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L'EFFET DE LA TENSION ET TEMPS DE CONTRACTION SUR LA SATURATION EN OXYGÈNE AU NIVEAU DU TRAPÈZE

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THE EFFECT OF TENSION AND TIMING OF CONTRACTION ON OXYGEN SATURATION IN THE TRAPEZIUS

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FOREWORD

There are many people I need to thank and acknowledge before I consider the subject matter of interest here. I would like to sincerely thank Dr. Stuart Warmington for introducing (exercise) physiology as an academic discipline to me. His technical and practical expertise, frequent (bad) jokes and teaching style made my introduction to the subject a most enjoyable and stimulating one. His colleagues and also my teachers Dr. Mikel Egana and Mr. Bernard Donne of Trinity College Dublin assisted Stuart in providing me with an excellent learning environment and practical skills upon which I have based all future work. Without such consistent quality teaching and demonstration, there is no question in my mind that I would not be in this position today where I can refer to myself as an aspiring physiologist - autonomous researcher. I would like to sincerely thank my MSc. supervisor Dr. Alain-Steve Comtois for his teaching and enthusiasm over the past three years. His calm but serious approach to this research project has allowed it to develop from an interesting idea to realisation and implementation. Dr. Comtois was also most generous in assisting my application for an international student scholarship as well as for directly funding the project. For all of the above I am most grateful. I must also thank Carole Roy for her numerous demonstrations of electromyography data acquisition, which have been important in allowing me to utilise the tool independently. I also thank Elise Busilacchi who was my research assistant for this project.

Most importantly, I am most grateful to my family and friends. I specifically extend the most sincere thank you to Joe, Sheila, Vincent and Annie. Thank you all for your support from afar. I am very lucky to have a terrific family. Finally, I thank Marie-Christine Dorion who is one of my best friends and the reason I came to Québec.

"*For all things difficult to acquire, the intelligent man works with perseverance*"

Lao Tzu

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LIST OF ACRONYMS

CNS: central nervous system

EMG: electromyography

HbO_2: oxyhaemoglobin

Hb_{TOT}: total haemoglobin

HHb: deoxyhaemoglobin

MFVC: mean fibre conduction velocity

MDF: average median frequency

RMS: root mean square

MVC: maximal voluntary contraction

NIRS: near-infrared spectroscopy

P_{di}: normalised diaphragmatic force

TT_{di}: tension time index

T_i: time spent on inspiratory contraction

TOI: tissue oxygen index

VDT: visual display terminal

ABSTRACT

Introduction: The aim of this project was to demonstrate muscle fatigue in the trapezius and to correlate that fatigue with local muscle blood flow. Electrophysiological measurements were recorded during trapezius contractions with surface electromyography, while measures of oxyhaemoglobin, deoxyhaemoglobin and tissue oxygen index were obtained using near-infrared spectroscopy. Seven healthy subjects (three male, four female) were randomly assigned to four experimental conditions where isometric contractions at 30% MVC were utilised and the time of contraction and relaxation varied (tension time index). Each condition lasted three minutes, and subjective ratings of effort for each condition were obtained based on the Borg CR10 scale.

Results: Fatigue in the trapezius was demonstrated with electromyography, with significant differences in mean power frequency and median frequency observed in minute three v minute one, $p < 0.05$. Linear regression demonstrated a strong relationship between tissue oxygen index and fatigue as measured electrophysiologically TT_{di} 0.24 condition ($r^2 = 0.58$), and statistically significant, $p < 0.05$. This observation was not demonstrated in any other condition. Subjective ratings of effort did not correlate well with the onset of muscle fatigue, as subjects did not rate their work as above moderate effort at any time.

Conclusion: Trapezius muscle fatigue does occur following repetitive elevations at low intensity. However the subjective perception of effort during fatiguing contractions is not well recognised by those performing the contractions. Oxygen desaturation correlates strongly to muscle fatigue as measured electrophysiologically where tension time indices of 0.24 are used. Further studies using variations on the present protocol may be able to determine a more detailed relationship between muscle oxygen desaturation and electrophysiological fatigue.

Key words: Surface electromyography, oxygen desaturation, tension-time index

RÉSUMÉ

Introduction : Le but de ce projet était de démontrer la fatigue musculaire au niveau du trapèze et de corréler cette fatigue avec le flot sanguin musculaire local. Des mesures électrophysiologiques ont été enregistrées avec un électromyogramme de surface pendant les contractions du trapèze alors que des mesures de l'oxyhémoglobine, de la déoxyhémoglobine et de l'indice d'oxygénation tissulaire étaient obtenues à l'aide d'un spectroscope infrarouge. Sept sujets sains (trois hommes et quatre femmes) ont été assignés de façon aléatoire à quatre conditions expérimentales où des contractions isométriques de 30% de la CVM ont été utilisées alors que le temps de contraction/relaxation variait (indice de temps de tension). Chaque condition durait trois minutes et des perceptions subjectives de l'effort fourni pour chaque condition ont été obtenues en se basant sur l'échelle de Borg CR10.

Résultats : La fatigue du trapèze a été démontrée grâce à l'électromyographie, par des différences significatives de la puissance de la fréquence moyenne et de la fréquence médiane ($p < 0.05$). La corrélation entre la fatigue et la déoxyhémoglobine, telle que mesurée électrophysiologiquement, était forte ($r^2 = 0,58$) Les perceptions subjectives de l'effort fourni ne corrélaient pas avec le début de la fatigue musculaire, les sujets n'ayant jamais noté leur effort plus haut que modéré à un quelconque moment lors de l'expérience.

Conclusion : La fatigue musculaire du trapèze survient après des élévations répétées à basse intensité. Par contre, l'effort lors des contractions « fatiguées » n'est pas bien perçu par les sujets performant en contraction. La désaturation en oxygène se corrèle fort avec la fatigue musculaire. D'autres études utilisant une variété de ce protocole pourrait déterminer une relation plus précise entre la désaturation en oxygène dans le muscle et la fatigue électrophysiologique.

Mots-clés : électromyographie de surface, désaturation en oxygène, indice de temps de tension

CHAPTER I

PROJECT INTRODUCTION

1.1 General Context

This project was an investigation into peripheral fatigue, whereby EMG centroid frequency and oxygen de-saturation was used to demonstrate muscular fatigue in the trapezius muscles during contractions of varying tension times and at a low intensity load. The interest into peripheral fatigue stretches as back to the early 19th century where Berzelius described muscles of the fatigued stag as containing large quantities of lactic acid (42). Just over one hundred years later, isolated frog muscle preparations stimulated to fatigue quickly accumulated lactic acid (28). Since those early studies, numerous authors have demonstrated that factors beyond lactic acid accumulation contribute to peripheral fatigue (2, 10, 11, 12, 14, 38, 41 & 51).

This research problem concerned itself with the effects of tension time on blood flow through the trapezius muscles during isometric contractions. Specifically, this problem was interested in demonstrating fatigue (via oxygen de-saturation) developed by these muscles during isometric contractions at thirty percent maximal voluntary contraction (MVC), held over varying duty cycles. This research project attempted to demonstrate that muscle fatigue in the trapezius can be demonstrated with electromyography and correlated to a reduction in blood flow to that muscle. A repeated-measures analysis of variance (ANOVA) demonstrated 1) significant differences in either of median frequency or mean power frequency per experimental condition 2) significant differences in muscle oxygenation in each of four experimental conditions. The reduction in skeletal muscle blood flow is a function of the intensity of contraction, and also of the duty cycle characterising those contractions.

1.2 Project Justification

Skeletal muscle blood flow is a vital component in the ability of a muscle to continue to perform repetitive contractions. There are a variety of ways to measure/characterise muscle fatigue including: 1) measurement of metabolic by-products and blood pH, 2) utilisation and depletion of substrates e.g. muscle & liver glycogen, 3) by neuromuscular stimulation following contractions to

fatigue, whereby total fatigue would prevent any further neuromuscular response despite stimulation. Two simple tools that can be used to induce muscle fatigue are those of normalised force and duty cycle. The product of normalising force held over various contraction- relaxation cycles is known as the tension-time index (TT_{di}) which is considered the gold-standard measurement of diaphragmatic fatigue. In combining normalised diaphragmatic force ($P_{di}/P_{di}max$) with a duty cycle, Bellemare & Grassino (5) allowed for prediction of diaphragmatic fatigue once a critical TT_{di} was reached for that muscle. A TT_{di} of 0.15 is predictive of diaphragmatic fatigue (43). The TT_{di} concept was applied to the trapezius in this project with a view to determining a TT_{di} after which fatigue would ensue. There exists at present a relatively small body of research where the TT_{di} has been used in protocols to elicit muscle fatigue, and indeed within that body of research variations in the functions of skeletal muscle blood flow relative to the intensity of MVC have been demonstrated. Therefore this research problem was unique in concentrating on a muscle which is used repetitively everyday for a variety of functions that is quite often a source of pain and soreness; and in doing so attempted to provide data on the level of fatigue associated with oxygen de-saturation within it.

On a personal level, research into fatigue is of particular interest to me. Fatigue may be described as the "*failure to maintain the required or expected power output*" (20), and therefore is a primary limiting factor in preventing sedentary populations, and athletic populations from continuing to work. This definition implies that fatigue occurs during physical activity, be it manual work or exercise, where a reduction in power output or decline in force takes place. A better understanding of fatigue should allow for better preventative measures being taken by people who are likely to experience fatigue. As a researcher with primary interest in muscle fatigue, it is of significant benefit to understand the time-course of biochemical/physiological events that lead to fatigue for any level of work, and for work of any duration. It is also important to know at what intensity of work, where repetitive actions are used that fatigue may ensue. This project demonstrated that low intensity work held for a variety of duty cycles fatigues the trapezius muscles enough to cause fatigue there. The fatigue experienced can be correlated to local intramuscular O_2 saturation. As a sports coach involved in Olympic weightlifting, soccer and rugby coaching, it is of primary interest to me to be able to predict when fatigue may ensue and in turn to allow players to employ strategies which will delay or perhaps prevent the onset of fatigue during sports competition or even when performing daily functional tasks.

1.3 Key Concepts

Tension-time index (TT_{di}): this is the key concept upon which the experimental protocol was based. The concept was developed by Bellemare & Grassino in 1983, with a view to developing a tool that allowed for prediction of diaphragmatic fatigue, respiratory muscle fatigue is common among critically ill patients. Diaphragmatic fatigue can result from increased work of breathing, and a measure of diaphragmatic work is transdiaphragmatic pressure (P_{di}). If the lungs resist inflation, P_{di} increases due to the increased contractile force of the diaphragm to overcome the resistance to inflation. A way to predict diaphragmatic fatigue is to use the ratio between quiet breathing P_{di} and maximal $P_{di}max$ ($P_{di}/P_{di}max$); this in fact is a measure of force output. Patients with a $P_{di}/P_{di}max$ ratio of 0.4 eventually experience diaphragmatic fatigue (5). The TT_{di} is the gold standard measure of diaphragmatic fatigue; it combines the $P_{di}/P_{di}max$ ratio with the time spent on inspiratory contraction (T_i). T_i is expressed as a fraction of the total contraction-contraction relaxation cycle T_i/T_{tot}. The product of both ratios gives us the tension-time index which is expressed as following:

$$TT_{di} = P_{di}/P_{diMAX} * T_i/T_{tot}$$

The TT_{di} considers the force produced by the contracting muscle, and the length of time that contraction is maintained for. A TT_{di} of 0.15 has been shown to be highly predictive of diaphragmatic fatigue (43).

Duty Cycle: this is the ratio of contraction time to total duration of contraction-relaxation cycle. The duty cycle is represented as a decimal point between 0.1 – 1.0. Examples of duty cycles are:

i. 0.2 2s contraction, 8s relaxation
ii. 0.4 4s contraction, 6s relaxation
iii. 0.6 6s contraction, 4s relaxation

The duty cycle as defined above refers to the "*time on, time off*" of a contracting muscle. Bellemare *et al.* demonstrated the effect of normalised force and duty cycle on muscle blood flow in the dog diaphragm (5). The authors demonstrated that a tension time index (TT_{di}) of 0.2 acted as a cut off point for blood flow into the muscle during contractions. Therefore, blood flow into the

muscle during contractions was obstructed at TT_{di} of 0.2 or greater, inhibiting the provision of oxygen (O_2) to fuel those contractions. As a consequence, the post-hyperaemic response of blood flow during the relaxation phase increases at a TT_{di} of 0.2. Similar results have been demonstrated in humans (9).

Skeletal Muscle Blood Flow: skeletal muscle blood flow is a function of the local muscle metabolism (50). During muscle contractions, skeletal muscle blood flow responds linearly to the intensity of contraction that preceded the relaxation phase (25, 42). As mentioned previously, the TT_{di} of 0.2 and above occludes blood flow to the muscle. A high duty cycle represents an increase in contraction time and reduction in relaxation time i.e. an increase in relative intensity. The response of local muscle metabolism is to increase blood flow via post contraction hyperaemia. This is demonstrated in the literature (3, 18, 47, 50, & 58). Reactive hyperaemia may be attributed to an increase in local vasodilation. This linear relationship between increased VO_2 and muscle blood flow is shown in figure 1.

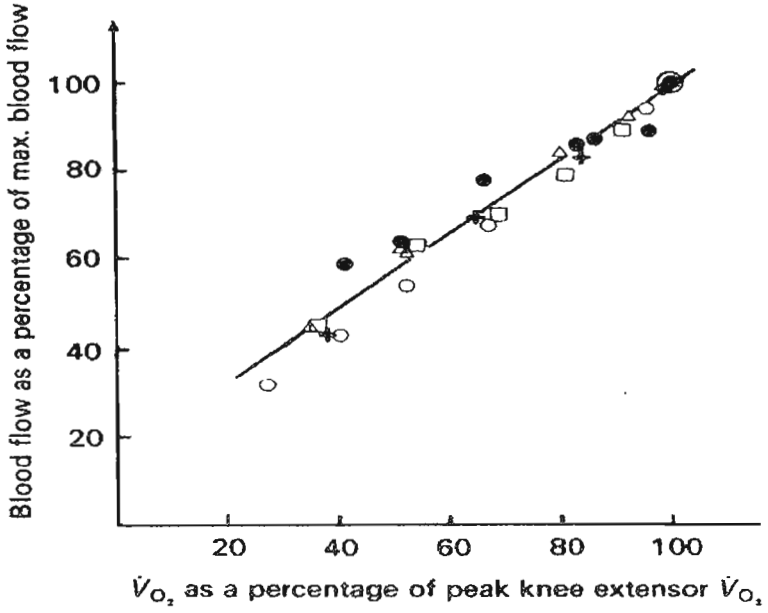

Fig. 1 Increase in blood flow in relation to relative work intensity. Reproduced from Andersen & Saltin [3]

Electromyography (EMG): EMG "*is the discipline that deals with the detection, analysis, and use of electrical signal that emanates from contracting muscles*" (17). Muscles demonstrate electrical activity following neuromuscular activation (elicited via motor unit action potential)

where any voluntary movements such as walking or lifting are performed, or during maintenance of posture and balance such as standing upright or keeping balance (4). EMG has been used to demonstrate the effect of muscle fatigue on posture, the changes in firing rates of individual motor neurones and also in conjunction with near-infrared spectroscopy (NIRS) to correlate muscle fatigue with muscle de-oxygenation (6, 56, 57). An efficient way to demonstrate fatigue using EMG is with via the power spectrum analysis, which displays itself as an altered skewness shape in the acquired EMG signal when fatigue occurs. EMG surface electrodes record changes in muscle action potential frequency and signal power when the data is transformed as a power spectrum. Changes in the median frequency of motor unit action potentials and/or signal power reflect the continual change in the physiological and biochemical intracellular environment. During this time, the combined increase in signal power and decline in median frequency indicate fatigue. An example of the power spectrum is shown below in figure 2. The data here was collected during a pilot study by the present author.

