMG for the matching arm did not increase with the same manner as matching force suggests that rmsEMG is not a good indicator of muscular effort. Paired t-tests were performed

relating the rmsEMG recorded at 0% to those at 20%, 40%, 60%, 80% and 100% with none of the differences found to be statistically significant.

4.4 RPE During the Matching Exercise

Progression of RPE from the measure corresponding to 0% of maximal endurance to 100% of maximal endurance is displayed graphically in Figure 4.6. Subject RPE increased in a linear fashion from 0% of maximal endurance to the measure at 60% of maximal endurance. As subjects neared maximal endurance (80% measure) the RPE values increased in a pattern steeper than the linear distribution then increased by only one value at 100%. The initial RPE taken within the first 5 seconds of commencement of the reference force ranged from 6 to 12 with a mean of 9. RPE recorded following the first matching contraction ranged from 7 to 12 with a mean of 10. RPE recorded following the final contraction ranged from 19 to 20 with a mean of 20. A paired t-test was performed on the first and last recorded RPE value with the observed change found to be statistically significant ($P<0.05$).

4.5 Recovery of MVC

Comparisons between rate of MVC recovery of the reference and matching arms are displayed in Figure 4.7. At 15 minutes post exercise MVC had recovered to 93.1 (±3.2) % of its pre exercise level in the reference arm and 94.6 (±2.2) % in the matching arm. Mean MVC force for the reference arm at 1 minute recovery was 84.1 (±2.8) % with the matching arm recording 91.6 (±2.5) %. It is interesting to note that after the first minute of recovery the matching arm was only able to produce 91.6% of its pre-exercise force even though it did not perform any specific fatiguing protocol. Also from these measures it can be seen that the reference arm although more fatigued following the endurance protocol, after 15 minutes, was able to recover to almost the same strength as the matching arm which was not fatigued. Paired t-test's were performed relating pre-exercise MVC's of both arms to MVC's measured at 1, 3, 5, 10, and 15 minutes recovery. There was a statistically significant reduction ($P<0.05$) in the force production of both the reference and matching arms up until the 15 minute mark.

4.6 Recovery of Maximal EMG

Recovery rmsEMG comparisons of the reference and matching arms are displayed in Figure 4.8. Recovery of maximal rmsEMG was not as marked as MVC recovery with the reference arm only reaching 82.7 (±6.7) % of its pre-exercise measure and the matching arm 91.3 (±2.6) %. Maximal rmsEMG of the reference arm stayed depressed over the course of the recovery period with a mean measure of 82.1 (±1.1) %. Maximal rmsEMG of the matching arm recovered to a greater extent with a mean of 89.7 (±1.5) %, but as in the reference arm, rmsEMG recovery was depressed when compared to MVC recovery. During all recovery measures the matching arm displayed a mean measure higher than that of the reference arm, a pattern also seen in the recovery of

MVC. Paired t-test's comparing pre-exercise values to recovery measures were performed on both arms. rmsEMG of the reference arm was still significantly ($P<0.05$) less at the 15 minute mark of recovery. The matching arm was only significantly less during the 1 and 3 minute recovery contractions.

4.7 Force During the Recovery Period

Comparisons of the recovery force of the reference and matching arms are displayed in Figure 4.9. During the five matching occasions, force of the reference arm was produced slightly above the required mark at a mean of 21.1 (±0.2) % with the force of the matching arm produced at a mean of 25.7 (±1.3) %. Matching force was more closely estimated as the recovery period progressed and fatigue decreased. During the 10th and 15th minute matching force was well estimated at 21.4 (±1.8) %, and 22.8 (±1.5) %, respectively. Force in the matching arm during the first and third and fifth minute was significantly greater ($P<0.05$) than force exerted during the first matching contraction of the endurance task.

4.8 EMG During the Recovery Period

Recovery force of the reference and matching arms are displayed in Figure 4.10. The mean EMG of the reference arm taken from the five recovery matching contractions was 21.9 (±0.2) %. This compared to the mean EMG of the matching arm which was 25.7 (±0.6) %. The distribution pattern of the data points as shown in Figure 4.10 follow a very similar course. There was no significant differences between recovery rmsEMG values and values recorded during the first matching contraction. There was a close similarity during the recovery period between mean force and mean rmsEMG for the reference arm with only 0.8% difference. This was also true for the matching arm which had the same mean percentage for force and rmsEMG.

4.9 RPE During the Recovery Period

The graph of RPE values during the recovery period Figure 4.11 shows that RPE values for the reference arm decreased back to the same values recorded following the first matching contraction during the 10th minute of recovery.

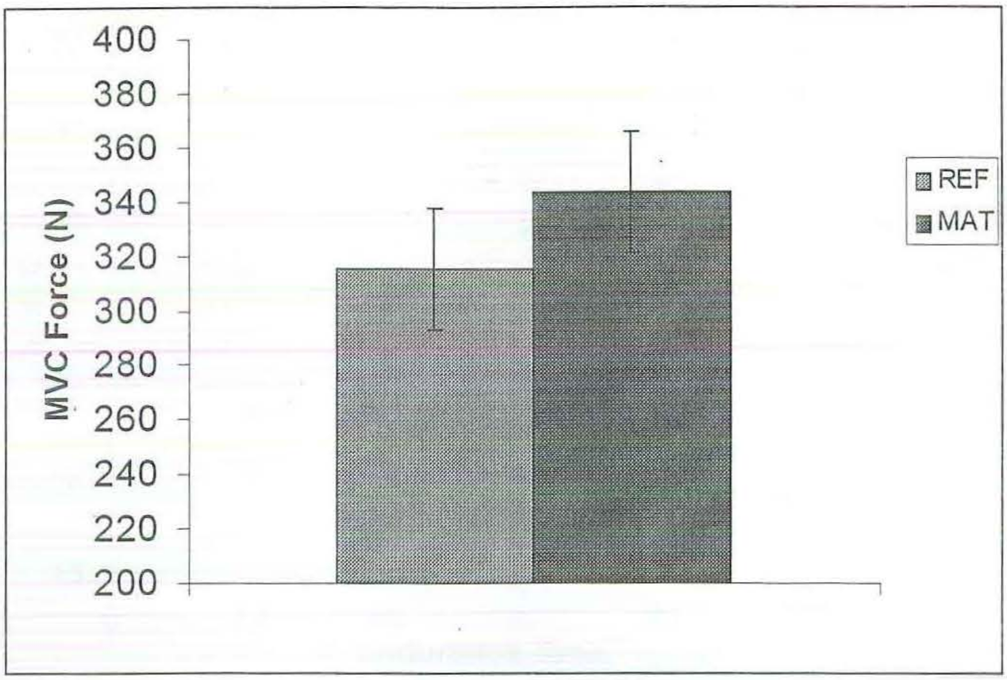

Figure 4.1 Comparison of mean pre-exercise MVC's in the reference and matching Arms (Means ± SEM).