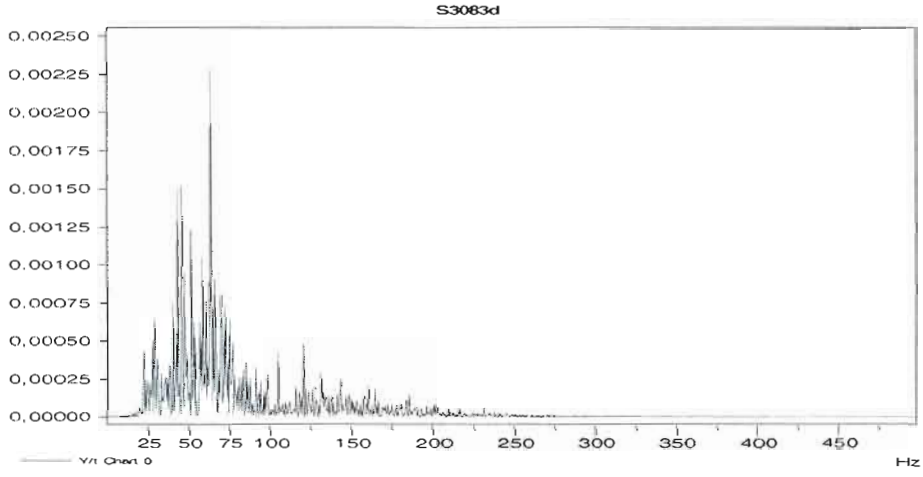

Fig. 2 Example of the total power spectrum of a surface EMG recording: note that most of the signal power is within 20-200Hz

Near Infra-red Spectroscopy (NIRS): NIRS is a non-invasive tool that gives valid measurements of oxygen saturation (HbO_2), oxygen de-saturation (HHb) and total haemoglobin (Hbtot) in the muscle (23, 57). Oxidative metabolism is the primary mechanism by which skeletal muscles transfer energy to contract and hence perform work. NIRS is a good indicator of VO_2 within the muscle, this tool also allows for the calculation of the Hb difference (HbO_2 – Hb) and also enables

the % change (%Δ) in oxygen saturation and de-saturation to be measured in the appropriate units (Δμm). A full discussion of the application of NIRS is given in the methodology of this paper.

1.4 Variables

This research question was specifically interested in the effect of tension and timing, and maximal voluntary contraction percentage on blood flow to the trapezius. The independent and controlling variables which facilitated such an investigation were:

i. Muscle tension expressed as a percentage of MVC, which in this experiment was 30% (controlling variable)
ii. Duty cycle: the ratio of contraction time to total contraction-relaxation cycle
iii. Isometric trapezius elevation held at 30% MVC

The dependent variables which allowed for analysis of fatigue are:

i. Oxygen de-saturation; which is a function of both duty cycle and intensity of contraction. The maintenance of a constant percentage of MVC (30%) during this research will mean that the "*time on*" period of the duty cycle will specifically determine the blood flow to the muscle, which in turn will affect oxygen de-saturation within the muscle
ii. Median frequency and signal amplitude of the EMG power spectrum

The research question here was interested in producing various TT_{di} values by maintaining relative force constant at 30% MVC, and by adjusting the duty cycle. Isometric contractions will be used to elicit variations in blood flow to the trapezius that coincided with changes in the EMG power spectrum variables. This allowed this project to determine what TT_{di} value leads to the greatest value of oxygen de-saturation, and also allow for observation of the hyperaemic responses to contractions held for different contraction-relaxation periods.

1.5 Research Hypothesis

The hypothesis for this project was as follows: trapezius muscle fatigue could be elicited by contracting the trapezius muscles at 25-35% MVC and by varying the duty cycle. Trapezius

muscle fatigue would be demonstrated with EMG. It was also hypothesised that oxygen de-saturation would occur within the muscle and that the fatigue developed could be correlated to the oxygen saturation levels.

The precise mechanism for limiting blood flow to the trapezius was in manipulating the independent variable of interest, the duty cycle. Low duty cycles should provide an adequate relaxation period and facilitate blood flow at 30% MVC during the relaxation phase. However the critical duty cycle at which blood flow to the trapezius is prevented remains to be determined. Once this is observed, the TT_{di} for which this duty cycle belongs will be considered a critical duty cycle for trapezius fatigue. When high duty cycles are utilised, the intensity of contraction should determine the magnitude of blood flow to the muscle. This project would then be in a position to provide an accurate estimate of the contraction intensities for high duty cycles where blood flow does not increase.

The supply of blood flow (dependent variable) is of critical importance to this project. Where blood flow is limited to a muscle, the working muscle is reliant on oxygen within the muscle to provide energy for work. For the range of duty cycles and the contraction intensity (30% MVC) that will be used in this project, oxygen de-saturation will be measured with NIRS. EMG was be used to assess changes in the power spectrum variables corresponding to a given oxygen de-saturation value. The combination of EMG and NIRS as determinants of muscle fatigue are not well documented and can provide for a new departure in muscle fatigue research.

1.6 Limitations

There were four key limitations surrounding this project. Firstly, non-invasive techniques were used to analyse intracellular physiological phenomena. EMG is a valid tool used to measure muscle activity, the literature to date employing EMG time dependent parameters in describing fatigue are at best descriptive. The median frequency and signal amplitude are widely accepted as muscle fatigue descriptors, but the precise origin of changes in signal conduction from action potential of central origin, to a motor unit action potential cannot be determined by EMG alone. Therefore, EMG offers a description of muscle fatigue at best where time dependent changes in the signal are observed. EMG does not provide a direct mechanism or explanation of fatigue.

Secondly, it is reasonable to suggest that maintaining the same duty cycle but altering the absolute contraction-relaxation time would exhibit differences in EMG median frequency and signal

amplitude, by virtue of the fact that both parameters are time dependent. For example, the duty cycle 0.8 could be maintained by either contraction-relaxation cycles of 8s contraction, 2s relaxation, or 16s contraction, 4s relaxation. However, the aim of this study is to demonstrate that the duty cycle alone will exhibit significant differences EMG median frequency and amplitude, therefore a variety of duty cycles are not necessary to that end. Thirdly, EMG data is best collected during isometric contractions. The EMG signal is sensitive to muscle position, muscle lengthening during contraction, and the depth below the surface of the emanating signal which is prone to change with muscle contraction. Isometric contractions control muscle position and limit muscle shortening and lengthening, but are not representative of the dynamic nature of human work. The final limit imposed on this project is in the innate nature of the collected data to be correlative rather than mechanistic. While correlation and regression are good predictive statistical models, the lack of mechanistic description that arises from EMG data collection is a limitation.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

The literature review comprises of three components. Two of those components relate specifically to the data collection tools used in this research project, namely EMG and NIRS. The studies presented here describe previous experiments successfully carried out using both EMG and NIRS and their results are presented and discussed. The third component of this literature review focuses specifically on tension time index. Each concept is discussed separately, specifically to breakdown the precise mechanisms behind choosing these tools to carry out this research.

2.2 Electromyography

Electromyography has been successfully used in a wide variety of study designs to demonstrate muscle fatigue (22, 26, 31, 37, and 45). Early work on EMG attributed muscle fatigue to reduced motor neuron firing rates (6), while more recent work on muscle fatigue utilise the power spectrum analysis describing decreases in median frequency and increased amplitude as fatigue indicators (37). An increase in EMG signal amplitude and decrease in median frequency are both associated with the onset of muscle fatigue during contractions (56). Signal amplitude and median frequency are obtained following Fast Fourier Transformation and is represented by the total power spectrum. The total power spectrum represents the frequency with which motor unit action potentials are conducted, the decline of which is associated with impaired signal conduction between the α-motor neuron and the fibres innervated by it. The amplitude component of the power spectrum represents motor units recruited to perform contractions, an increase of which indicates motor unit recruitment due to the onset of fatigue in motor units already contracting. The combination of both measures is a good indicator of the onset of muscle fatigue, as both are time dependent measures, which change in value with progressive contractions. Today, advances in decomposing the EMG signal describe the signal in terms of five major parameters: mean spike amplitude (MSA), mean spike frequency (MSF), mean spike slope (MSS), mean spike duration

(MSD) and mean number of peaks per spike (MNPPS) (26). The studies of interest to this project are described now.

Bigland-Ritchie (1982) using both surface EMG and tungsten micro-electrodes isolated the frequencies of single motor unit potentials during maximal contractions of the human adductor pollicis muscle. The study demonstrated a decline in EMG signal amplitude coinciding with a loss of force over time. The experimental protocol consisted of a control period where a series of 10s MVC contractions (each of which were separated by 3min rest) were conducted to obtain maximal EMG amplitude and motor unit firing rates, and was followed by a fatiguing contraction held over 40-120s. The fatiguing contraction was also a MVC. Following the fatiguing contraction, the original control period of contractions were repeated. During the control period, the firing rates of 20-100 motor units were obtained. Mean firing frequency for the adductor pollicis ranged for 22-28Hz for most subjects, with one subject exhibiting a mean of 35.4Hz.

The results of this study demonstrate that both force and motor unit firing rate declined over time during the sustained MVC. Mean motor unit firing rate decreased by 50% during the first minute of contraction to 15Hz. Figure 3 displays force decline and motor unit discharge values during experimentation.

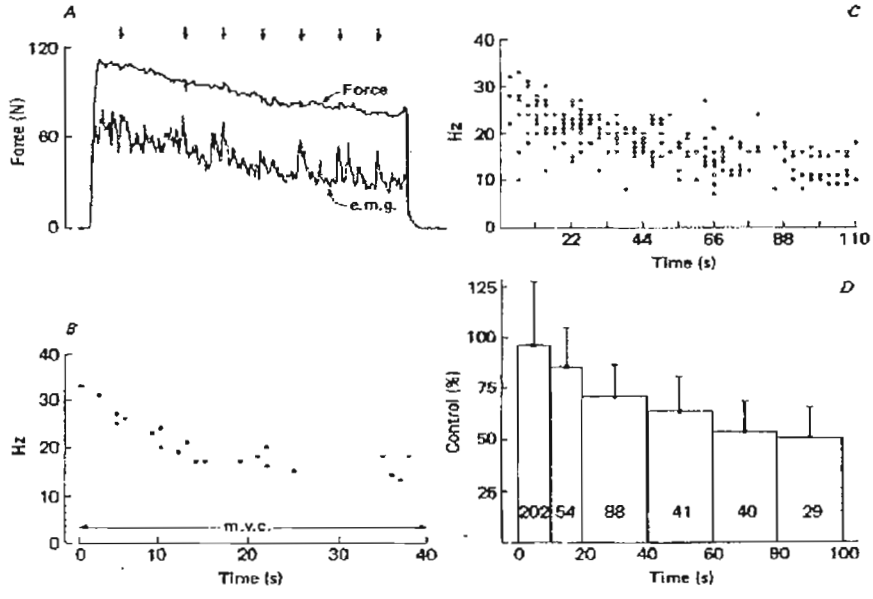

Fig. 3 Adductor pollicis muscle force decline (A), single motor unit discharge rate (B), pooled data from nine trials on one subject (C) and pooled data motor unit firing rates from five subjects. Reproduced from Bigland-Ritchie *et al.* [6]

To test the integrity of the motor unit innervating the adductor pollicis, the muscle was electrically stimulated supra-maximally (50Hz). The stimulation demonstrated no change in muscle mass action potential, thereby ruling out neuromuscular block during fatigue.

A recent study by Kimura *et al.* (2007) used a low-intensity protocol to elicit physiological fatigue and compare it with subjective feelings of fatigue both during muscle contraction and during the recovery period (39). The protocol determined the MVC of the trapezius; details are outlined in reference 39. The experimental protocol involved 4*25min periods of typewriting, each period being separated by 5min recovery. The subjects typed while sitting in front of a visual display terminal (VDT) where they were instructed to maintain their relative force at 30% throughout. Subjects wore a 1kg resistive load during typing and elbows were kept off their work station. EMG parameters (mean fibre conduction velocity, median frequency, and root mean square amplitude) were taken for the trapezius before and at the end of each 5min rest period following typing (0min, 30min, 60min, 90min and 120min respectively) as well as during recovery (160min & 175min). Subjective measures of fatigue were also taken, including muscle hardness and self-rating. The experimental scheme and placement of electrodes is shown in figure 4.

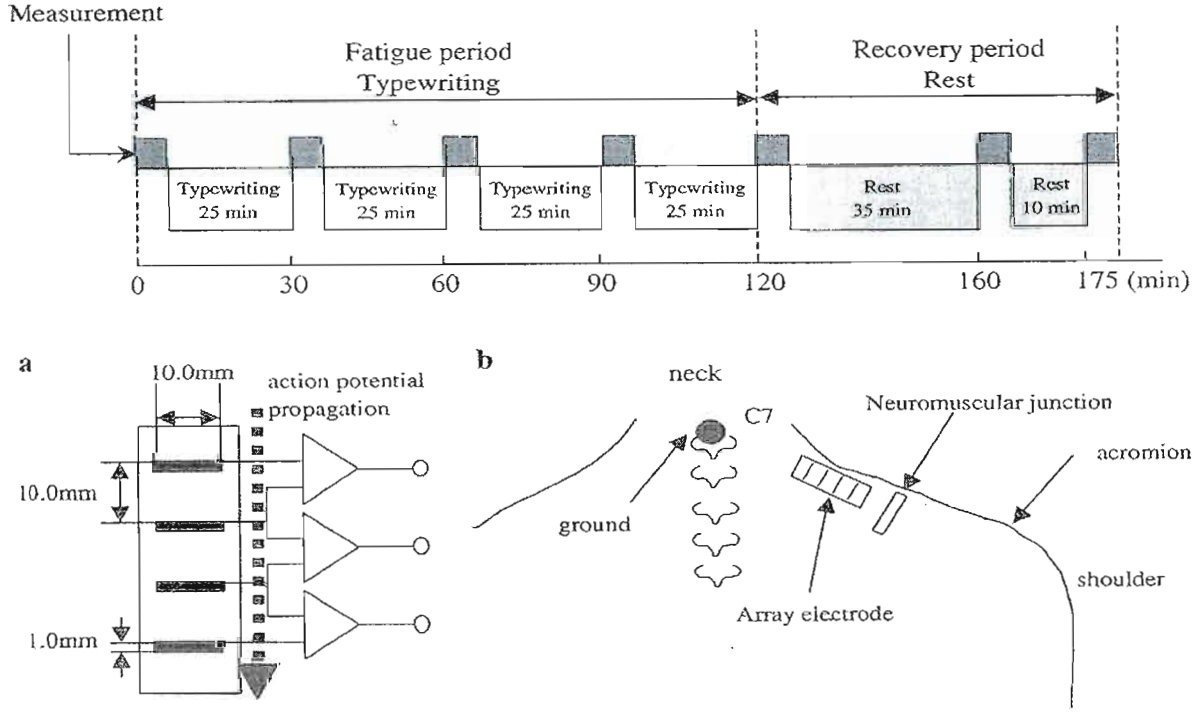

Fig. 4 Sample of protocol and electrode placement for upper trapezius recording. Reproduced from Kimura *et al.* [39]

The results of this experiment demonstrate fatigue related responses in the EMG signal. The average mean fibre conduction velocity (MFCV) decreased by 13.6% to 4.67 ± 0.47m/s as the protocol came to an end. Average median frequency (MDF) decreased significantly by 10.6% (7.7Hz) during the protocol. Significant differences in MDF were also observed at 60 and 90min compared to 0min. RMS amplitude increased significantly from 101.9 ± 26.5μV before typewriting to 116.8 ± 32.2μV after typewriting. The same EMG parameters were measured at 40 and 55min during recovery. During this period neither MFCV MDF nor RMS increased significantly indicating a prolongation of physiological fatigue after the protocol. Subjective ratings of fatigue were also taken during and after typewriting: subjects demonstrated subjective fatigue ratings from 0-3 (with 0 corresponding to no fatigue and 3 corresponding to severe fatigue) during typewriting, but most of which had fully recovered during recovery. EMG measures and during experimentation are shown in figure 5.

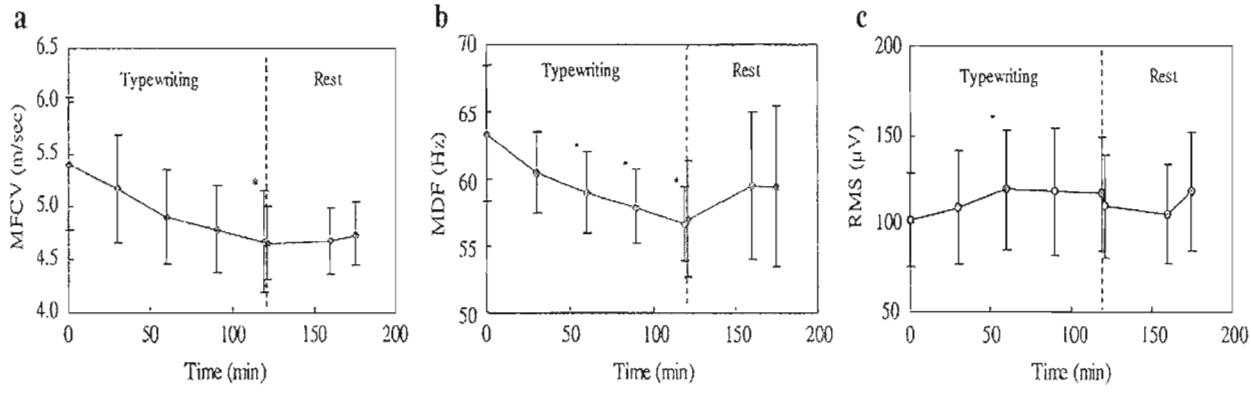

Fig. 5 Muscle fibre conduction velocity (A), mean frequency (B), root mean square (C) from 0-120min.

	Fatigue period Typewriting				Recovery period Rest		
Time (min) Fatigue score	0	30	60	90	120	160	175
0: none	6	2	1	0	0	4	4
1: slight	0	2	2	2	2	1	2
2: moderate	0	2	2	3	1	1	0
3: severe	0	0	1	1	3	0	0

Fig. 6 Lower panel: subjective fatigue rating in the shoulder-neck region during fatigue and recovery. Reproduced from Kimura *et al.* [39]

The subjective ratings of fatigue are displayed in figure 6. The changes in EMG parameters observed here are good indicators of muscle fatigue, and were closely correlated with subjective feelings of fatigue during the task. Specific decreases in MDF are attributed to a decrease in MFCV while the corresponding increased RMS is due to an increase in the number motor units firing and the increased motor unit synchronisation. However, MDF and MFCV changes are also a result of the changing physiological muscle environment, of which oxygen de-saturation may be at least a causal factor. As muscle fatigue develops, there is a shift in the types of motor units employed to carry out the task from low threshold slow type (S-type) motor units to high (-er) threshold fatiguable fast type (F-type) motor units. This may also explain the increase in RMS during fatigue. Interestingly, this study demonstrated a delayed recovery from fatigue following the protocol. Neither MFCV nor MDF returned to baseline in the 55min following the protocol despite a significant decrease in subjective feelings of fatigue. This implies that low frequency fatigue which is maintained for long durations of time is not easily recovered from, and that low force efforts are significant causes of fatigue for a continuous task. The second implication, however, is that physiological muscle fatigue and subjective fatigue do not correlate well in the recovery period following low intensity work. This may mean that people will continue to work through physiologic fatigue – stress if they do not feel fatigue. Here in lies a potential risk factor in the aetiology of chronic muscle pain/fatigue.

A study by Holtermann *et al.* (2005) examined motor unit recruitment patterns in the trapezius for both ramp and sustained isometric contractions. The authors hypothesised that an increase in motor unit recruitment would compensate for fatigue during sustained contractions, whilst also regulating force during ramp contractions in the trapezius muscle. For this study, 18 female and 7 male subjects were used (mean age 25yrs). Prior to the protocol implementation, all subjects performed 3 MVC's (trapezius elevation) that were held for a period of 5s each, and separated by 10s rest. Each subject was positioned in front of a monitor that gave them visual feedback of their force production during the MVC. The MVC value was determined with a 0.5s filtered window, with the highest value after averaging chosen. The highest MVC value was chosen as that from which relative loads could be calculated. The experimental protocol consisted of two strands: a ramp contraction involving each subject smoothly increasing isometric force from 0-90% MVC in a window totalling 10s i.e. an increase in force by 9% was required for every second. This was repeated three times with 10s rest between each attempt. The second contraction was a sustained contraction for 3min at 25% MVC. RMS and MDF were calculated for each contraction in time frames of 500ms, but MDF was only calculated for the sustained 3min contraction.

During the sustained contraction, RMS amplitude increased by 13%, whilst median frequency decreased by 19%. For the ramp contraction, median RMS increased from 0-90% of RMS during MVC. However the relationship between RMS values was non-linear; as the mean RMS value at 25% MVC was only 18% of maximal RMS. The increase in RMS and decrease in MDF at 25% MVC indicates that the trapezius muscle fatigues at this intensity. The authors argue that the decrease in MDF is significant given that the decrease is of greater magnitude than previously observed. What is interesting about the onset of fatigue is that it is attributed to the F-type motor units. MDF decreases have been reported by Gerdle *et al.* (1993) in F-type motor units mainly and not S-type, indicating the activation of F-type motor units here at 25% MVC.

There are two strategies, the authors claim, to describe the increased EMG amplitude with fatiguing contractions. Either motor unit recruitment can increase towards F-type units, or the firing rate of motor units already recruited can increase. Gabriel *et al.* (2007) have demonstrated that increased motor unit firing rate is unlikely to occur until higher forces are achieved, leaving motor unit recruitment as the most likely strategy for increasing EMG amplitude at low force outputs. The decreased MDF underscores a decrease in the velocity of conduction of motor unit action potentials. The fact that MDF decreases and corresponds to increased RMS amplitude

implies that it may influence the RMS signal. The overall findings of the authors here state that during sustained contractions, the amplitude distribution of the trapezius during a 25% MVC contraction is similar to that of a contraction generating high force. This finding attests to the observation that motor unit recruitment of F-type units occurs during sustained contractions to fatigue, where S-type units may not generate the force sufficient to maintain 25% MVC. Data including RMS, median frequency, RMS as a percentage of MVC percentage and force as a percentage of MVC are shown below in figure 7.

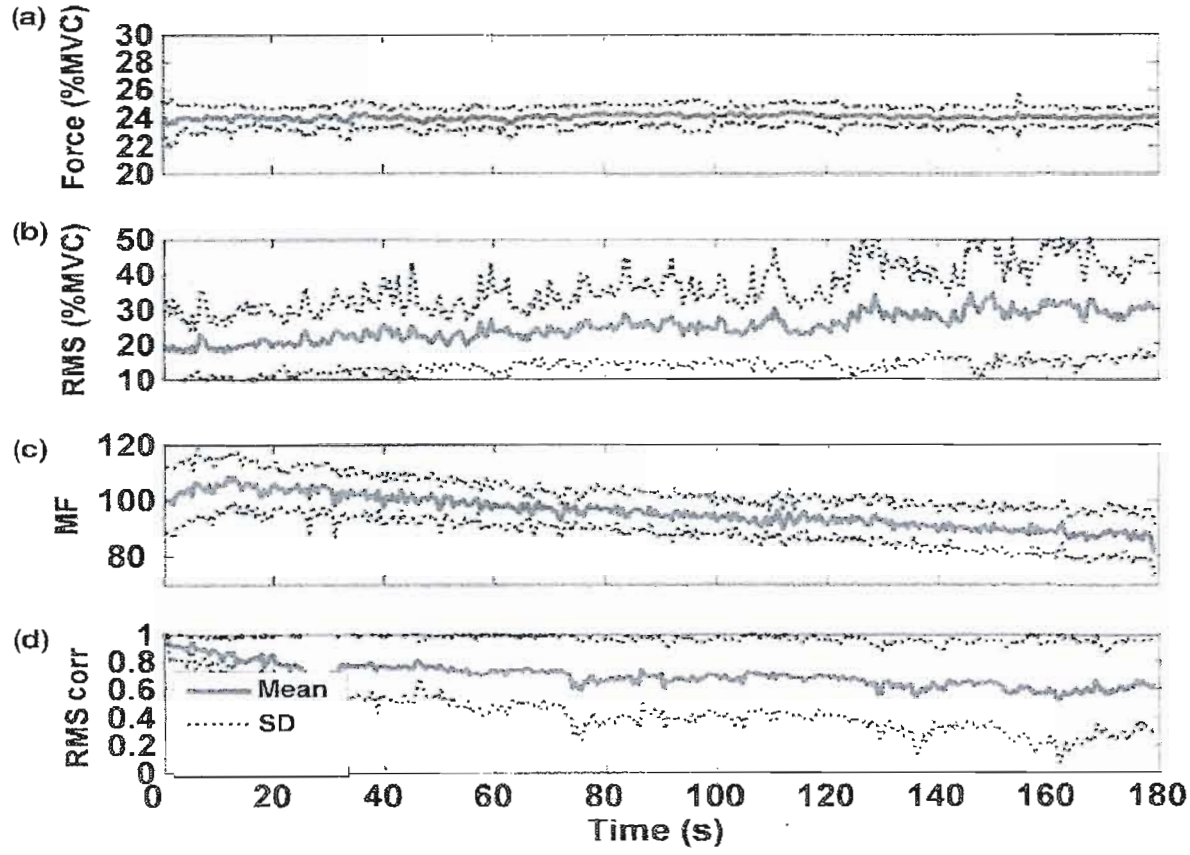

Fig. 7 Mean changes and SD in time during sustained contraction of force (A), root mean square (B), median frequency (C), and ROMS correlation with the first time epoch as a reference (D). Reproduced from Holtermann *et al.* [31]

Minning *et al.* (2006) utilised a functional movement to demonstrate rate muscle fatigue in four muscles surrounding the shoulder: the middle deltoid, the upper and lower trapezius and the serratus anterior. Their study sought to determine whether or not their functional movement would elicit different rates of fatigue in these muscles during an isometric contraction. The author's interest in this study lies in the fact that shoulder fatigue has been demonstrated to elicit changes in joint mechanics, sometimes leading to tendonitis and dislocations of that joint (44). They point to a number of authors who have demonstrated the relationship between shoulder fatigue and destabilisation of the scapula, coinciding with a reduced rhythm in scapulohumeral movement. Sixteen subjects took part in the study (9 female, 7 male) aged 21-30yrs, none of whom had previously reported a history of shoulder pain or reduced range of motion.

In terms of the muscles chosen for the study, the authors suggest that the four chosen represent those primarily involved in arm elevation and scapular rotation i.e. subscapularis, supraspinatus, infraspinatus and teres minor. The experimental protocol is described in full in their paper, surface electrodes were placed on each of the four muscles from which EMG data was obtained. The functional movement as mentioned earlier was a lateral shoulder elevation to 90°. This movement was chosen due to its application in a wide variety of movements and tasks on a daily basis. It represents lifting and reaching movements, the repetition of which over long time periods may fatigue the shoulder muscles.

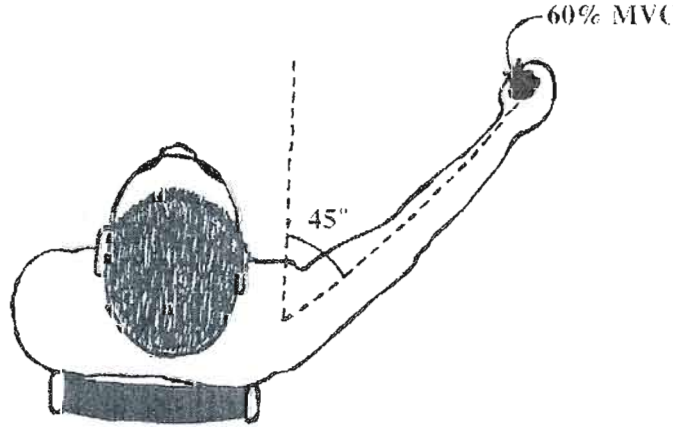

Fig. 8 Horizontal flexion of shoulder used in experimental protocol. Reproduced from Minning *et al.* [44]

The subjects performed two isometric MVC contractions using a hand held dynamometer in the 90° position and from that value, 60% MVC was chosen for the experimental protocol (Fig. 8).

According to the authors, 60% MVC has been demonstrated as a force which recruits F-type motor units compared with lower force outputs. Isometric contractions were chosen due to its facilitation in controlling the movement and also to reduce synergy with other muscles e.g. hip sway, to gain momentum with the lift. With the relative load established for each subject, subjects performed two isometric contractions at 60% MVC. Each contraction was separated by 5min rest. The contractions were held at 90° shoulder elevation until either of two conditions was satisfied: the subject could no longer hold the contraction, or 30s had elapsed. Both conditions satisfied the fatigued state for the authors here. One week later, the same protocol was employed where subjects returned to the laboratory to perform two more contractions. Prior to returning to the laboratory a second time, the subjects verbally agreed to avoid lifting movements or shoulder training. Raw data collected here was transformed via Fast Fourier transformation, with median frequency reported in 512ms windows, where data includes muscle activity from 50ms following the initiation of contraction.

Data collected from both days one and two show decreases in MDF were most apparent in the middle deltoid and upper trapezius compared with the lower trapezius and serratus anterior for both days. MDF in the middle deltoid ranged from above 100Hz at the onset of contraction to below 80Hz after 30s. Upper trapezius MDF declined by more than 15Hz during the protocol. Despite the most significant decreases in median frequency observed in the middle deltoid and upper trapezius, all muscles demonstrated decreases in median frequency over time (Fig. 9)

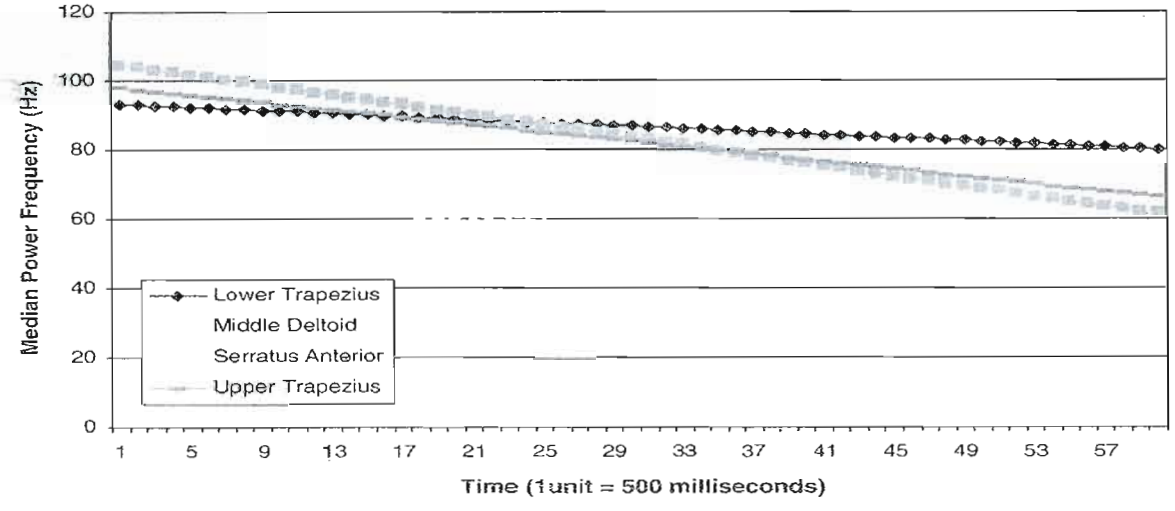

Fig. 9 Average shift in median frequency across subjects and trials on day 2, Reproduced from Minning *et al.* [45]

Data collected during day 2 effectively reinforce the results of day 1. The authors explain the decrease in median frequency in terms of muscle fibre activation. They argue that peripheral fatigue as demonstrated here is a function of type II muscle fibre fatigue. They point to previous authors (Gerdle *et al.* 1993, Moritani *et al.* 1986) that have shown shifts to lower frequencies of muscle activation to occur during fatigue, in both dynamic and static conditions. The authors use a very simple analysis to explain their results. They hypothesise that type II fibres are fatigued more easily than type I fibres, and given the short duration of the experimental protocol, they assume that fatigue has occurred here in type II fibres which are continuously recruited. Their analysis stems from findings by Johnson *et al.* (1973) who demonstrates that phasic muscles express mainly type II fibres, and since the middle deltoid movement is primarily phasic, it is logical to assume type II fibre fatigue during this protocol. A weakness in this analysis, however, lies in the assumption that decreases in median frequency is a sole function of type II fibre fatigue. The shoulder/rotator cuff contains more muscles than those studied here, any combination and activation of which may have influenced fatigue development. Smaller rotator muscles such as subscapularis or supraspinatus may place additional stress on the shoulder joint during 90° elevation, which in turn could influence the rate of fatigue development. In terms of the degree of elevation, Inman *et al.* (1944) has shown the medial deltoid to be most active between 0-110° elevations with no significant increase in muscle activity beyond this point, but other deltoid muscles (anterior & posterior deltoids) used here are activated throughout entire elevation and depression movements. Therefore the full activation potential of the lower and upper trapezius in particular, and serratus anterior may not have been achieved with the functional movement employed here.