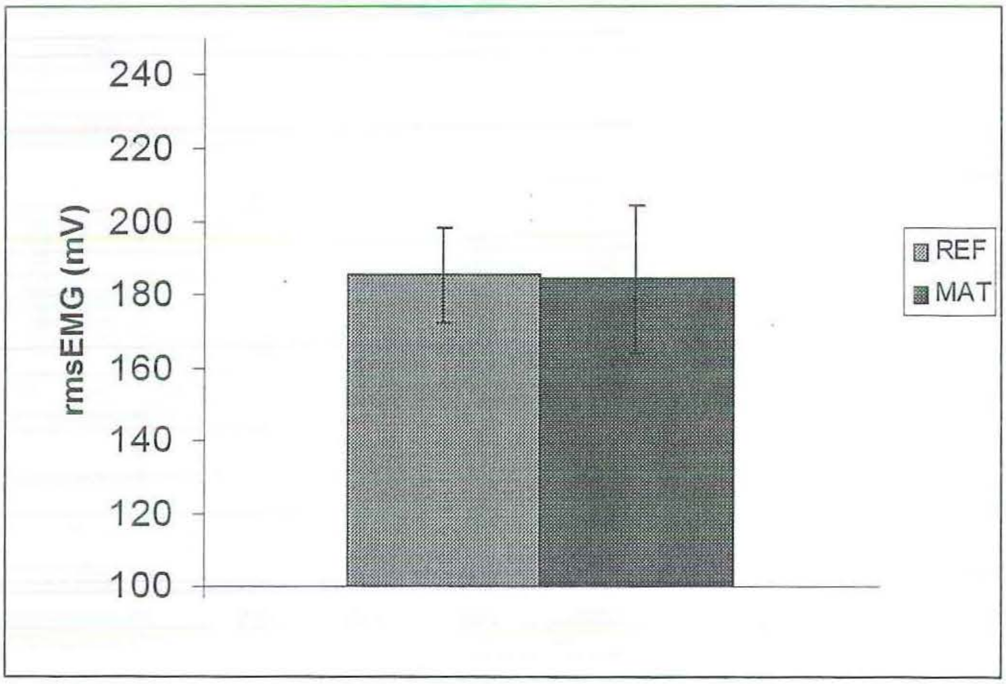

Figure4.2 Comparison of the mean maximal pre-exercise rmsEMG in the reference and matching arms (Means ± SEM).

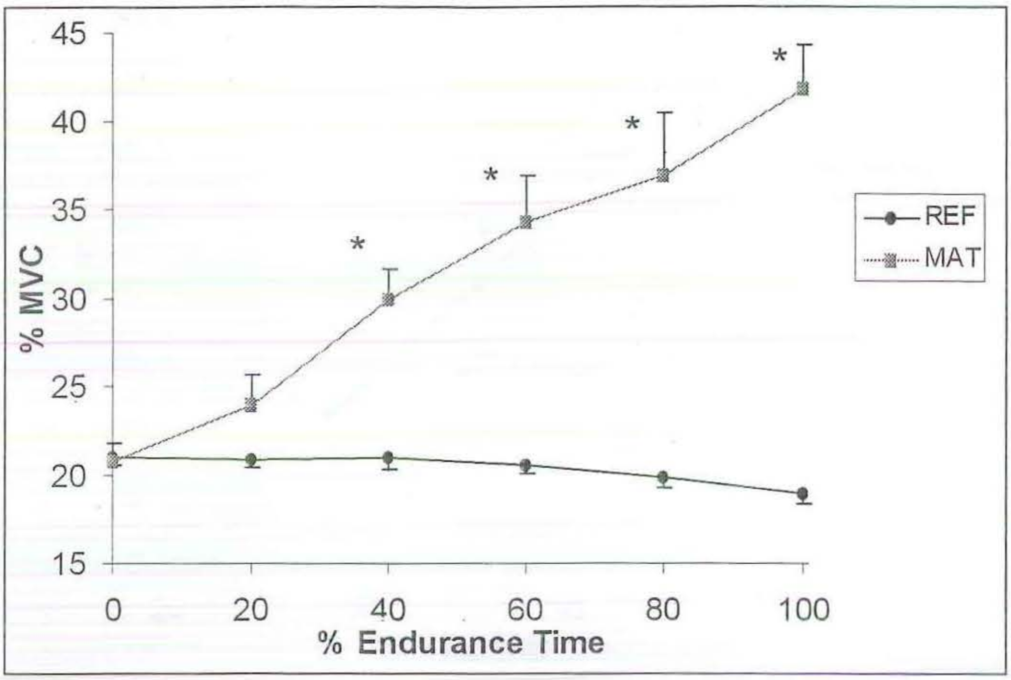

Figure 4.3 Relationship between reference and matching arm forces during the endurance task (Means ± SEM). * Denotes significant difference at the level of 0.05 between given value and initial value.

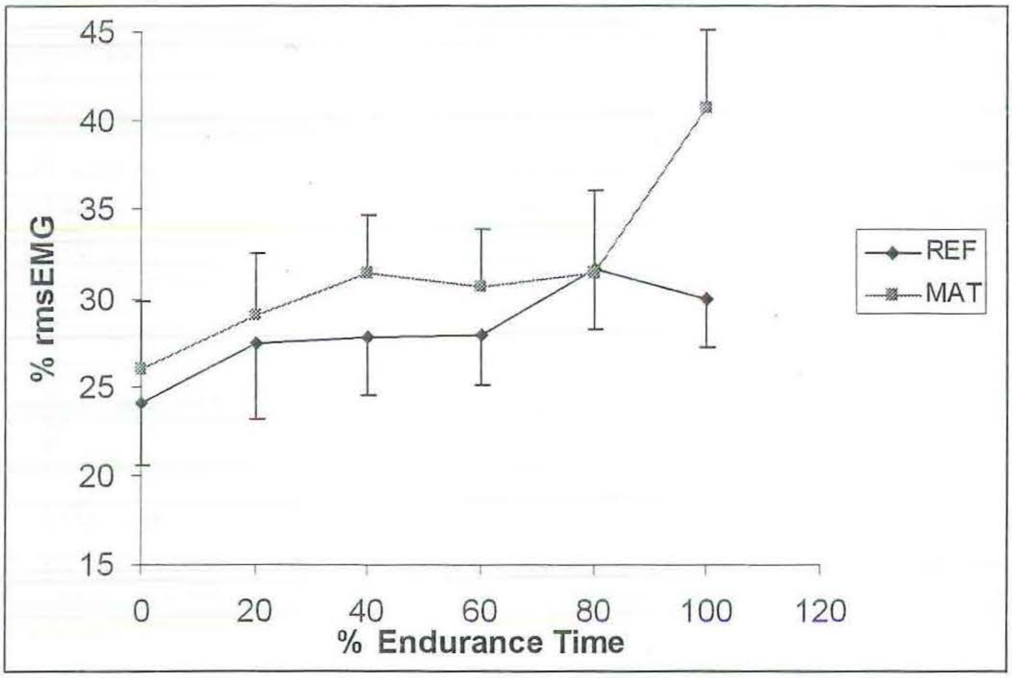

Figure 4.4 Relationship between reference and matching arm rmsEMG during the endurance task (Means ± SEM).