A study by Falla and Farina (2007) demonstrated the spatial distribution of muscle activity in the upper trapezius during fatiguing contractions. The authors developed on previous work which has demonstrated that a fatiguing muscle exhibits spatial variance in terms of motor unit recruitment. This means that muscle activity during contractions is distributed across the muscle; this is in agreement with the Henneman size principle where the non-uniform arrangement of muscle fibres and motor units are recruited in order of size and as a function of force output and time to failure. However, the spatial distribution of muscle activity across the muscle may also indicate an ability to control local muscle activation, and may serve as a strategy to reduce the onset of fatigue by distributing the workload away from specific motor units and to other ones. This study utilised two

protocols; the first protocol utilised a sustained upper trapezius contraction held for 6min at 20% MVC, the second protocol involved a sustained contraction held at 20% MVC interspersed with a 2s increase of force to 25% every 30s (variable force contraction). The second protocol sought to develop on previous work whereby an increase in endurance time had been demonstrated where contractile force was variable over time instead of uniform. Task variability had not been demonstrated to relate to spatial distribution variance of muscle activity, therefore the aim of this study was to compare the onset of fatigue and spatial distribution of muscle activity (via EMG) for a sustained contraction and a variable force contraction.

Nine subjects took part in the study, where mean age, height and weight were 26.6 ± 2.2yrs, 1.70m ± 0.13m, and 67.1 ± 15.2kg respectively. Four subjects were female, and no subject had reported a history of neck or upper limb disorder or injury. Subjects sat down with chair placed directly onto a shoulder dynamometer, upon which was a 64 surface-electrode grid. The grid consisted of 13 rows and 5 columns with one electrode non-functional. Subjects performed 3 shoulder elevations MVC's each held for 3-4s, each MVC was separated by 1min rest. The maximal MVC value was chosen as that from which the relative load was calculated. Subjects performed either 1) shoulder elevation at 20% MVC for 6min, or 2) 20% MVC for 6min interspersed with an increase in contraction force to 25% MVC held for 2s, every 30s. Each subject then immediately performed another MVC from which fatigue could be determined. A period of 48hrs separated each experimental trial, and the order of trials was randomised.

The results of this experiment showed that MVC assessed after each condition decreases significantly (↓3.9%) following sustained contraction at 20% compared to MVC assessed after the second experimental condition (↓2.8%). RMS data demonstrated significant variability among subjects, while average RMS did not change between conditions. Interestingly, MDF decreased significantly only for the sustained contraction (2.5 ± 4.2%) but not for the variable contraction (0.7 ± 4.1%). This study also demonstrated a shift in muscular activity in the cranial direction during the variable contraction compared to the constant force where little spatial distribution of muscle activity occurred. The changes observed here in the EMG signal relate to changes in muscle fibre conduction velocity. The slowing of impulses is likely to be caused by an increased duration of action potentials. The fact that EMG root mean square varied between the constant and variable contraction indicate changes in the properties associated with the muscle membrane. This is attested to in the variability in power density spectrum demonstrated between contractions,

indicating a possible differing mechanism of fatigue in the same muscle. The results of this study are shown in figure 10.

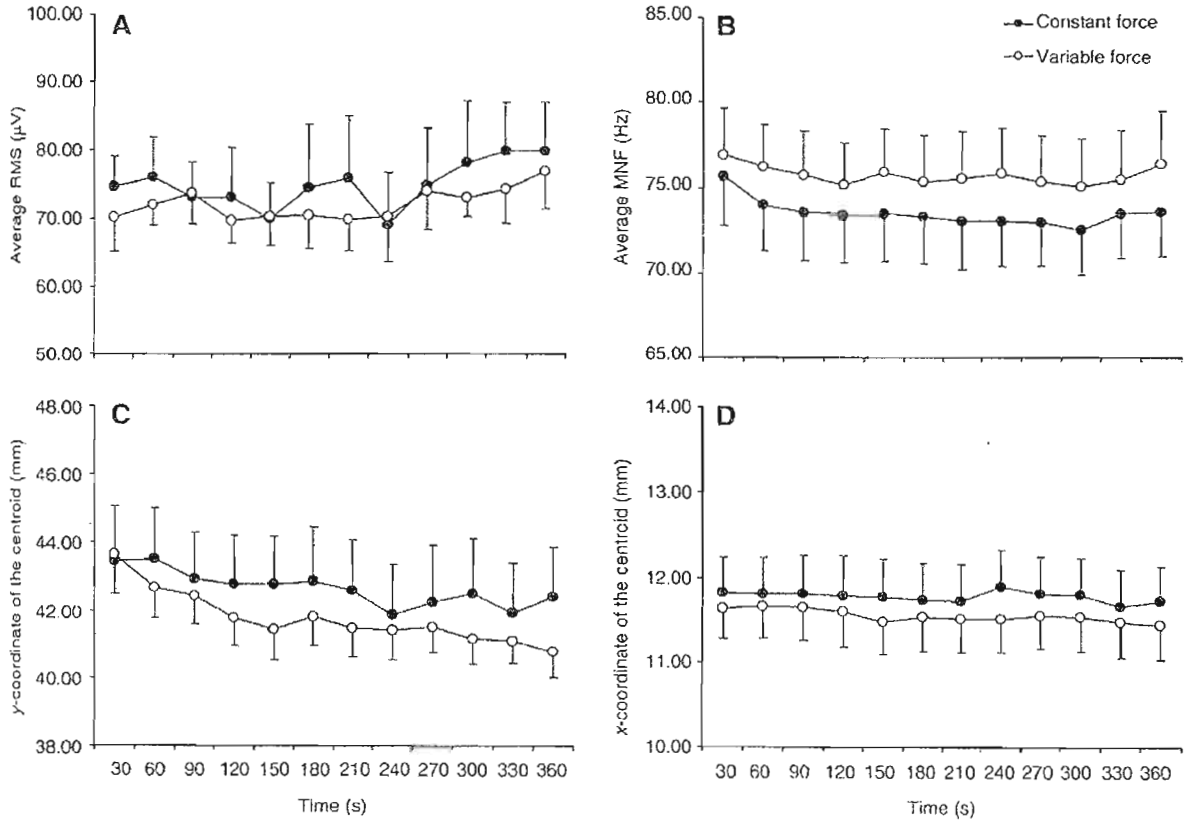

Fig. 10 Mean (± SE) average root mean square (RMS), average mean power (A), y co-ordinate (B), x co-ordinate (C), x co-ordinate of centroid for constant and variable force. Reproduced from Falla & Farina [22]

Figure 11 displays EMG centroid displacement both constant and variable force production, as well as the vector those shifts which were observed during experimentation.

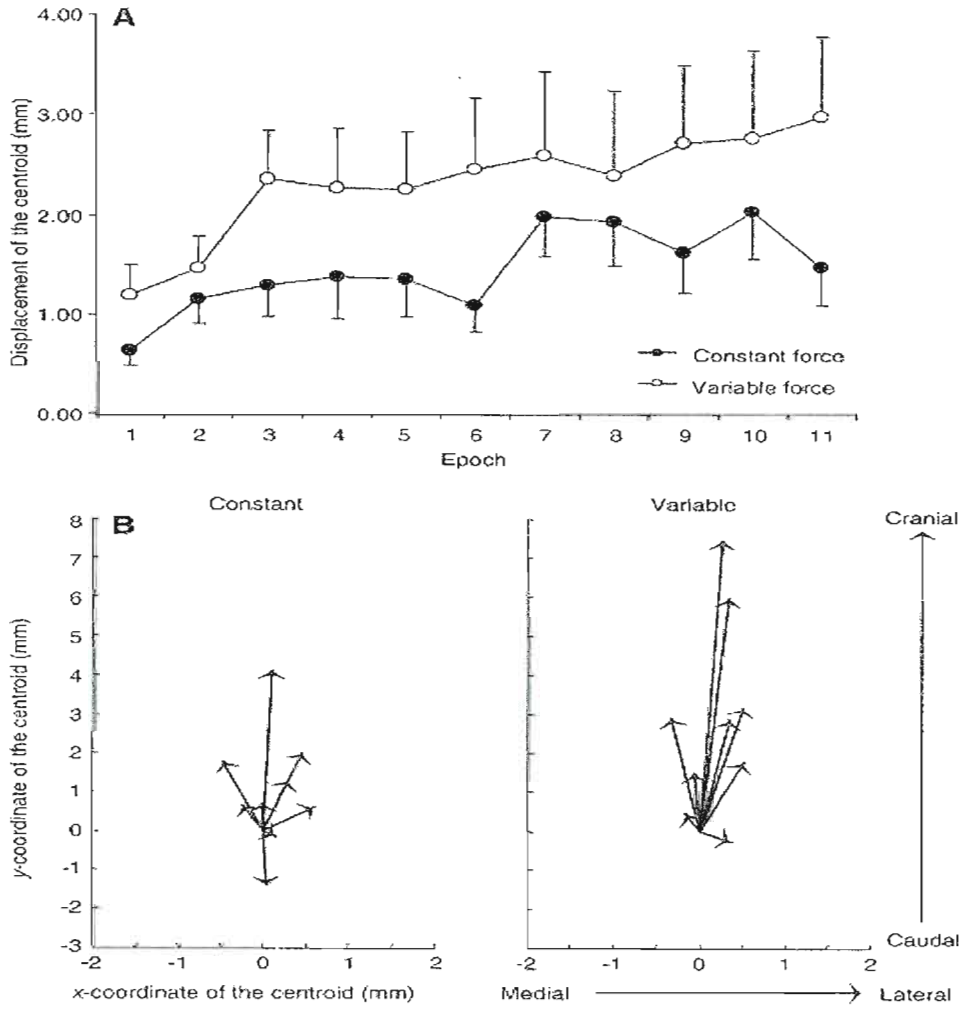

Fig. 11 Mean (SE ±) of centroid displacement (A) for both constant and variable force contraction. The vector of the shift (B) for all subjects, Reproduced from Falla & Farina [22]

2.3 Skeletal Muscle Blood Flow

A considerable body of data exists in relation to skeletal muscle blood flow and the mechanisms which underlie it (3, 13, 25, 29, 33 & 58). Within this body of research there are three principal mechanisms which account for the facilitation of blood flow: 1) research focusing on vasodilation, 2) research focusing on the skeletal muscle pump, 3) research which explains skeletal muscle blood flow in terms of both of the former.

Evidence is provided by Tschakovsky *et al.* (2004) that rapid vasodilation is primarily responsible for the immediate increase in blood flow following forearm contractions. The authors challenge the theory that the muscle pump is a primary determinant of muscle blood flow following contractions. The hypothesis for vasodilation is supported by studies which have demonstrated a contraction-intensity blood flow response i.e. the higher the contraction intensity, the greater reactive hyperaemic response. Their results indicate a vasodilation response proportional to muscle activation.

Subjects performed 2 forearm MVC's with the handgrip held isometrically. From here, relative loads were calculated. In the experimental protocol, subjects performed contractions at 5, 10, 15, 20, 30, 50 and 70% MVC each held separated by 2min rest. Contractions were performed for two conditions: 1) lying supine with forearm 20cm below the heart 2) lying supine with forearm 20cm above the heart. This amounted to a pressure difference of ~ 30mmHg in local forearm pressure. During this period, heart rate (HR) and mean arterial pressure (MAP) were monitored. Forearm blood flow in the immediate post-contraction period was determined by Doppler probe attached over the brachial artery. From here, the correlation between arterial mean blood velocity (MBV), forearm blood flow (FBF) and the %ΔFBF could be assessed.

The results of this study support the vasodilation as a primary mechanism for the increased hyperaemia witnessed after muscle contraction. In contractions made with the arm below heart level, forearm venous emptying was similar across all contraction intensities (Fig. 12).

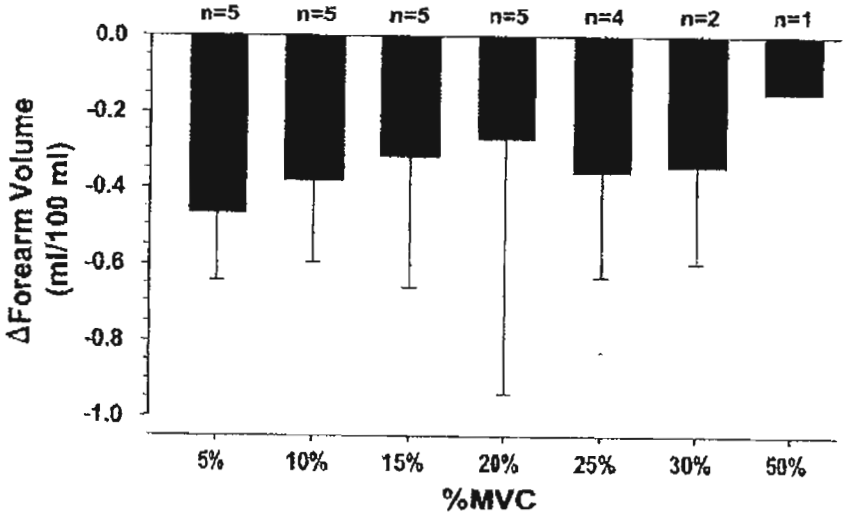

Fig. 12 Change in forearm venous volume after 1-s contractions. Reproduced from Tschakovsky *et al.* [57]

Therefore the effect of the muscle pump does not seem to be intensity dependent. FBF increased linearly for all contraction intensities up to 70% MVC in both arm above and arm below conditions, with the peak response witnessed in the 4th cardiac cycle post-contraction. In the first second following muscle contraction for all intensities, reactive hyperaemia is proportional to contraction intensity. In the arm above heart position, the relationship is linear. However, in the arm below heart position, the slope of reactive hyperaemia is steeper than in the arm above heart level and then curvi-linear at higher contraction intensity (Fig. 13). The authors argue that this is clear evidence that even at low intensity contraction the lack of difference in reactive hyperaemia in either condition when venous emptying was maximal indicates a lack of muscle pump influence.

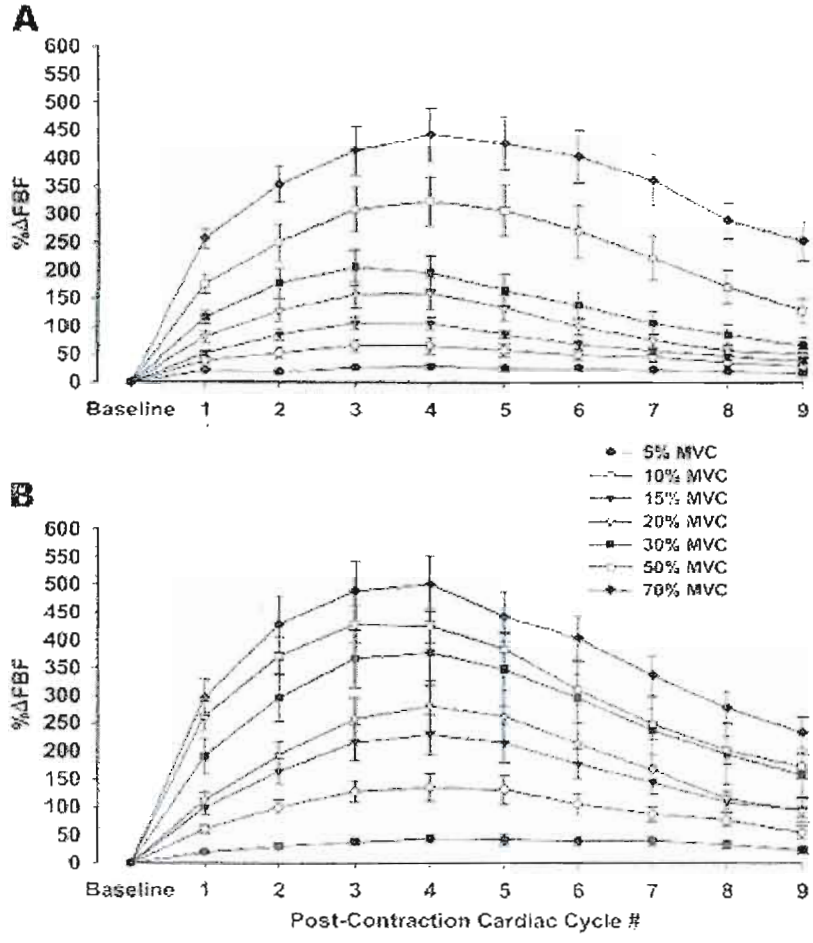

Fig. 13 Percent change in forearm blood flow in arm above heart position (A), arm below heart position (B). Reproduced from Tschakovsky *et al.* [5]

The key findings here are: 1) immediate reactive hyperaemia is contraction-intensity dependent when the forearm is in an above the heart condition 2) in the forearm below heart position, the greater reactive hyperaemic response could be due to an increase in arterial driving pressure. With the arm in an above the heart position, forearm venous volume is minimised. Isometric contractions also minimise the time period allowed for venous filling by compressing the vessels. Under these conditions, they argue that if the muscle pump was the primary mechanism responsible for blood flow increase immediately after contraction, little difference in hyperaemia should be observed across a range of contractions. However, if vasodilation was the primary mechanism involved, FBF following contraction would be contraction-intensity dependent. The evidence for vasodilation is observed where FBF increases immediately at each contraction intensity and increases in magnitude as contraction intensity increased. Furthermore, forearm venous volume in this experiment is near-maximal at low intensity contraction, indicating that the role of muscle pump is limited in isometric contractions. There were also differences observed in the hyperaemic response of both experimental conditions with the arm in above or below the heart positions. The steeper slope of %ΔFBF at low to moderate intensity contraction when the arm was below the heart may indicate that immediate reactive hyperaemia is attributed to an increase in arteriovenous pressure i.e. vascular conductance, following contraction.

A study by Fumiko *et al.* (2007) demonstrated that the time course for hyperaemia did not differ between contraction intensities performed at 15%, 30% and 50%, however the absolute blood flow response did. Seven women participated in this study, where seated plantar flexion contractions were performed at 15, 30 and 50% MVC. MVC was determined prior to the experimental protocol where the average of the best 3 contractions from 5 total contractions was used from which the relative load for each subject was calculated. Two experimental protocols were implemented: 1) a single plantar flexion contraction was performed and from here the hyperaemic response to peak post-contraction blood flow was obtained from the first cardiac cycle onwards 2) two contractions were performed, where the second contraction was implemented based upon data obtained from the first contraction: the second contraction occurred at three different stages: at the time where peak blood flow occurred following contraction 1 (T_{peak}), the time pre T_{peak} and the period immediately following T_{peak}.

The results indicate that blood flow increased immediately following the initiation of the plantar flexion, and peaked after 3.8-4.7s. The data indicates that beat by beat time to peak blood flow

between contractions were not significantly different, however the absolute magnitude of blood flow was significantly different. In the second experiment, peak blood flow was obtained when the second contraction occurred before the onset of T_{peak} following contraction 1. This was demonstrated for each of 15, 30 and 50% intensities. Beat by beat blood flow response to both single and two contractions are shown in figures 14 and 15.

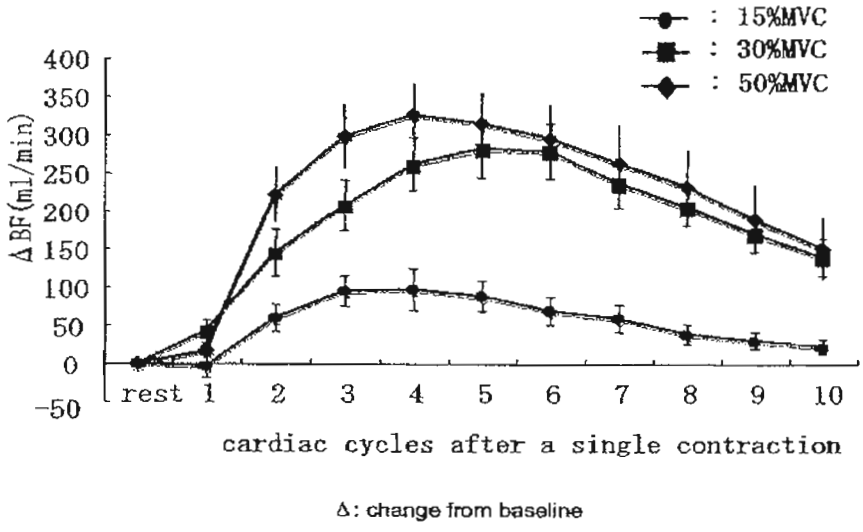

Fig. 14 Beat by beat blood flow following contraction at 15, 30, and 50% MVC. Reproduced from Fumiko *et al.* [25]

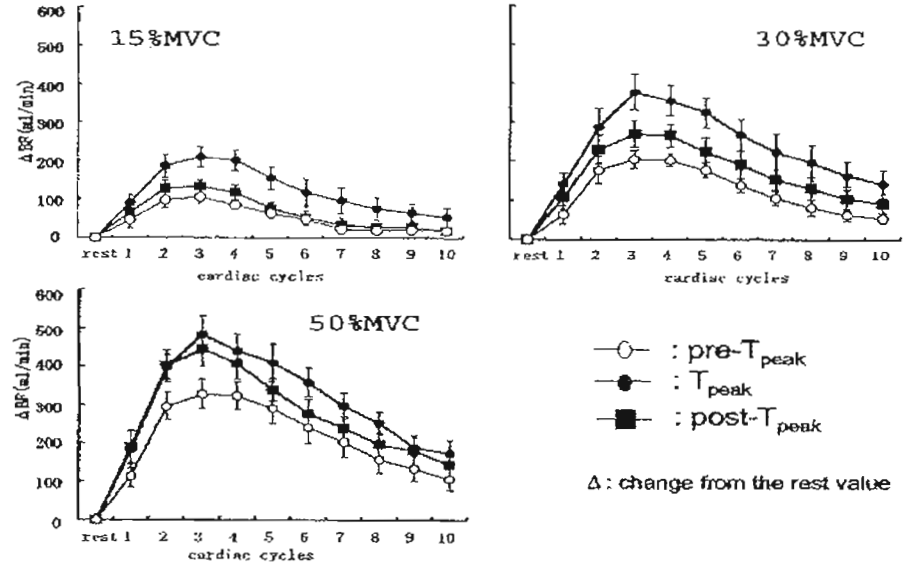

Fig. 15 Beat by beat blood flow after two successive contractions. Reproduced from Fumiko *et al.* [25]

The lowest blood flow value was observed when the second contraction occurred after T_{peak}. The relaxation time before the second contractions was implemented in experiment 2 was adjusted for each subject, i.e. it was a relative relaxation time. The advantage in having a relative relaxation time is in that the second contraction could be implemented in relation to the specific blood flow of each subject. The findings here indicate that blood flow will be augmented if two contractions are performed successively when the second contraction is initiated at the halfway point to maximal blood flow following the first contraction (Fig. 16). This is in agreement with research that has demonstrated that blood flow into the muscle increases if the period between successive contractions is short.

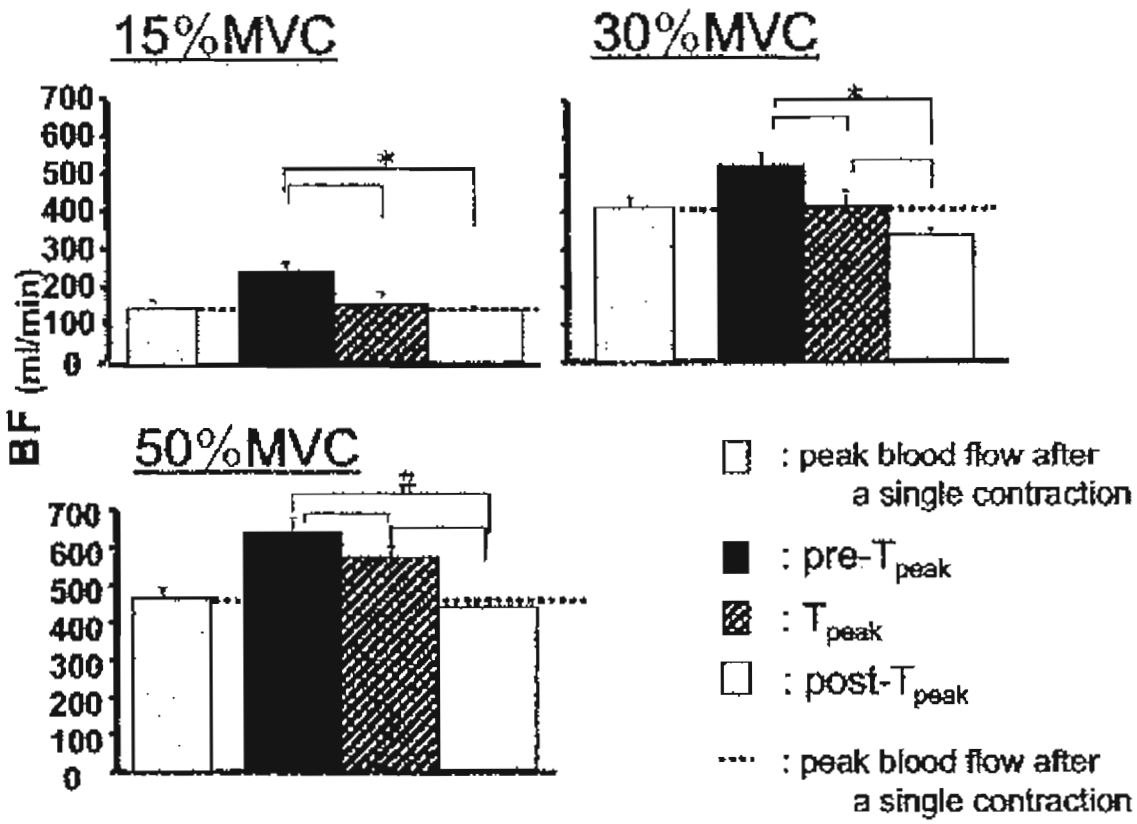

Fig. 16 Peak blood flow in exercise at three different relaxation times. Reproduced from Fumiko *et al.* [25]

A recent study by Cook *et al.* (2007) demonstrated that a combination of low intensity exercise (20% MVC) and blood flow restriction is equally as fatiguing as a high intensity exercise (80%

MVC). The basis for this study lies in the practical limitations placed upon individuals who, in periods of recovery from surgery or other cannot perform moderate-high intensity resistance training. In Japan, a form of low intensity training known as *Kaatsu* is commonly used where muscular adaptations in cross-sectional area (CSA) and strength similar to those following moderate to high intensity training have been demonstrated. *Kaatsu* is based on using low intensity loads and blood flow restriction to the contracting muscle. The same physiological response governing muscle hypertrophy and strength increases is demonstrated in *Kaatsu* i.e. increased serum insulin growth factor-1 (IGF-1), increased protein synthesis via the growth hormone – insulin growth factor-1 (HG – IGF-1).

Twenty one subjects took part in this study. Subjects participated in five protocols, each of which was conducted on separate days. MVC was determined by knee extension where two MVC's with a difference of <5% between contractions was required. A further MVC was conducted within 30s of the exercise protocol. Subjects performed two exercise protocols, each separate by 30min. The protocols utilised two different loads: 20 or 40% MVC, with two different blood flow occlusion pressures at ~160mmHg or ~300mmHg. An 80% MVC protocol was also performed. In total, 8 exercise protocols were performed (Fig. 17). Fatigue was defined as a decrease in % of MVC.

		Protocol		
	% MVC	Pressure Duration	Pressure Intensity	Repetitions
HL	80	—	—	33 ± 10*
$20\%_{IntPar}$	20	Intermittent	Partial	194 ± 100
$20\%_{IntCom}$	20	Intermittent	Complete	143 ± 75
$20\%_{ConPar}$	20	Continuous	Partial	182 ± 153
$20\%_{ConCom}$	20	Continuous	Complete	140 ± 102
$40\%_{IntPar}$	40	Intermittent	Partial	90 ± 47†
$40\%_{IntCom}$	40	Intermittent	Complete	84 ± 37†
$40\%_{ConPar}$	40	Continuous	Partial	83 ± 32†
$40\%_{ConCom}$	40	Continuous	Complete	73 ± 53†

Data are displayed as means ± SD.
HL, high-load exercise; MVC, maximal voluntary contraction; int, intermittent; con, continuous; par, partial; com, complete.
* Significant difference from all occlusion protocols ($P < 0.05$); † significant difference from all occlusion protocols at 20% MVC ($P < 0.05$).

Fig. 17 The eight experimental protocols used. Data displayed as mean and SD. Reproduced from Cook *et al.* [13]

Mean force output for the MVC's was 609.3N ± 170.8N, mean force output for 20% load was 161.1N ± 50.4N while for 40% load mean force output was 304.2N ± 85.0N. A higher number of repetitions were performed in both 20 and 40% load protocols compared with the 80% load. No significant difference in the number of repetitions performed between low load protocols was observed. The lowest fatigue value was observed in the high load protocol (~19 ± 12%) and in two 20% MVC protocols (33 ± 18% and 32 ± 12% respectively). Only one low intensity protocol ($20\%_{ConPar}$) demonstrated a significant difference in fatigue compared with the high intensity load (Fig. 18)

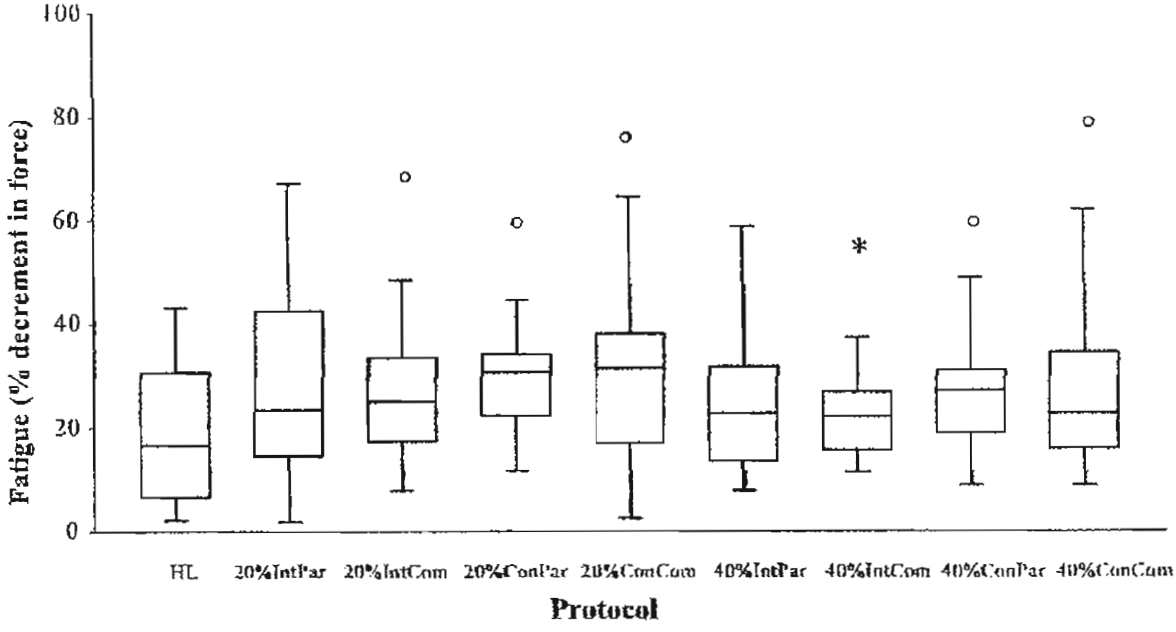

Fig. 18 Box-plot of force decrement for each protocol. Reproduced from Cook *et al.* [13]

The results of this study indicate that each low intensity exercise protocol with blood flow restriction is as fatiguing as high load exercise. High load exercise here led to a 19% force reduction, but low load protocols led to decreases in strength of 24-33%. The reductions in blood flow alone resulted in muscle fatigue and a rise in serum growth hormone, whereas low intensity exercise and blood flow restriction resulted in both muscle fatigue and significantly elevated serum GH. This indicates that the reduction in blood flow alone is a stimulator of GH, an effect which is accentuated with exercise. Reduced blood flow is also a key determinant of fatigue in this study.

2.4 Tension Time Index (TT_{di})

The TT_{di} is a product of normalised force and the duty cycle. A TT_{di} of 0.15 and above has been shown to produce fatigue in a contracting muscle (5). The duty cycle is the ratio of the contraction time to total duration of contraction-relaxation cycle. It is represented as a decimal point ranging from 0.1 – 1.0. Of key interest to this project is the effect that the duty cycle has upon blood flow and how it may influence the onset of fatigue. A low duty cycle of 0.2 for example may represent a contraction-relaxation period of 2s contraction, 8s relaxation. Therefore, a greater proportion of the contraction-relaxation cycle occurs during the relaxation phase facilitating blood flow. The duty cycle can be used as an independent determinant of blood flow to the muscle and a variety of inter-muscular, duty cycle relationships have been reported. This article will now refer to some of these and in doing so will bring us toward the specific hypothesis of this research project.