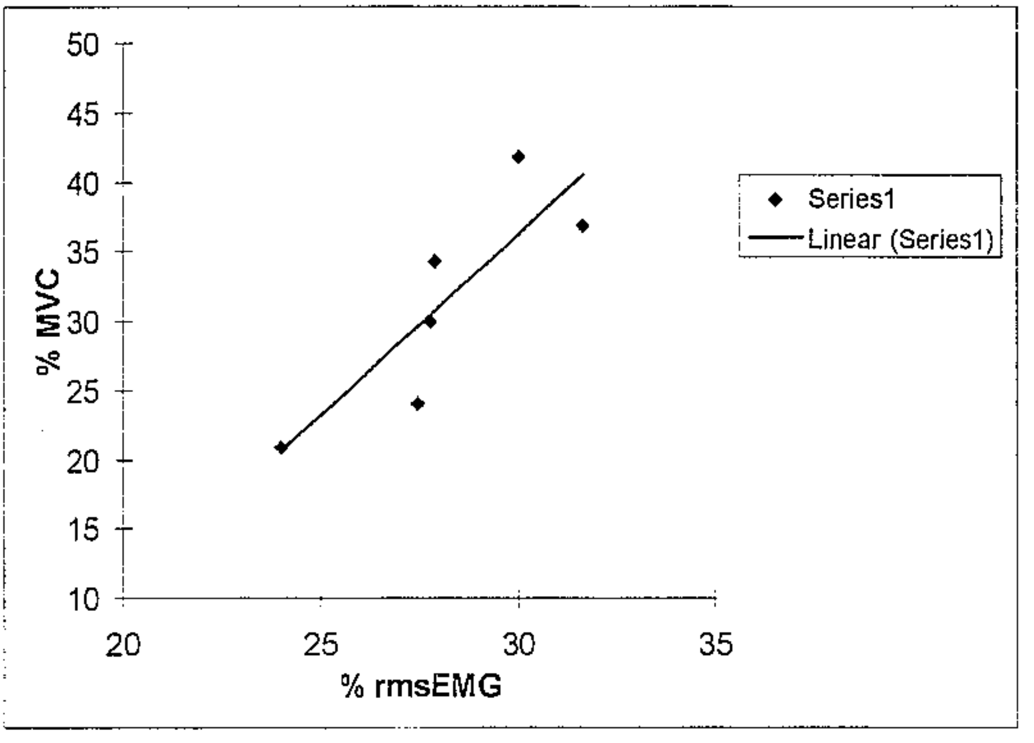

Figure 4.5 Correlation between matching arm force and reference arm rmsEMG mean values (r = 0.85).

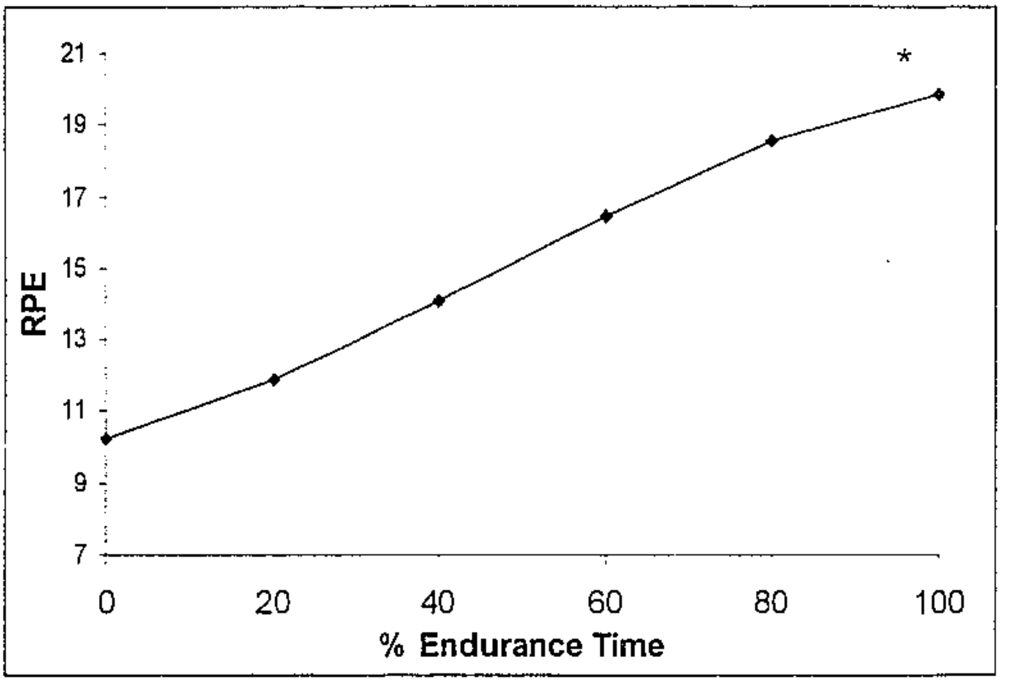

Figure 4.6 Progression of RPE measures during the endurance task (Means ± SEM). * Denotes significant difference at the level of 0.05 between given value and initial value.

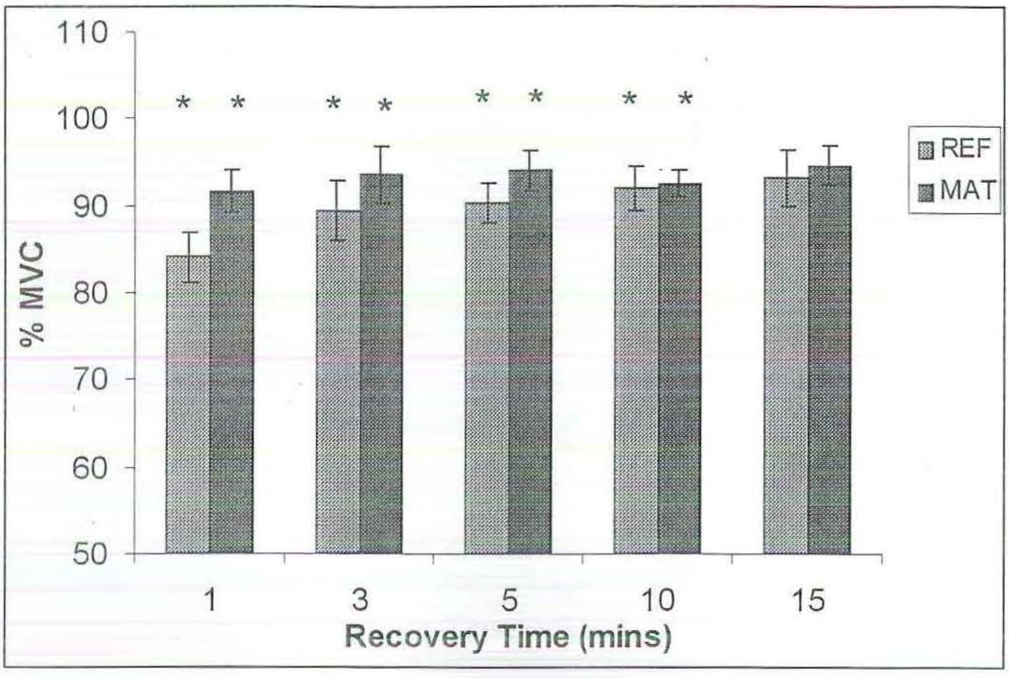

Figure 4.7 Comparative display of MVC recovery in the reference and matching arms (Means ± SEM). * Denotes significant difference at the level of 0.05 between recovery and pre-exercise value.

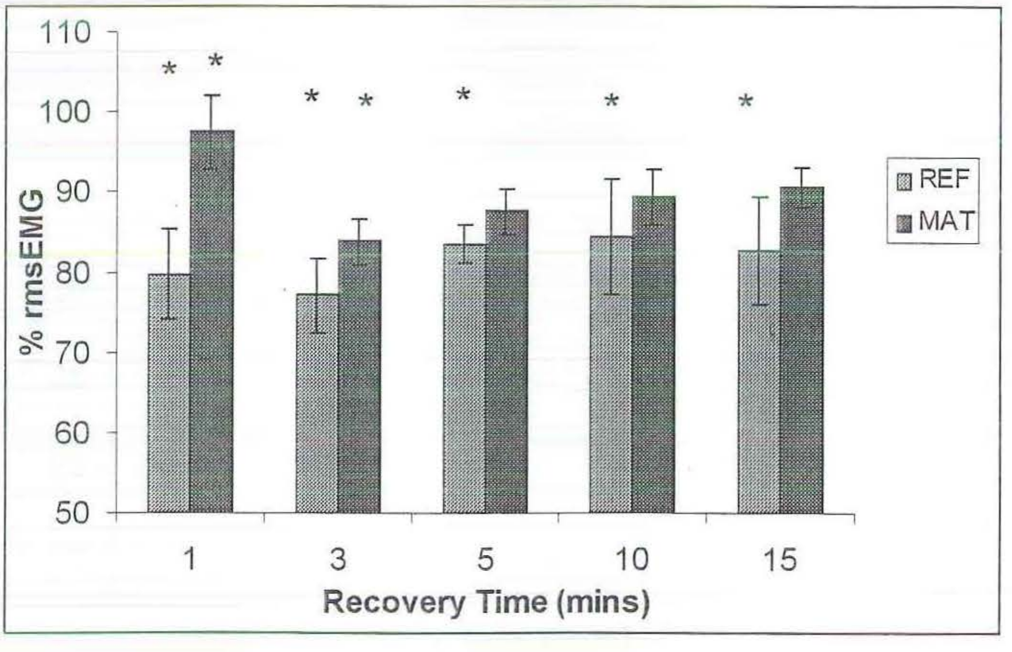

Figure 4.8 Comparison between reference and matching arm maximal rmsEMG recovery (Means ± SEM). * Denotes significant difference at the level of 0.05 between recovery and pre-exercise value.