Bellemare *et al.* (1983) measured diaphragmatic blood flow in dogs using both intermittent and continuous contractions. In presenting their hypothesis, the authors claim that diaphragmatic fatigue occurs in humans similar to other muscles partly as a result of reduced blood flow. The results of this study indicate that diaphragmatic blood flow always increased during intermittent contractions, but that the primary determinant of blood flow increase during their study was the tension time index (Fig. 19)

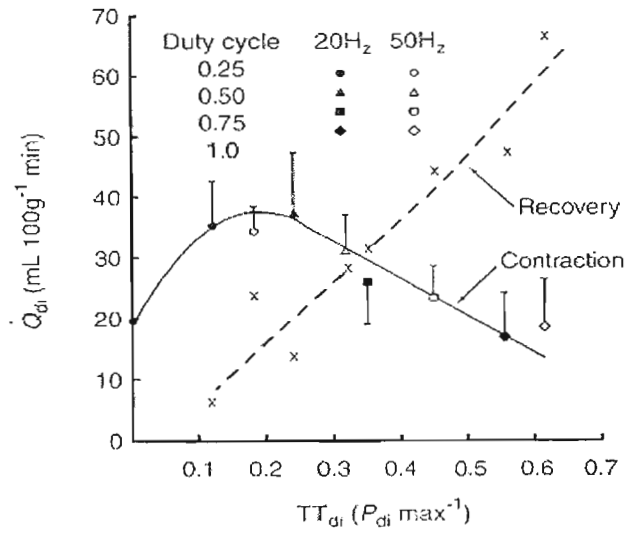

Fig. 19 Relationship between final diaphragm blood flow during contraction period (solid line), debt measured following relaxation (dashed line). Reproduced from Bellemare *et al.*

Bellemare *et al.* demonstrate that blood flow is determined by the length of the relaxation phase of a contraction cycle. Up to a TT_{di} of 0.2, blood flow is maximal from which a linear decline in blood flow to contracting muscle occurs (Fig. 19). At a TT_{di} 0.75 and above, blood flow is completely occluded. Also, the duty cycle beyond which any increase in diaphragmatic blood flow is prevented (critical duty cycle) is determined by the amount of blood flow entering the diaphragm during contraction. This in turn, is a function of the intra-muscular pressure developed. In the dog diaphragm, the authors claim that a critical duty cycle is reached in the dog diaphragm at a TT_{di} of 0.2.

The findings here indicate that if a critical duty cycle is not reached i.e. a contraction-relaxation series which does not prevent muscle blood flow, fatigue should not ensue due to adequate blood supply. But where a critical duty cycle is reached, blood flow is occluded and only an increase in the relaxation period can facilitate blood flow. Low tension time indexes therefore should not lead to fatigue during continuous contractions due to the long relaxation phase characterising these periods of contraction. However if a 30% MVC is used with a low tension time index, a critical duty cycle may be reached which prevents further muscle blood flow due to intra-muscular pressure. This can occur at a low duty-cycle.

2.4 Near-infrared Spectroscopy (NIRS)

A summary of studies using NIRS is provided by Ferrari *et al.* (1997). NIRS is a non-invasive tool which is used to measure oxygen consumption in skeletal muscle. Oxidative metabolism is the primary mechanism by which muscles achieve energy transfer. Due to the increasing technicality associated with research methods and clinical trials, many of which use multiple invasive techniques, the advent of technology that can measure oxidative metabolism in muscle (and other tissues) that has high interclass reproducibility and reliability is desirable. NIRS is a valid and ubiquitously used technique, providing three measurements of key interest: oxyhaemoglobin (HbO_2), deoxyhaemoglobin (HHb) and the tissue oxygen index i.e. the ratio of HbO_2 over Hb_{TOT}. The aim of the present study is to demonstrate changes in tissue oxygenation for a series of duty cycles held under 30% MVC. It is hypothesised that higher duty cycles which will occlude blood flow to the trapezius at this intensity will display an increased tissue deoxygenation and subsequent hyperaemic response compared with low duty cycles, where the longer relaxation will facilitate blood flow and ensure a greater tissue oxygenation during contractions.

A study by Ahmadi *et al.* (2008) demonstrated the applicability of NIRS technology in a study hypothesising that prolonged downhill walking would induce eccentric quadriceps muscle damage and alter muscle O_2 oxygenation in the following 1-5 days. The authors postulated that eccentric muscle damage may have at least two primary effects, each of which would increase local O_2 consumption: 1) that eccentric muscle damage may lead to a selective recruitment of slow oxidative muscle fibres, due to damage caused to fast glycolytic fibres during downhill walking 2) that eccentric muscle damage would increase local O_2 consumption to accelerate the repair process. The hypothesis was tested in a protocol using nine healthy males (aged 27 ± 4.7 year; body mass 70.7 kg ± 14.8kg) who were un-involved in resistance training for the previous six months. Each subject walked downhill for 40min on a gradient of -25%, with a 5% relative body weight load on their back. Average velocity for the protocol was 6.4km.hr^{-1}. Muscle oxygen saturation (O_2Sat), oxyhaemoglobin (HbO_2), deoxyhaemoglobin (HHb) and total haemoglobin (THb) were measured at rest with NIRS prior to experimentation, and for four days post-experimentation.

The results of the study indicate that muscle blood flow (ml.min^{-1}.100g) was significantly higher in day 1 of post-experimentation than in measurements taken prior to downhill walking. Similarly, mVO_2 was significantly elevated for two days post-experimentation compared with baseline measurements. The data is displayed in figure 20 (panel c and d).

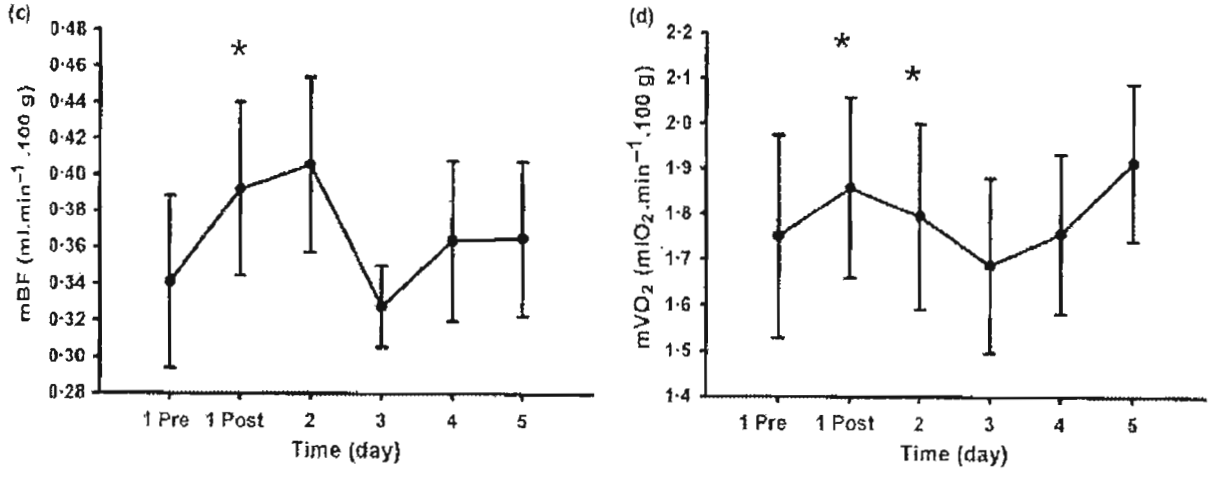

Fig. 20 Muscle blood flow and muscle oxygen consumption before and after downhill walking. Reproduced from Ahmadi *et al.* [1]

The results of this experimentation are in agreement with other studies that have demonstrated muscle damage following eccentric exercise. The increase in muscle blood flow in day 1 post experimentation may be due to an inflammatory response, a result of local muscle damage. Similarly, mVO_2 was significantly greater for two days following experimentation when compared to baseline recording. This suggests that downhill walking and isometric contractions may have acted as a stimulus to increase quadriceps oxygen consumption. Factors such as increased recruitment of slow oxidative fibres over fast glycolytic fibres, and alterations in mVO_2 due to essential repair of the muscle may all be contributory factors to this augmented mVO_2.

In a second experiment, arterial occlusion using a cuff pressure of 270mmHg was implemented to demonstrate the minimum and maximum local values of O_2 saturation, the time course of O_2 saturation changes (labelled as O_2 kinetics by the authors) and to calculate muscle VO_2 (mVO_2). The lowest point of oxygen de-saturation was achieved after 5-8min of arterial occlusion, held for 30s and then released. The reactive hyperaemic response was used to estimate mVO_2. Muscle oxygenation was also measured during 3 MVC's, and for 30%, 50% and 80% MVC respectively held isometrically for 20s, these contractions were performed on both legs and every day (Fig. 21)

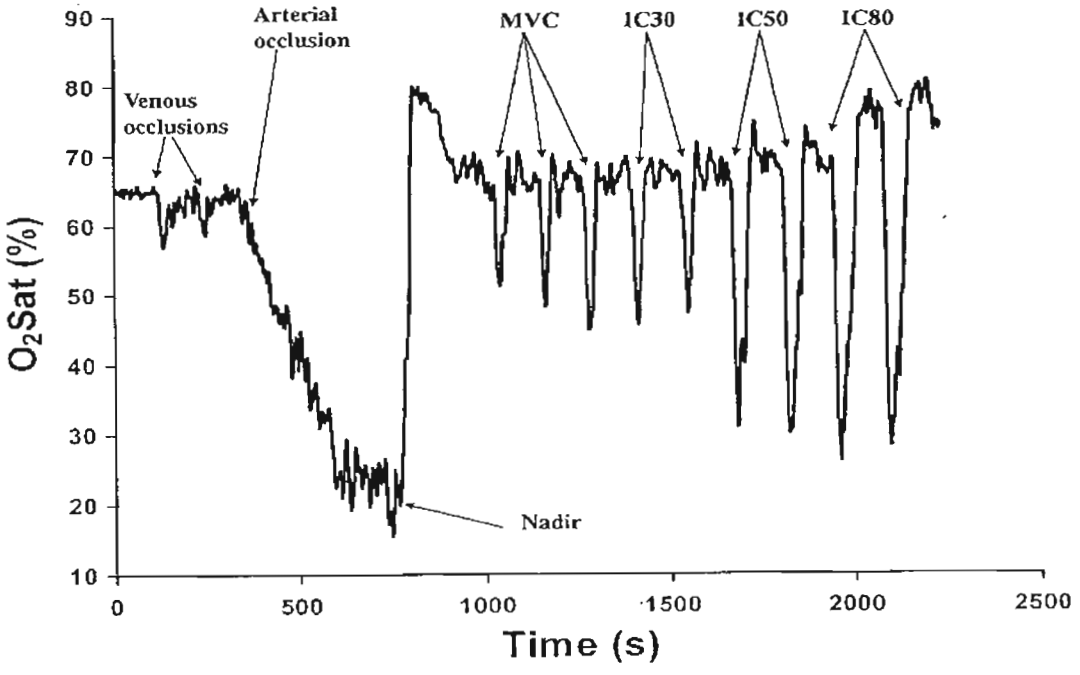

Fig. 21 Sample of NIRS data taken during both arterial and venous occlusion, and MVC contractions. Reproduced from Ahmadi *et al.*

Studies to date using NIRS technology have investigated quadriceps oxygenation during constant and incremental bike exercise, the effect of hypoxia on muscle oxygenation in the arms, and also the muscle oxygenation in rhythmically contracting forearm. The effect of vascular occlusion on muscle oxygen saturation and de-saturation has been demonstrated with NIRS (Fig. 22).

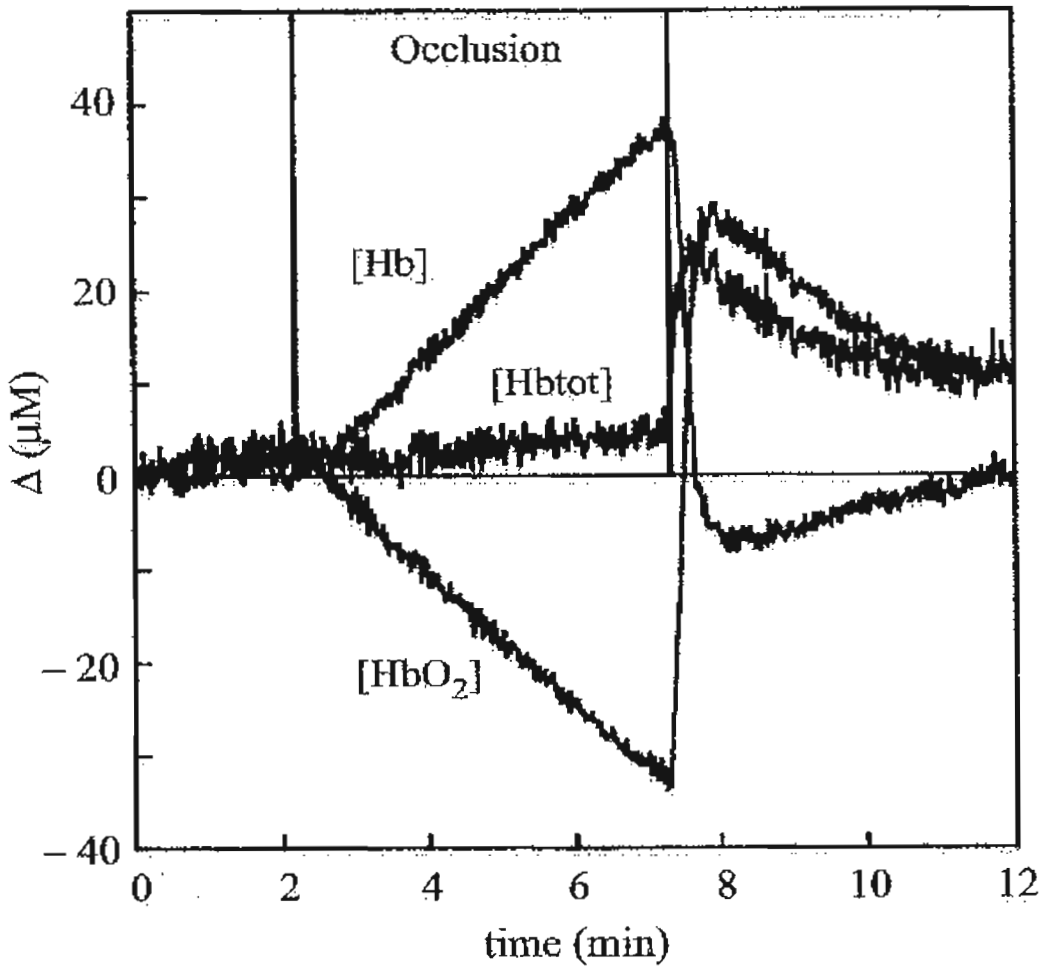

Fig. 22 NIRS data during control (0-2min) and during occlusion. Measures include oxyhaemoglobin (HbO_2), deoxyhaemoglobin (Hb), and total haemoglobin (Hb_{TOT}). Reproduced from Ferrari *et al.* [23]

If after two minutes of baseline haemoglobin measurements, vascular occlusion is applied to a resting muscle, an increase in deoxyhaemoglobin coupled with a decrease in oxyheamoglobin and moderate changes in the tissue oxygen index will occur. Following occlusion, the data also display the recovery period and changes in Hb and HbO_2. One experiment by Ferrari *et al.* demonstrated the effect of arterial occlusion on muscle oxygenation; the data are demonstrated in figure 21.

In the present experiment, a decrease in oxyhaemoglobin with the corresponding increase in deoxyhaemoglobin will occur during sustained sub-maximal isometric contractions. This occurs due to mechanical compression of arterioles supplying blood to the muscle, and indicates O_2 utilisation is a contributory factor in sustaining muscle contraction at sub-maximal loads. The reactive hyperaemic response to tissue oxygenation which is proportionate to contraction intensity, will also reflect O_2 utilisation, and shall be obtained via NIRS during relaxation periods.

Three measures of oxidative metabolism will be collected with NIRS, namely oxyhaemoglobin (HbO_2), deoxyhaemoglobin (HHb) and tissue oxygen index (TOI). Haemoglobin binds to O_2 to form HbO_2 in a reversible reaction. When Hb and O_2 are not combined, haemoglobin is said to be reduced, known as deoxyhaemoglobin (HHb). Heamoglobin is found in erythrocytes (red blood cells or RBC's) and contains two parts: a globin portion which is a protein made of four polypeptide chains, and four iron non-protein components known as heme groups, each of which binds one molecule of O_2. Four O_2 molecules can bind to one haemoglobin molecule, due to the poor solubility of O_2 in blood 98.5% of haemoglobin is carried bound to haemoglobin. Haemoglobin unloads O_2 at tissue level, as the PO_2 of blood entering systemic capillaries is higher than that or the tissues surrounded by those capillaries. O_2 diffuses from the RBC into the local tissue where it allows for energy transfer and in this experiment, for muscular contractions to continue. The reversibility of HbO_2 occurs here as oxygen is unloaded from haemoglobin and the percentage of unbound haemoglobin i.e. deoxyhaemoglobin rises. One factor that contributes to deoxyhaemoglobin is the increase in CO_2 production, as a by-product of cellular metabolism. The rise in local CO_2 shifts the O_2-Hb curve to the right (Fig. 20).