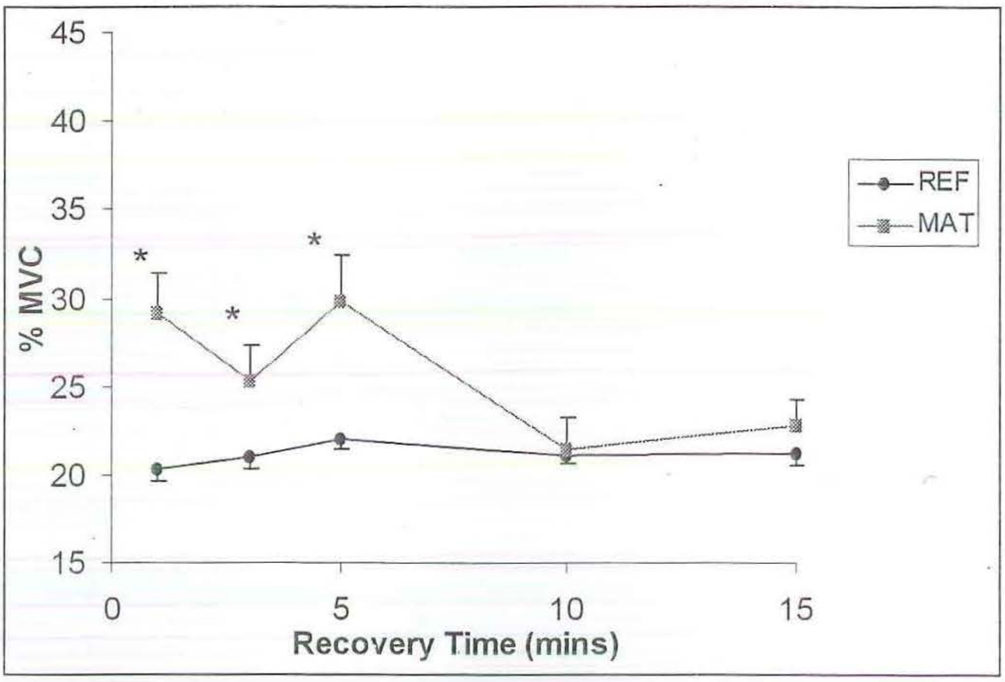

Figure 4.9 Display of reference and matching arm force relationship during the recovery period matching tasks (Means ± SEM). * Denotes significant difference at the level of 0.05 between given value and initial endurance task value.

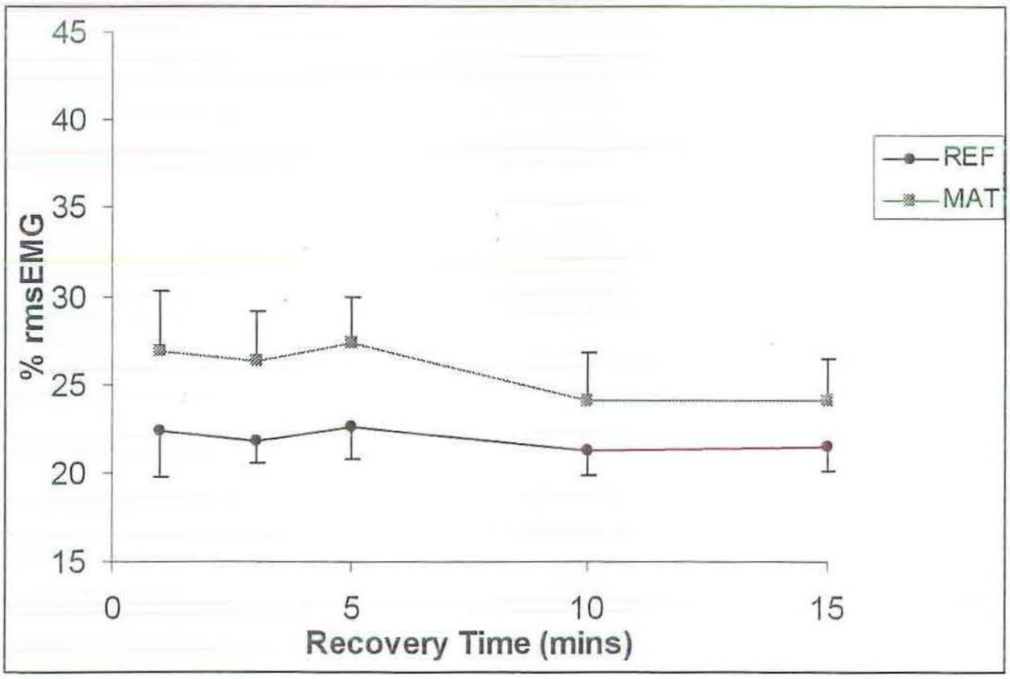

Figure 4.10 Relationship between rmsEMG of the reference and matching arm during recovery (Means ± SEM).

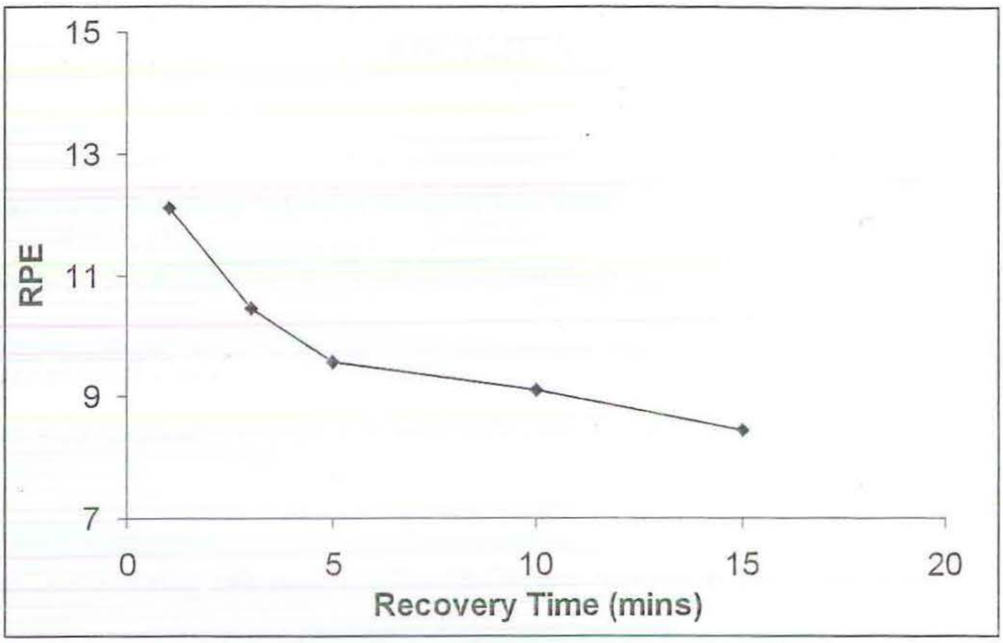

Figure 4.11 RPE measured during the recovery period.