CHAPTER III

METHODOLOGY

3.1 Introduction

The methodological considerations governing equipment, subject choice, experimental conditions and protocol, and the analysis of data are now described. The aim of this project was to demonstrate muscle fatigue during sub-maximal contractions with the aid of two key techniques: electromyography (EMG) and near-infrared spectroscopy (NIRS). A repeated- measures ANOVA demonstrated significant differences in electromyography and muscle oxygenation across the four experimental conditions. These differences in muscle oxygenation correlated with the electrophysiological properties of the working muscles, measured with EMG. The power spectrum of data acquired using EMG was used to demonstrate an early increase in signal amplitude and in conjunction with a decline in median frequency of motor unit action potentials. Near-infrared spectroscopy provided measures of oxyhaemoglobin, deoxyhaemoglobin as well as a measure of the tissue oxygen index. The combination of EMG and NIRS data enabled this project to demonstrate muscle fatigue during sub-maximal isometric contractions and its relationship to tissue O_2 content. In other words, this project correlated electrophysiological properties with the blood flow response to isometric contractions in the trapezius.

3.2 Subjects

The subject choice for this project consisted of male and female students or professionals whose work involved repetitive movements, or constant load muscle contractions throughout their day. Repetitive movement include continuous repetitive elevation of the trapezius e.g. hotel porters carrying luggage, personal trainers that carry loads repetitively, builders or manual labourers carrying materials in their hands, and students carrying heavy loads on their backs where the trapezius is depressed. Horizontal flexion of the shoulder joint is among one of the most common movements performed on a daily basis in both manual and clerical labour. Computer typing with arms stretched out whilst typing, cashiers scanning items during sales transactions are examples of this movement. Trapezius activation and fatigue has been demonstrated during horizontal shoulder flexion, indicating the importance of this manoeuvre in the aetiology of trapezius fatigue (39, 45).

Subjects were free of any musculo-skeletal disorder or injury of their trapezius. Subjects older than 35yrs. did not take part due to the possible stress associated with performing MVC of the trapezius prior to experimentation protocol, and following repeated experimental conditions. Healthy males and females aged 20 – 30yrs, who were in good health, and involved in professions where their trapezius muscle were activated daily participated in the study. Subjects were moderately active 3-4 times per week.

This experiment was a descriptive study, with the aim of demonstrating muscle fatigue during sub-maximal isometric contractions. A specific effect size e.g. specific decrease in median frequency of motor unit action potentials during contractions, or a definitive decrease in tissue oxygen index is not the object of this study. The number of subjects in this study was between 8-10 in total, in agreement with previous studies (6, 22 and 37). Prior to subjects participating in the study, each subject gave voluntary informed consent. This implies that following explanation of all procedures including preparation for, and participation in the experiment, all subjects voluntarily agreed to participate verbally and with their signature. All protocol procedures and risks associated with testing were clearly outlined in the informed consent document. Prior to signing, each subject was assured that the highest ethical standards would be applied during their particular experimental involvement. This project was approved by the ethics committee of the Kinanthropologie Department at the University of Quebec, Montréal.

3.3 Independent Variables

The one independent variable in this experiment was the duty cycle. The contraction percentage chosen for each experimental condition was 30% MVC, and acted as a control variable by staying constant. The relative load for experimentation protocol was 30% MVC, this has been demonstrated to induce vascular occlusion into the muscle after which reactive hyperaemia occurs (25, 58). This load ensures that the contracting muscle works in the absence of oxygen, ensuring oxygen de-saturation. This load is also a relatively comfortable load at which isometric contractions can be tolerated, but also sufficient to induce muscle fatigue after a relatively short period of time.

The duty cycle serves as the independent variable. The duty cycle is a ratio of contraction time to total contraction-relaxation time. It is represented as a decimal point from 0.1 – 1.0 Four experimental conditions were implemented, with duty cycles of 0.8 (16s contraction, 4s

relaxation), 0.6 (12s contraction, 8s relaxation), 0.4 (8s contraction, 12s relaxation), and 0.2 (4s contraction, 16s relaxation). The higher duty cycles ensured a longer contraction period relative to relaxation time, and therefore a limited hyperaemic response. Low duty cycles are characterised by shorter contraction periods relative to relaxation time, thereby allowing for increased hyperaemia following contractions.

The experimental scheme was a repeated measures design, where a constant load of 30% MVC was maintained and duty cycle changed. Experimental conditions were randomly assigned per subject to ensure minimal unsystematic variation entering the trials. Each contraction period lasted three minutes and was followed by a five minute rest period. This ensured that EMG and NIRS parameters returned to baseline levels between conditions.

3.4 Dependent Variables

The dependent variables in this experiment are those associated with data collection via EMG and NIRS: amplitude and median frequency of the EMG power spectrum, and tissue oxygen saturation and de-saturation. EMG amplitude is defined as "*the quantity which expresses the level of signal activity*". The median frequency is defined as that frequency that divides the power density spectrum in two regions having the same amount of power (4). NIRS measures including HbO_2, HHb and Hb_{TOT} are measured in conjunction with EMG measures. Correlation and regression analysis will demonstrate the relationship between the electrophysiological properties associated muscle contraction and the saturation/desaturation of the contracting muscle.

3.5 Experimental Set-up and Procedures

Prior to participation in the experiment, all subjects entered the laboratory and gave their verbal and written voluntary informed consent. Once consent was given, subjects underwent skin preparation for electrode placement.

The upper trapezius was located in each subject through a combination of voluntary trapezius contraction which exposed the muscle belly, and verified as the mid-point between the seventh cervical vertebrae (C7) and the acromion point of the shoulder (45). Once located, any surface hair was gently removed with Gillette Mach 3 razor to improve electrode adhesion and to reduce signal impedance (4). The skin was carefully prepared by rubbing abrasive gel until the skin was a faint red colour, indicating good preparation and reduced impedance condition. A cotton towel dabbed

in 70-30% ethanol-water solution as recommended by DeLuca and Basmaijan (3) was used to cleanse the surface conducting area, and remove and dead skin cells or flakiness associated with skin preparation. Following skin preparation, one bipolar Delsys electrode (model DE-.21 Single Differential Detection) was applied to the trapezius. The electrode is rectangular (dimensions 41*20*5mm), with silver-silver chloride bars oriented parallel and 1cm apart.

The input impedance-capacitance of this electrode is > $10^{15}\Omega$//O.2pF, where the signal is pre-amplified prior to being sent to the EMG recording unit. This reduces impedance at the electrode-skin detection site (16). The Delsys electrode is shown in figure 23.

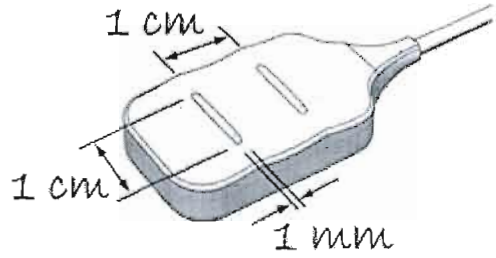

Fig. 23 Delsys bi-polar electrode. Reproduced from www.delsys.com

A rectangular reference electrode was placed on the tibia. Bipolar electrodes have the advantage of detecting electrical muscle signals at two points, amplifying the difference between signals detected at these points with respect to the ground electrode, thereby amplifying the electrical muscle signal obtained while rejecting the noise component associated with the signal acquisition at both points. The resulting amplified signal was a differential EMG signal, where noise had been corrected. The electrode was connected on one channel to an A-D converter where digital sampling of the analogue voltage signal was converted to a digital signal. The A-D had a 12 bit binary card which was a measure of signal sensitivity, it allowed for ideal signal recording (+/-5V) while attenuating noise. The 12 bit binary card is capable of separating the voltage range from the recorded signal into 4096 intervals. The signal obtained here was band pass filtered with the high pass filter (Butterworth 2nd Order Filter) component set at 6Hz, and low pass at 500Hz. Digital sampling of the recorded signal was set at 1 KHz.

Once electrodes were in place, a baseline EMG signal was taken for 8s where signal bias was visualised, its value recorded and subsequently removed. Signal bias following good skin

preparation should be in the order of a 10-15 micro-volts (μV). The EMG signal obtained during baseline and for the experimental procedures was rectified, removing negative values recorded during baseline. All negative spikes were removed and transformed into positive spikes; from here it was possible to record maximal EMG values. The baseline signal was recorded in milli-volts (mV). All data collected during experimentation was transformed via Fast Fourier Transform in windows of 2048ms.

NIRS (Hamamatsu NIRO-200) was used to measure tissue oxygen index during experimentation. A fibre optic probe (model C9343) was placed on the trapezius and secured with adhesive tape. The probe is calibrated (model A9344 calibrator) and Tissue Oxygen Index (TOI %), oxyhaemoglobin change (ΔO_2Hb) and deoxyhaemoglobin change (ΔO_2HHb) recorded in micromoles per litre ($\mu mol.L^{-1}$). Data was collected at 2Hz and recorded for the duration of muscle contractions.

Once EMG and NIRS were set up, experimentation took place. Subjects stood on a 20*20inch square wooden platform, attached with hand grip and force dynamometer (Shimpo FGV 500HX). The Shimpo was calibrated, being set at zero and ready to record MVC in kg. Subjects stood for 5min during which baseline EMG and TOI values were taken. Once baseline measures were recorded, subjects stood on the force plate with hand grip resting by their side, were asked to perform three maximal voluntary contractions (MVC) of the trapezius without movement of the hips or biceps. The highest MVC value was recorded and used to set the 30% relative load for each condition. The maximal EMG voltage value for the MVC was obtained and recorded coupled with force output in the Shimpo. From the force output on the Shimpo, the relative load of 30% MVC was set for each subject. Each subject worked at 30% MVC (expressed in kg); the visual display terminal (VDT) on which all data is recorded provided visual feedback from which subjects can adjust their force output to 30% MVC. Each subject was given a short 4-5min trial during which they became accustomed to controlling their contractions at the required load. Subjects performed isometric contractions for 3min for each of the following duty cycles. The order of duty cycles is randomised for each subject to eliminate practice or boredom effects. Simple randomisation is used, where each subject chooses the order of duty cycle from a hat held by an independent laboratory assistant.

i. 0.8 16s contraction, 4s relaxation
ii. 0.6 12s contraction, 8s relaxation
iii. 0.4 8s contraction, 12s relaxation
iv. 0.2 4s contraction, 16s relaxation

Each contraction set lasted a total of 3min, meaning that each subject performed nine contractions per condition. Each 3min contraction period and was separated by 5min to allow for all measures to return to baseline value. Force output, EMG amplitude and median frequency, and tissue oxygen index measures were recorded during experimentation. Total experimentation lasted approx. 80-90min.

3.6 Quantification and Analysis

Baseline measurements of resting EMG voltage and resting tissue oxygen index were recorded. Maximal EMG voltage, force output (kg) and tissue oxygen index were recorded subsequently. These measures provided the ability to set the relative load of 30% MVC per subject during experimentation. A one way repeated measures ANOVA was performed to demonstrate significant changes in EMG measures for minute one v minute 3 per condition. Linear regression was performed to determine the relationship between TOI and EMG measures, and also between subjective perceptions of effort (Borg CR10 scale) and EMG median frequency.

THE MANUSCRIPT

THE EFFECT OF TENSION AND TIMING ON OXYGEN SATURATION IN THE TRAPEZIUS MUSCLE

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ABSTRACT

Introduction

The purpose of the present study was to demonstrate muscle fatigue in the trapezius using low intensity loads, and to correlate muscle fatigue with oxygen saturation in the muscle. Electromyographical signals were obtained from three male and four female subjects, where trapezius elevations were performed at 25-35% MVC (relative load). Near-infrared spectroscopy was used to obtain values of oxyhaemoglobin, deoxyhaemoglobin and tissue oxygen index during contractions. Force dynamometry determined absolute and relative loads for the protocol. Four experimental conditions were used where the absolute time of contraction-relaxation was varied while force output remained constant (TT_{di} 0.06, 0.12, 0.18 and 0.24).

Results

Force was maintained at 25-35% for all conditions by all subjects, and average median frequency decreased significantly in minute three in TT_{di} 0.24 v TT_{di} 0.18 and in TT_{di} 0.12 v TT_{di} 0.06 $p < 0.05$. Mean signal power increased significantly in minute one for TT_{di} 0.24 v 0.18 and in minute three in TT_{di} 0.18 v TT_{di} 0.12 $p < 0.05$. Regression analysis demonstrated a strong relationship between tissue oxygen index (TOI) and EMG median frequency ($r^2 = 0.58$). The subjective perception of effort did not correlate well with physiological fatigue as demonstrated by a decrease in median frequency and increase in mean signal power. Subjects rated each condition between weak and moderate but not above.

Conclusion

Muscle fatigue in the trapezius does occur at low intensity where the muscle contraction is sustained, and this fatigue can be demonstrated (electro)-physiologically with EMG signals. A strong relationship exists between the tissue oxygen index and median frequency of motor unit action potentials of the muscle performing low intensity fatiguing contractions. Subjective perceptions of effort do not correlate well with physiological fatigue and is in agreement with other studies that have demonstrated same.

Key words: tension time index (TT_{di}), tissue oxygen index (TOI), EMG median frequency (MF), muscle fatigue

Introduction

Skeletal muscle fatigue remains a hot topic of research, due to the fact that no clear mechanism has been proposed. Skeletal muscle fatigue is experienced regularly during activities which require maximal or sub-maximal efforts. Low intensity loads can induce muscle fatigue (2, 14, 17, & 23). A muscle may be described as fatigued where either 1) a loss of force or 2) an increased half-time to relaxation are observed (9, 15).

Metabolic factors including lactic acid and inorganic phosphate have been implicated in muscle fatigue (3, 8, 9, 16, 18 & 21) yet neither mechanism can account fully for why muscle fatigue occurs. Muscles that work an-aerobically during maximal or sub-maximal efforts produce lactic acid which may increase the half-time to muscle relaxation (15). Two problems associated with the lactic acid hypothesis on muscle fatigue are that lactic acid, while increasing intracellular acidity, is transported to adjacent muscles or the liver where gluconeogenesis occurs (15, 18). Lactic acid in these cases may therefore provide a muscle-performance sustaining function. Secondly, patients that suffer McArdle syndrome lacking the enzyme myophosphorlyase are unable to breakdown muscle glycogen as occurs during resistance training. In the absence of an-aerobic metabolism in these subjects, they still suffer severe exercise limitations in the absence of lactic acid (15, 18). Inorganic phosphate (P_i) has a demonstrated negative effect on force production, which indicates a negative effect of P_i on actomyosin cross-bridge cycling. Inorganic phosphate may also have an effect on Ca^{2+} sensitivity within myofibrils, where an accumulation of P_i causes a rightward shift in the force-Ca^{2+} relationship (8, 9 & 15). The result is a greater quantity of Ca^{2+} needed to achieve 50% muscle activation. However, P_i alone does not fully explain muscle fatigue.

Muscle fatigue has been successfully demonstrated with electromyography (6, 7, 10, 11, 12, 17 & 24). A decline in median frequency of motor unit action potential conductance and/or an increase in the mean power of the signal emanating from the electrode are valid indicators of fatigue (6, 7 & 24). Skeletal muscle blood flow is a vital component of its ability to transfer energy via aerobic metabolism. Where skeletal muscle blood flow is occluded, oxyhaemoglobin (HbO_2) decreases and in increase in deoxyhaemoglobin (HHb) occurs. Where HHb rises in a muscle with a concomitant decrease in HbO_2, muscle fatigue occurs. Near-infrared spectroscopy (NIRS) has been successfully used to provide valid measurements of HbO_2, HHb and the tissue oxygen index (TOI).