CHAPTER FIVE

DISCUSSION

The purpose of this study was to investigate how sense of effort changed during fatigue In order to achieve this, a contralateral limb matching paradigm employing a low-level isometric contraction to maximal endurance was performed. Force and rmsEMG changes were measured in both arms with RPE recorded only in the reference arm.

Data collected during this study confirmed the first hypothesis that force production in the matching arm would increase as the endurance task progressed and remain elevated during the recovery period. Force during the pre-fatigue 20% MVC contraction was matched quite accurately, however a significant increase in force production was recorded at the point corresponding to 40% of the subjects maximal endurance and at subsequent matching contractions. During the recovery period force in the matching arm remained significantly elevated at the 1, 3 and 5 minute mark but had decreased to a nonsignificant difference after 10 minutes. It was most likely that after 10 minutes the subjects reference arm had recovered sufficiently from the endurance task that fatigue was no longer an influencing factor.

The fact that force exerted during the first matching contraction was found to accurately estimate reference force indicates that forces are able to be estimated accurately in a fresh muscle. The ability to accurately estimate static forces has been previously demonstrated by Cafarelli and Bigland-Ritchie (1979) using unfatigued subjects to perform a series of force matching contractions with the muscle held at varying lengths.

Matching contractions performed where one limb was in a stronger mechanical position resulted in an increased force output of up to 30%, but when both limbs were positioned at angles representing equal strength, forces were accurately matched. As maximal strength in this study was not found to vary significantly between limbs and initial matching force estimates were accurate, it can be can safely assumed that the recorded force differences were not related to an interlimb strength variation.

This study confirms the results of investigations performed by Jones & Hunter (1983a, & 1983c) who also used a contralateral limb matching paradigm to explore force relationships during fatigue with reference forces being maintained at between 30 and 70% MVC and matching contractions performed for 2 seconds once every 15 seconds. As in their studies, an increase in matching force was observed as the endurance task progressed. This increase in force also occurred in a linear fashion. During their experiments the rate of matching force increase was found to vary with initial force of the reference arm, with force increasing at a greater rate, the higher the initial force. Jones and Hunter (1983a) developed an equation to predict the increase in matching force from the initial force during an endurance task.

$$P = (100 - F)aT + F$$

P = matching force (% MVC),
F = reference force (% MVC),
T = % endurance time, and
a = constant (0.0047).

The fact that subjects force production increased with endurance time leads us to conclude that they could not distinguish between sensations of effort and sensations of force when the muscle was fatigued. This was a conclusion also reached by McCloskey et al. (1974) and Jones (1983) and supports the hypothesis of a centrally generated process being responsible for force estimation during fatigue. The increase in force data as the task progressed also suggests that the more fatigued a muscle is the less a subject is able dissociate the absolute force exerted from the effort needed to sustain it. This process has been discussed in detail by Gandevia and McCloskey (1976) and Aniss et al. (1988), who state that when judging a weight subjects are guided more by effort than actual muscular tension. The use of a 20% initial force could have influenced the subject performance with previous investigators (Jones & Hunter, 1982) finding that most accurate force estimations occur near the middle of the subjects force range.

The second hypothesis which stated that EMG amplitude would increase during the endurance task and remain elevated during the recovery period was also confirmed by the test data. rmsEMG values increased steadily with percentage endurance time but there were no significant differences between the values measured at 0% and those at 20%, 40%, 60%, 80% and 100% of the endurance time, for both the reference and matching arms. A gradual increase in surface EMG amplitude over the course of a fatiguing contraction would be expected and signifies increasing recruitment of motor units or higher firing frequencies in motor units already recruited (Lind & Petrofsky, 1979; Petrofsky, Glaser & Phillips, 1982). As the recovery period progressed, amplitude of rmsEMG of both arms gradually decreased until at the 15 minute mark it was

between 2 and 3% below that recorded during the first matching contraction of the endurance task, with no significant differences being noted.

The EMG/force relationship in the matching arm followed a pattern very similar to that described for an unfatigued biceps brachii by Bigland-Ritchie (1981). Other muscles (eg, soleus and adductor pollicis) follow a linear pattern but the biceps brachii has a nonlinear one possibly related to variations in motor units and the force range each is activated in (Bigland-Ritchie, 1981).

rmsEMG of the reference arm has previously been found to display a linear relationship with force exerted in the matching arm to the extent of being able to predict matching force from reference rmsEMG (Jones & Hunter, 1983a; 1985). This relationship has led investigators to hypothesis that over-estimation of forces is due to increased excitatory input into the reference arm. This relationship is confirmed in this study with a high correlation coefficient (0.85) for normalised reference arm rmsEMG and matching force mean values. Previous investigations (Jones & Hunter, 1983b) described this relationship as only occurring at low initial forces (35% of max) and not with contractions performed at 50% and 65% of maximum. Investigators (Oda & Moritani, 1995) have suggested that electrical activity in one arm is independent of activity in the other arm during fatigue. They found that during the course of a bilateral fatiguing contraction, cross-correlation of rmsEMG values decreased as the contraction progressed leading them to suggest that as fatigue increases there is a neural derangement of the common drive. If this were true then as fatigue progressed subject

force estimations would be less likely to be based on electrical activity in the contralateral arm, a relationship not found in this study.

Hypothesis 3 stated that perceived effort will increase as the endurance task progresses and remain at an increased value during recovery. Based on previous literature (Borg & Noble, 1974; Cain, 1973; Stevens & Cain, 1970) and common sense we would expect a subjects perception of effort to increase, the longer an effort is maintained and to be at a maximal value at maximal endurance. Authors (eg Pandolf, 1982) have stated that a subjects RPE can be based on peripheral or central factors. During this study it was assumed that the subjects RPE, was based on local cues experienced in and around the contracting muscle. RPE collected during this study followed a steady linear progression, reflecting the progress of muscular fatigue, until the subject reached 80% of maximal endurance where a shaper increase followed by a plateau at maximal endurance occurred.

The use of an RPE scale during this investigation to quantify subject effort resulted in a pattern similar to that described by other investigators. It has been noted that perceived effort gets progressively harder to accurately quantify the closer a subject is to a maximal effort with Jones and Hunter (1982) recording a horizontal asymptote towards maximal forces. Subjects during this investigation perceived effort at 80% of maximal endurance to be almost as difficult as that required at maximal endurance. Also following this line it has been found that estimations of RPE involving the same stimulus intensity vary depending on whether a contraction of similar magnitude is performed in a

fatigued or unfatigued state (Teghtsoonian, Teghtsoonian, and Karlsson, 1977) with subjects in this study exerting the same force during an unfatigued or fatigued state.

RPE recovered faster than strength which would seem to indicate that recovery of a subjects sense of effort is independent of their strength recovery. This is further demonstrated by the fact that when subjects returned to a pre-fatigue RPE they were also able to accurately estimate matching forces.

The final hypothesis of a decrease in maximal strength and EMG during recovery was also confirmed by this investigation. A decrease in maximal strength of the reference arm would be expected because a contraction to maximal endurance had been performed. Maximal force in the reference arm was found to be significantly lower up until after the tenth minute. Maximal rmsEMG of the reference arm was still significantly less than pre-exercise measures when the recovery period ended at the 15 minute mark. This drop in both maximal force and surface EMG may indicate that fatigue has occurred through mechanisms relating to electrical transmission (Lind & Petrofsky, 1979). A significant decrease in the maximal force of the matching arm was also recorded until the fifteenth minute but matching arm maximal rmsEMG measures were only significantly lower until the fifth minute of recovery.

It is interesting to note that maximal force in the matching arm was significantly lower up until after the 15 minute mark, but that maximal rmsEMG was only significantly lower until the fifth minute. Maximal force in the reference arm had recovered to a nonsignificant difference by the fifteenth minute but maximal rmsEMG at this time was

still significantly depressed. This would seem to indicate that loss of force in the matching arm was due to a failure in the contractile apparatus and force loss in the reference arm was due to altered electrical transmission. Findings in this study can be parallelled to those of previous investigators (eg Loscher, Cresswell & Thorstensson, 1996) who found that following a maximal effort EMG remained depressed even though muscle force was found to be able to be activated at close to a maximal level, indicating the possibility of central fatigue. However authors Lind and Petrofsky (1979) found the opposite with MVC recovering by the seventh minute post-exercise following a contraction to maximal endurance at 25% of MVC while surface EMG had recovered within 3 minutes. Variations in recovery rate may be due the experiments being performed using different muscle groups.

With hindsight it seems that several experimental procedures could have been modified to improve the study. In order to ensure that the 20% target force was based on a true measure of maximal force the use of nerve stimulation could of been employed. However, according to data presented by Cafarelli and Bigland-Ritchie (1979) when there was a comparison of voluntary MVC's to forces elicited by stimulation a subjects voluntary MVC's was only minimally different to one elicited by stimulation. Occasionally the subject was found to move the upper arm resting on the padded board and also to move the forearms in a lateral fashion towards each other during the matching contractions. Usage of molded arm rests as described by (Jones, 1989) and an apparatus to minimise lateral movement of the forearm would of contributed to a decrease in arm movement and the risk of inaccurate measures. Subjects also frequently commented towards the end of the endurance task that there was a "pins and needles"

sensation experienced above the wrist. This would have resulted from the wrist straps occluding blood flow and compression of nerves. Attempts had been made to adequately pad the straps and excess padding did not seem to solve the problem. The use of a hand held grip placed in the palm would most likely eliminate the problem but may be the cause of others.

Observation taken from this study may have applications to sporting actions involving prolonged contractions at a constant force (eg gripping a tennis racquet or cricket bat). To avoid possible errors in judgement related to muscle fatigue athletes could be encouraged to release the grip as often as possible and concentrate on relaxing and stretching the used muscles. This could possibly delay the onset of fatigue thus aiding concentration maintenance. Future studies could be designed to monitor the actual fatiguing effect grip maintenance has during a competitive situation with the use of surface EMG and pre/post activity MVC

In conclusion this study investigated how normal subjects sense of effort altered during fatigue. It was found that matching force increased in a linear fashion with fatigue and displayed a strong correlation (0.85) to rmsEMG in the reference arm. It was also found that a subject was able to estimate force accurately a short time (in 10 minutes) after the fatiguing influence was removed. It was concluded that judgements of force production were based on the subjects internally generated perception of effort and not on the absolute force being generated.

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APPENDIX A

Subject Characteristics

	Age (Yrs)	Weight (kg)	Dom-arm	Exercise participation
S1	33	69	right	Frequent aerobic work
S2	21	110	right	Sedentary
S3	23	76	right	Frequent aerobic work and light resistance training
S4	37	55	right	Frequent aerobic work and light resistance training
S5	20	95	right	Occasional aerobic work
S6	21	73	right	Sedentary
S7	25	89	right	Competitive sport and occasional weight training
S8	32	86	left	Occasional aerobic and weight training
S9	36	65	right	Competitive sport and aerobic work

APPENDIX B

Subject Informed Consent Sheet

Consent Form for Participation in the Investigation into

"Muscle Fatigue and Sense of Effort"

The purpose of this study is to record the effects of muscular fatigue on sense of effort. You will be asked to hold a contraction of the biceps of your non-dominant arm at 20% of your maximal strength, as measured on the day, until you are unable to sustain the force any longer. At this point the exercise will be terminated. During the contraction period you will be asked verbally every minute to hold a contraction for 10 seconds with your dominant arm, attempting to match the force in the right one. You will also be asked to rate your "perceived effort" on a number scale. Throughout the procedure the electrical activity of your biceps will be monitored with surface electrodes. It is a painless procedure.

The above protocol will be clearly demonstrated and you will have a chance to practice before the testing commences.

Some slight delayed soreness may be experienced in the exercised arm 24 - 48 hours after the testing day.

The results gained from this research may be used to further our insight as to how muscle fatigue effects our sense of effort.

Having read the above statements I acknowledge that I am able to withdraw from the study at any time and are aware of the possible experienced side-effects. I also release Edith Cowan University of any claim arising from experimental procedures.

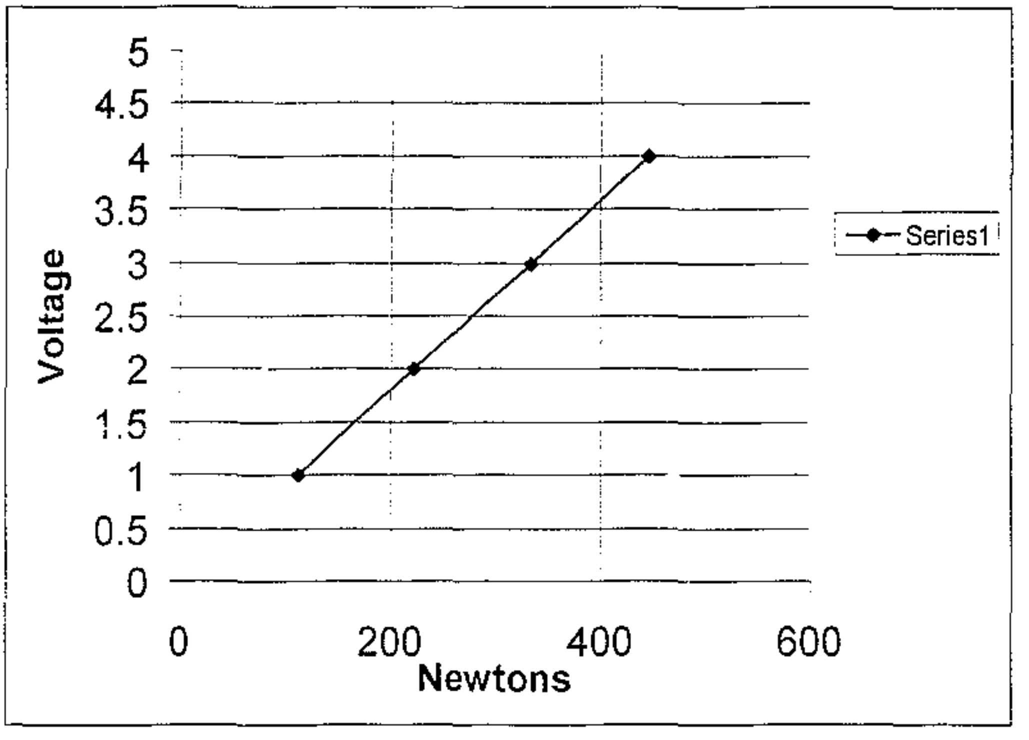
I......................................., age.......years, agree to participate as a subject in the above study.

Signed................................

Witness......................................Date...............

APPENDIX C

Strain Gauge Calibration



5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Voltage
0
200
400
600
Newtons
Series1

APPENDIX D

RPE Data Collection Sheet

REFERENCE ARM (RIGHT/LEFT)		
TIME (min)	RPE VALUE	COMMENT
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		
21		
22		
23		
24		
25		
26		
27		
28		
29		
30		

RECOVERY		
TIME (mins)	RPE VALUE	COMMENT
1		
3		
5		
10		
15		

APPENDIX E

Raw Data

PRE-EXERCISE AVERAGE MAXIMAL VALUES FOR FORCE AND EMG

	MVC (N)		MAX rmsEMG (mV)	
	REF	MATCH	REF	MATCH
av	315.1	343.7	185.4	184.6
sd	66.8	67.6	38.1	60.0
ME	22.3	22.5	12.7	20

REFERENCE ARM FORCE DURING THE ENDURANCE TASK (N)

S1	65	65	65	63	65	65	63	64	62	66	64	63	55
S2	79	78	77	75	74	71	65						
S3	56	55	55	53	58	55	60	49	48	48			
S4	54	45	51	56	61	55	54	52	49	50	51	52	57
S5	80	82	78	81	82	82	79	85	80	81	89		
	83	82	81	87	81	82	79	78	83	80	81		
	80	80	83	81	79	79	79	76	77	76	81	90	
S6	57	59	58	60	64	58	60	58	53	56	58	53	49
S7	80	78	77	75	74	71	66						
S8	72	83	77	74	83	76	70	68					
S9	46	44	43	44	46	42	42	44	42	43	35		

	MATCHING ARM FORCE DURING THE ENDURANCE TASK (N)												
S1	57	58	72	89	97	114	113	105	113	109	127	119	124
S2	91	103	90	122	121	114	152						
S3	40	37	55	92	84	66	76	73	142	121			
S4	59	76	45	116	147	151	119	115	121	125	130	103	134
S5	99	117	133	52	104	105	100	108	161	135	130	147	122
	147	122	163	122	108	132	97	88	113	110	110		
	104	112	103	115	114	98	137	124	136	132	156	178	
S6	68	88	106	113	122	105	106	116	118	123	128	115	103
S7	94	101	89	122	120	115	152						
S8	88	135	115	130	155	161	134	148					
S9	45	62	56	55	56	74	94	110	129	99	129		
	REFERENCE ARM rmsEMG DURING THE MATCHING TASK (mV)												
S1	42	49	58	56	79	106	113	124	115	141	151	164	122
S2	82	86	76	112	59	53	51						
S3	19	23	20	21	20	22	23	52	24	29			
S4	26	24	27	28	30	34	29	40	37	69	68	49	63
S5	20	14	19	18	29	22	20	26	17	17	26		
	20	21	24	20	16	15	18	18	20	21	22		
	21	28	17	26	19	19	25	25	28	27	69	28	
S6	52	67	73	71	91	75	72	78	88	86	89	72	65
S7	103	121	73	104	63	53	51						
S8	36	41	30	36	44	52	50	78					
S9	21	21	24	24	21	25	25	24	22	25	23		
	MATCHING ARM rmsEMG DURING THE MATCHING TASK (mV)												
S1	40	45	45	45	46	95	64	58	54	40	68	54	59
S2	118	104	63	75	54	41	74						
S3	31	32	31	28	36	33	26	38	50	46			
S4	22	29	26	45	68	84	60	61	62	68	85	56	75
S5	26	23	17	28	29	33	28	23	24	16	12		
	24	18	20	23	29	17	37	41	35	20	33		
	13	12	63	53	17	13	17	25	48	21	47	48	
S6	37	43	60	73	102	97	99	81	90	109	116	111	92
S7	111	114	56	73	54	42	76						
S8	18	26	28	27	27	32	26	47					
S9	31	34	32	33	33	36	49	51	57	50	75		

	REFERENCE ARM RPE DURING THE ENDURANCE TASK (BORG SCALE)												
S1	10	10	11	12	14	15	16	16	17	18	19	20	
S2	13	15	15	16	17	19	20						
S3	12	12	13	13	15	16	16	17	18	19			
S4	9	10	11	11	12	13	13	15	16	18	19	19	20
S5	9	9	9	9	11	12	12	14	15	15	15		
	16	16	17	17	17	18	18	18	18	18	19		
	19	19	19	20	20	20	20	20	20	20			
S6	9	9	10	11	12	13	14	15	16	16	18	18	19
S7	11	12	13	15	17	19	20						
S8	7	9	12	14	17	18	19	20					
S9	12	12	12	12	13	15	16	18	19	19	20		
	REFERENCE ARM FORCE DURING RECOVERY (N)							MATCHING ARM FORCE DURING RECOVERY (N)					
S1	49	57	62	63	57			59	83	92	75	61	
S2	82	82	85	79	83			118	85	105	57	69	
S3	44	51	54	54	53			67	42	60	37	43	
S4	50	58	64	52	60			119	95	137	70	74	
S5	87	86	85	86	81			136	118	148	133	121	
S6	56	49	59	50	55			102	102	111	76	73	
S7	80	80	77	82	76			125	109	93	74	93	
S8	81	78	83	85	79			91	71	84	68	89	
S9	46	48	46	45	49			59	52	55	57	64	
	REFERENCE ARM rmsEMG DURING RECOVERY (mV)							MATCHING ARM rmsEMG DURING RECOVERY (mV)					
S1	50	67	46	47	52			50	49	50	37	33	
S2	26	42	40	32	29			42	29	36	34	39	
S3	17	21	24	26	27			22	29	38	33	32	
S4	46	43	52	46	45			113	65	78	31	36	
S5	35	24	29	25	24			19	41	32	26	30	
S6	54	46	49	47	45			50	45	61	55	51	
S7	55	39	42	46	42			84	83	69	80	77	
S8	33	43	45	41	49			16	22	22	28	22	
S9	27	28	27	27	30			37	33	35	41	44	

	REFERENCE ARM MVC DURING RECOVERY (N)				
	1 min	3 min	5 min	10 min	15 min
S1	218	232	246	254	263
S2	395	405	367	387	386
S3	222	295	303	299	294
S4	161	170	179	182	168
S5	366	371	372	372	450
S6	226	223	249	236	234
S7	251	288	303	305	296
S8	406	418	394	410	420
S9	179	172	169	184	179

	MATCHING ARM MVC DURING RECOVERY (N)				
	1 min	3 min	5 min	10 min	15 min
S1	308	298	303	296	298
S2	395	407	407	405	407
S3	294	312	299	289	300
S4	202	200	204	206	215
S5	456	484	496	478	530
S6	241	256	269	279	263
S7	384	330	331	333	332
S8	407	413	414	369	395
S9	179	181	176	183	181

	REFERENCE ARM MAX rmsEMG DURING RECOVERY (mV)				
	1 min	3 min	5 min	10 min	15 min
S1	298	261	261	290	286
S2	172	128	165	120	105
S3	80	103	137	97	108
S4	167	176	169	219	155
S5	80	75	73	88	100
S6	97	102	124	129	135
S7	149	154	180	149	138
S8	178	178	179	145	154
S9	106	102	105	136	142

	MATCHING ARM MAX rmsEMG DURING RECOVERY (mV)				
	1 min	3 min	5 min	10 min	15 min
S1	271	217	272	224	244
S2	226	199	174	222	210
S3	207	202	234	202	222
S4	179	180	170	159	152
S5	110	66	64	76	72
S6	100	118	123	109	139
S7	270	238	246	255	294
S8	84	73	80	81	81
S9	134	105	114	140	112

APPENDIX F

Normalised and standardised data

REFERENCE FORCE DURING THE ENDURANCE TASK

	0%	20%	40%	60%	80%	100%
S1	22.1	22.1	21.9	22.0	21.6	19.0
S2	20.2	19.9	20.0	19.3	18.0	17.0
S3	20.5	20.2	19.0	19.9	18.0	18.9
S4	24.1	23.0	24.5	22.6	22.8	24.8
S5	18.7	18.7	19.3	19.0	19.2	21.9
S6	20.7	21.1	20.7	20.7	20.8	18.4
S7	23.5	23.0	22.9	22.2	21.1	19.1
S8	18.0	18.7	18.1	18.4	17.4	17.4
S9	22.0	22.3	22.1	19.6	20.3	17.3

MATCHING FORCE DURING THE ENDURANCE TASK

	0%	20%	40%	60%	80%	100%
S1	17.8	22.9	35.8	33.3	39.7	39.3
S2	23.1	26.0	22.6	31.2	29.2	39.1
S3	11.7	11.2	26.5	19.2	21.0	34.9
S4	25.1	19.0	34.5	49.0	54.9	57.0
S5	19.5	19.7	32.0	21.9	22.0	34.9
S6	22.5	35.0	35.3	37.8	40.7	34.7
S7	24.7	27.2	23.5	32.2	30.4	40.0
S8	22.2	29.4	33.0	41.3	34.0	37.3
S9	20.8	26.0	26.4	44.3	59.7	60.7

REFERENCE rmsEMG DURING THE ENDURANCE TASK

	0%	20%	40%	60%	80%	100%
S1	15.1	20.6	37.8	45.2	54.2	43.9
S2	43.0	45.1	40.0	30.7	27.0	27.0
S3	9.8	11.8	11.4	11.4	26.8	14.9
S4	13.6	14.2	18.0	21.5	36.0	32.7
S5	25.6	26.0	30.8	26.0	23.9	35.9
S6	29.7	41.7	43.0	45.4	50.8	36.7
S7	45.6	54.3	32.3	28.4	23.3	23.0
S8	17.6	15.1	17.8	25.0	25.0	38.1
S9	15.9	18.2	19.3	19.7	17.9	17.2

MATCHING rmsEMG DURING THE ENDURANCE TASK

	0%	20%	40%	60%	80%	100%
S1	15.0	16.9	36.0	21.9	25.8	22.3
S2	56.0	49.1	29.8	25.1	19.0	35.1
S3	11.6	12.4	9.9	12.0	14.2	69.8
S4	12.7	14.7	49.1	34.6	48.7	43.4
S5	30.6	33.0	23.8	40.7	19.2	56.2
S6	20.7	34.5	53.5	45.0	64.7	50.5
S7	42.4	44.0	21.0	21.1	16.0	29.1
S8	21.4	32.8	31.6	37.6	30.9	55.8
S9	23.5	23.9	26.5	37.0	42.5	57.2

RPE DURING THE ENDURANCE TASK

	0%	20%	40%	60%	80%	100%
S1	10	11	15	16	19	20
S2	13	15	15	17	19	20
S3	12	12	13	16	17	19
S4	9	11	13	15	19	20
S5	9	12	16	18	19	20
S6	9	10	13	15	17	20
S7	11	12	13	17	19	20
S8	7	12	14	18	19	20
S9	12	12	15	16	19	20

	REFERENCE FORCE DURING RECOVERY				
	1 min	3 min	5 min	10 min	15 min
S1	16.7	19.4	21.1	21.4	19.4
S2	20.9	20.9	21.7	20.2	21.2
S3	16.1	18.7	19.8	19.8	19.4
S4	22.3	25.9	28.6	23.2	26.8
S5	20.4	20.1	19.9	20.1	19.0
S6	20.4	17.8	21.5	18.2	20.0
S7	23.5	23.5	22.6	24.0	22.3
S8	20.2	19.5	20.7	21.2	19.7
S9	22.0	23.0	22.0	21.5	23.4

	MATCHING FORCE DURING RECOVERY				
	1 min	3 min	5 min	10 min	15 min
S1	18.4	25.9	28.8	23.4	19.1
S2	29.9	21.6	26.6	14.5	17.5
S3	19.6	12.3	17.6	10.9	12.6
S4	50.6	40.4	58.3	29.8	31.5
S5	26.8	23.2	29.1	26.2	23.8
S6	33.8	33.8	36.8	25.2	24.2
S7	32.9	28.7	24.5	19.5	24.5
S8	22.9	17.9	21.2	17.1	22.4
S9	27.3	24.1	25.5	26.4	29.6

	REFERENCE rmsEMG DURING RECOVERY				
	1 min	3 min	5 min	10 min	15 min
S1	18.0	24.1	16.5	16.9	18.7
S2	13.5	21.9	20.8	16.7	15.1
S3	8.8	10.9	12.4	13.5	14.0
S4	24.1	22.5	27.2	24.1	23.6
S5	44.9	30.8	37.2	32.1	30.8
S6	30.9	26.3	28.0	26.9	25.7
S7	24.3	17.3	18.6	20.4	18.6
S8	16.2	21.1	22.1	20.1	24.0
S9	20.5	21.2	20.5	20.5	22.7

	MATCHING rmsEMG DURING RECOVERY				
	1 min	3 min	5 min	10 min	15 min
S1	18.8	18.4	18.8	13.9	12.4
S2	19.8	13.7	17.0	16.0	18.4
S3	8.2	10.8	14.2	12.3	11.9
S4	65.3	37.6	45.1	17.9	20.8
S5	22.4	48.2	37.6	30.6	35.3
S6	27.9	25.1	34.1	30.7	28.5
S7	32.1	31.7	26.3	30.5	29.4
S8	19.0	26.2	26.2	33.3	26.2
S9	28.0	25.0	26.5	31.1	33.3

	RPE DURING RECOVERY				
	1 min	3 min	5 min	10 min	15 min
S1	12	11	10	10	10
S2	13	11	9	9	9
S3	13	11	9	9	8
S4	16	12	11	9	7
S5	10	9	9	8	8
S6	11	10	10	10	9
S7	15	12	10	10	8
S8	8	6	6	6	6
S9	11	12	12	11	11

REFERENCE MVC DURING RECOVERY

	1 min	3 min	5 min	10 min	15 min
S1	74.1	78.9	83.7	86.4	89.5
S2	100.8	103.3	93.6	98.7	98.5
S3	81.3	108.1	111.0	109.5	107.7
S4	71.9	75.9	79.9	81.3	75.0
S5	85.7	86.9	87.1	87.1	105.4
S6	82.2	81.1	90.5	85.8	85.1
S7	73.6	84.5	88.9	89.4	86.8
S8	101.2	104.2	98.3	102.2	104.7
S9	85.6	82.3	80.9	88.0	85.6

MATCHING MVC DURING RECOVERY

	1 min	3 min	5 min	10 min	15 min
S1	96.3	93.1	94.7	92.5	93.1
S2	100.3	103.3	103.3	102.8	103.3
S3	86.2	91.5	87.7	84.8	88.0
S4	86.0	85.1	86.8	87.7	91.5
S5	89.8	95.3	97.6	94.1	104.3
S6	79.8	84.8	89.1	92.4	87.1
S7	101.1	101.1	101.1	101.1	101.1
S8	102.5	104.0	104.3	92.9	99.5
S9	82.9	83.8	81.5	84.7	83.8

REFERENCE MAXIMAL rmsEMG DURING RECOVERY

	1 min	3 min	5 min	10 min	15 min
S1	107.2	93.9	93.9	104.3	102.9
S2	89.6	66.7	85.9	62.5	54.7
S3	41.5	53.4	71.0	50.3	56.0
S4	87.4	92.1	88.5	114.7	81.2
S5	102.6	96.2	93.6	112.8	128.2
S6	55.4	58.3	70.9	73.7	77.1
S7	65.9	68.1	79.6	65.9	61.1
S8	87.3	87.3	87.7	71.1	75.5
S9	80.3	77.3	79.5	103.0	107.6

MATCHING MAXIMAL rmsEMG DURING RECOVERY

	1 min	3 min	5 min	10 min	15 min
S1	101.9	81.6	102.3	84.2	91.7
S2	106.6	93.9	82.1	104.7	99.1
S3	77.2	75.4	87.3	75.4	82.8
S4	103.5	104.0	98.3	91.9	87.9
S5	129.4	77.6	75.3	89.4	84.7
S6	55.9	65.9	68.7	60.9	77.7
S7	101.1	89.1	92.1	95.5	110.1
S8	100.0	86.9	95.2	96.4	96.4
S9	101.5	79.5	86.4	106.1	84.8