The duty cycle is the ratio of contraction time to total duration of contraction-relaxation cycle in

skeletal muscle, it is expressed as a decimal point between 0.1 – 1.0. The duty cycle *in tandem* with normalised force characterising a contracting muscle produces a tension time index (TT_{di}), a concept developed to study the effect of resisted inspiratory work on diaphragmatic fatigue (5, 20). In the diaphragm, a tension time index of 0.15 produced fatigue after an indefinite period. The tension time index was used in the present study as a model for which four experimental conditions were introduced. The experimental conditions were: 1) TT_{di} 0.06 (30% MVC * 0.2 Duty Cycle); 2) TT_{di} 0.12 (30% MVC * 0.4 Duty Cycle); 3) TT_{di} 0.18 (30% MVC * 0.06); TT_{di} 0.24 (30% MVC * 0.8 Duty Cycle). It was hypothesised that a tension time in TT_{di} index of 0.24 would produce muscle fatigue, while lower tension time indices 0.06, 0.12 would not produce muscle fatigue. It was questionable whether or not a TT_{di} of 0.18 would produce fatigue.

Trapezius muscle fatigue has not been well documented in scientific literature. Many studies use large (quadriceps or biceps) or very small (adductor pollicis) in fatigue studies. The trapezius muscle is activated during movements where trapezius elevation or depression occur e.g. typing (17). Anecdotally, the trapezius muscle is often a source of discomfort or "*stress*" and for this reason warrants investigation. This project attempted to demonstrate muscle fatigue in the trapezius while using low intensity contractions which frequently characterise its activation. This project hypothesised that muscle fatigue could be demonstrated with 30% MVC controlling variable where different duty cycles of contraction were used. Electromyography was used in this study to demonstrate muscle fatigue, while the utilisation of NIRS was used to provide measures of oxyhaemoglobin, deoxyhaemoglobin and the tissue oxygen index. Data from NIRS was collected in an attempt to correlate it to electromyographic data, to determine whether or not oxygen de-saturation is implicated in muscle fatigue. Finally, a Borg Scale (CR10) was used to obtain psychophysiological perceptions of effort at the end of each condition.

Methodology

Subjects

A total of 11 subjects participated in the experimental protocol. However data for 7 subjects is presented due to poor signal to noise ratio in the EMG signal which presented in the case of 4 subjects. In the case of our regression analysis, data is presented from 6 subjects. Numerous efforts were made to elicit a clean EMG signal but noise presented consistently in each case. In relation to omitted NIRS data, every effort was made to obtain tissue oxygen index but poor signal quality presented in four subjects. Anthropometric data for seven subjects (3 males, 4 females) are presented in table 1.

Inclusion factors for participation included those whose work involved lifting light to heavy loads with the upper limbs, and were randomly selected to participate in the study. Most subjects were personal trainers whose job included repetitive horizontal shoulder flexion and trapezius depression and elevation during their daily work. All subjects were physically active 3-4 times per week and free of musculo-skeletal disorders. Subjects aged 35yrs and older were excluded from experimentation due to associated stress of performing three maximal voluntary contractions of the trapezius.

Materials and Data Collection

Electromyographic signals were recorded with a single rectangular (dimensions 41*20*5mm) Delsys bi-polar electrode (model DE-.21 Single Differential Detection) on the trapezius located at the mid-point between the seventh cervical vertebrae (C7) and the acromion point of the shoulder. The signal was captured between silver-silver chloride parallel oriented bars 1cm apart. A rectangular reference electrode was placed on the tibia. The electrode was connected on one channel to an A-D converter where digital sampling of the analogue voltage signal was converted to a digital signal. The A-D converter consisted of a 12 bit binary card which is a measure of signal sensitivity, allowing for ideal signal recording (+/- 5V) while attenuating noise. The 12 bit binary card is capable of separating the voltage range from the recorded signal into 4096 intervals. The signal obtained was band pass filtered with low pass filter (Butterworth 2^{nd} Order Filter) component set at 6Hz, and high pass at 500Hz. Digital sampling of the recorded signal is set at 1000Hz. Data collected was translated into a power density spectrum via Fast Fourier Transformation, in windows of 2048ms. Data is expressed as median frequency (Hz) and mean

signal power (μV). Oxygen saturation data for the trapezius was collected via near-infrared spectroscopy (Hamamatsu NIRO-200) with a fibre optic probe (model C9343). The probe was calibrated prior to data collection (model A9344 calibrator). Oxyhaemoglobin (HbO_2), deoxyhaemoglobin (HHb) and tissue oxygen index (TOI) values were recorded ($\mu mol.L^{-1}$). The path-length chosen for collection of NIRS data was 10mm. Force output was measured with force dynamometry (Shimpo FGV 500HX), and used to determine maximal trapezius elevation force per subject, and to adjust the relative load per subject to 30% MVC. Force output was recorded in kilograms.

Experimental Protocol

Subjects arrived to the laboratory in the morning (10:00). All subjects were given written and verbal assurances of the benefits and risks associated with participation in the study, and signed voluntary informed consent.

Subjects performed three maximal voluntary contractions each separated by 5min where maximal force output (kg) was recorded. The maximal value was recorded in kilograms and was the reference point from which a 30% MVC load could be determined for each subject. Subjects participated in four randomly assigned conditions where TT_{di} was varied. Each duty cycle totalled 20s. Force was set to 30% MVC per condition, and was displayed on a visual display terminal where subjects could visualise their force output and maintain at 30%. Due to the difficulty of voluntarily activating force output at precisely 30%, subjects were given the flexibility to maintain force within a 25-35% MVC range. Each condition consisted of 3min contraction according to the following experimental conditions:

i. Duty Cycle 0.2 (4s contraction, 16s relaxation)
ii. Duty Cycle 0.4 (8s contraction, 12s relaxation)
iii. Duty Cycle 0.6 (12s contraction 8s relaxation)
iv. Duty Cycle 0.8 (16s contraction, 4s relaxation)

Subjects performed nine contraction-relaxation cycles totalling 3min, where force was maintained at 30% MVC throughout. Following each 3min condition, subjects rested for 5min within which

time EMG and NIRS values returned to resting values. The duty cycles used across conditions correspond with tension time indices of 0.06, 0.12, 0.18 and 0.24 respectively.

Trapezius elevation with handheld grip elevation was performed to activate the trapezius. Subjects stood on a 2 * 2 foot wooden platform where a stainless steel chain consisting of links 5cm length attached centrally to the Shimpo and handgrip. The handgrip rested laterally on each subject's dominant side, and adjusted to a height where maximal trapezius elevation could be performed i.e. handgrip usually placed just below hip height.

Statistical Analysis

All values are reported as mean ± standard deviation (SD). Differences in median frequency and mean signal power were analysed with repeated measures ANOVA (SPSS version 16.0), post-hoc test was performed with Bonferroni pairwise comparisons. Regression analysis was performed to correlate shifts in EMG centroid frequency with oxygen desaturation in males and females. The BorgCR10 scale was used to obtain subjective perception of effort for each condition, and regression analysis performed to see if these ratings correlated with the EMG data. Values of $p < 0.05$ were established as significant.

Results

Subject Characteristics

The anthropometric data for all subjects is presented in table 1.

Group MVC Force %

Average MVC force for the group was 55.47 ± 24.89kg. For male subjects, average force output was 80.07 ± 15.08kg. For female subjects, average force output was 37.03 ± 5.38kg. Maximum force output was 93.2kg and minimum force output was 29.3kg. All subjects apart from subject two for TT_{di} 0.06 maintained an average force output within 25-35% MVC for each TT_{di}. Repeated measures ANOVA showed no significant differences in MVC% across conditions $F(6, 18) = 0.896$, $p > 0.05$. This data is presented in figure 1. Table 2 displays the MVC values and force output for each condition for all subjects.

Group EMG Centroid Frequency: Min 1 v Min 3

For the first minute of trapezius elevation contractions, average EMG centroid frequency was 74.02 ± 13.31Hz for TT_{di} 0.06, 70.41 ± 16.97Hz for TT_{di} 0.12, 66.63 ± 11.47Hz, and 66.60 ± 16.57Hz. In minute three, average EMG centroid frequency was 72.91 ± 13.36Hz for TT_{di} 0.06, 66.08 ± 13.40Hz for TT_{di} 0.12, 64.11 ± 16.89Hz for TT_{di} 0.18, and 60.09 ± 21.48Hz for TT_{di} 0.24. For minute one, repeated measures ANOVA demonstrated no significant difference in average centroid frequency across conditions, $F\ (3, 15) = 2.269$, $p > 0.05$. For minute three, repeated measures ANOVA demonstrated a significantly lower EMG centroid frequency in TT_{di} 0.24 v TT_{di} 0.18, and also in TT_{di} 0.12 v TT_{di} 0.06 $F\ (3, 15) = 4.483$, $p < 0.05$. This data is displayed in figure 2. Average centroid frequency

Group Mean Power Frequency Min 1 v Min 3

For the first minute of trapezius elevation contractions, mean power frequency was 73.81 ± 61.61μV for TT_{di} 0.06, 61.11 ± 47.85μV for TT_{di} 0.12, 72.87 ± 63.44μV for TT_{di} 0.18 and 105.79 ± 78.13μV for TT_{di} 0.24. Repeated measures ANOVA demonstrated a significant increase in mean power in minute between TT_{di} 0.24 v TT_{di} 0.18, $F\ (3, 15) = 2.600$, $p < 0.05$. For the third minute of contractions, mean power frequency was 99.35 ± 78.77μV for TT_{di} 0.06, 100.38 ± 124.51μV for TT_{di} 0.12, 175.50 ± 217.59μV for TT_{di} 0.18 and 161.14 ± 119.54μV for TT_{di} 0.24. Repeated

measures ANOVA demonstrated a significant increase in mean power for TT_{di} 0.18 v TT_{di} 0.12 but not for other experimental conditions, F (1, 11) = 0.243, $p < 0.05$. This data is presented in figure 3.

Linear regression: tissue oxygen index and EMG centroid frequency

The mean values for tissue oxygen index have been correlated with EMG centroid frequency for all conditions, and presented here for the TTdi 0.24 condition i.e. the condition hypothesised where muscle fatigue would present. Linear regression demonstrated a strong relationship between tissue oxygen index and EMG centroid frequency in male subjects, $r^2 = 0.58$. This correlation was determined to be significant, F (1, 51) = 70.44, $p < 0.05$. This data is presented in figure 4.

Group Subjective Perception of Work: Borg CR10

Subjects rated their perception of effort at the end of each three minute condition using the Borg CR10 scale. A weak correlation between EMG centroid frequency and Borg CR10 values was observed. This data is presented in figure 6. Values ranged from weak to moderate for TT_{di} 0.06 and 0.12 respectively, and only moderate for TT_{di} 0.18 and 0.24. The subjective perception of effort for each subject and condition is presented in table 4.

Discussion

The key findings of this research project are as follows: 1) 30% MVC trapezius contractions were fatiguing after three minutes 2) fatigue as demonstrated by EMG was well correlated to oxygen de-saturation in males and weakly in females 3) subjective perceptions of effort did not correlate well with muscle fatigue.

Muscle Fatigue and EMG

The research hypothesis that muscle fatigue could be demonstrated with shifts in EMG centroid frequency with a low intensity load is supported in the literature (2, 15, 17 & 24). A shift of median frequency to lower frequencies i.e. shift to the left combined with an increase in mean power amplitude are valid indicators of fatigue. A decline in median frequency occurs when the motor unit action potential signal is interfered with and cannot propagate within the muscle. Potential sites of failure include the neuromuscular junction, the surface membrane the t-tubules and also the force generating cross-bridges. Motor unit action potentials are conducted rapidly, crossing the neuromuscular junction and propagating along the surface membrane and down into the t-tubule system. Signal propagation along the surface membrane is essential to ensure synchronous activation of all parts of the muscle, while conduction within the t-tubule system appears to be less rapid due to the shorter distance relative to the muscle cell length. A number of ions are involved in propagation of action potentials and are worth consideration here. Muscle cells need to be polarised for successful action potential conduction, resulting in calcium Ca^{2+} release from the sarcoplasmic reticulum and force generation on the cross-bridges. Ca^{2+} release is essential for exposing actin binding sites for myosin after which force is generated. A popular hypothesis explaining the decrease in median frequency is that potassium ions (K^+) accumulate in the extracellular fluid during sustained muscle contractions (2, 15). Extracellular K^+ accumulation has the effect of depolarising the t-tubule system, thereby reducing muscle excitability and force concomitantly. Figure 2 in our study shows that median frequency decreases significantly in the third minute of sustained contractions. Due to contractions in this study were isometric, the muscle is repeatedly activated which may cause a net efflux of K^+ into the extracellular fluid to the order of $9mmol.L^{-1}$ from values of ~2μM to 10 μM in both slow and fast-twitch muscle per action potential respectively. The effect of such K^+ accumulation causes action potential conduction velocity and force to decline. Depolarisation of the muscle fibre probably leads to slow

inactivation of sodium channels which can block action potential generation or reduce its conduction velocity (6, 7).

Strategies to compensate for a reduction in excitability occur in the higher central nervous system (CNS) centres allowing for the maintenance of force output. The CNS may distribute work performed among a greater number of motor units, thereby reducing the absolute work being done by any one particular motor unit (2). Recruitment of additional motor units explains the increase in mean power as observed in figure 2 in this study. This has in agreement with the literature where sub-maximal loads have been used (2, 3, 6, 7 & 24).

The Relationship between Tissue Oxygen Index and Median Frequency

Our data demonstrates a strong relationship between muscle TOI and median frequency in TT_{di} 0.24, our hypothesis predicted physiological fatigue which would correlate with the tissue oxygen index of the muscle in this condition. Figure 4 (panel D) shows that when TOI is increased, so too is median frequency. However the relationship demonstrated here between a decrease in TOI and a concomitant decrease in median frequency of motor unit action potentials is a strong one (r^2 = 0.58, $p < 0.05$). TOI is relatively unaltered in each of the three other conditions (Panels A-C), none of which were expected to demonstrate muscle fatigue correlating to TOI. The importance of skeletal muscle blood flow has been well documented; it is an essential component of nutrient and oxygen delivery to muscles particularly during exercise. Oxidative metabolism is the primary mechanism through which muscles transfer energy and perform work. Contracting muscles demonstrate an increase in local blood flow in during the relaxation phase, the magnitude of blood flow is proportional to contraction intensity (3). This reflects the metabolic demands within the muscle and is load or time dependant. In this study, the utilisation of four conditions allowed for the absolute time of contraction/relaxation to vary. This had the effect of altering the absolute time under tension which either; 1) facilitated blood flow to the muscle when contraction phase was short and relaxation phase was long, 2) favoured long contractions where blood flow is obstructed and oxygen desaturation occurs. When this occurs, muscle TOI also decreases. The TOI is the ratio of oxyheamoglobin to total haemoglobin in the muscle. Importantly, the 30% MVC relative load is one which has been shown to reduce local blood flow (3, 5, 13, 14, 15 & 18), this is likely due to compression of arterioles.

In males, the mean MVC value was 80.07 ± 15.08kg, and in females was 37.03 ± 5.38kg. The fact that the absolute MVC values in males were higher would mean that any intramuscular pressure for these subjects would be absolutely greater than for females during contractions.

Subjective Perception of Effort: Borg CR10 Scale

The subjective perception of effort was rated at the end of each condition. Ratings were assigned to each condition using the Borg CR10 scale, displayed in figure 7 and all ratings per condition is displayed in table 4 for males and females. For the two conditions hypothesised as non fatiguing (TT_{di} 0.06 and 0.12), the average perception of effort was that either weak to low moderate. For conditions where fatigue occurred (TT_{di} 0.18 and 0.24) the perception of effort was rated as moderate only. This finding is in agreement with the literature where the subjective rating of work does not correlate well with the work performed (17). Figure 6 in our study demonstrates the significant decrease in median frequency correlates poorly with subjective perception of effort. The implication arising from this is that physiological fatigue may occur under conditions where work is sustained under low intensity loads. In a previous study, similar observations were observed in the trapezius where typewriting was sustained for 4 * 25min bouts with 5min rest in between (17). During typewriting, the trapezius is contracted isometrically while the shoulders are in a position of horizontal flexion. In this study, trapezius elevation with low intensity exhibited muscle fatigue after three minutes. Both studies here suggest that the trapezius muscle is sensitive to the onset of muscle fatigue where it is activated at low intensities during sustained work; however the perception of effort involved in trapezius activation is low to moderate. The anecdotal evidence where one feels "stressed" with sensations of pain or discomfort in the trapezius may reflect physiological fatigue occurring in the muscle, albeit undetected in the acute onset.

Muscle Fatigue and Loss of Force

Although there are polar theoretical positions on what constitutes muscle fatigue, there is no doubt that surface electromyography is capable of detecting changes in signal conduction of the motor unit action potential. The characteristics of these signals are time dependant, and may give clues as to the working status of a muscle. It is widely accepted that a decrease in median frequency and an increase in mean power of the EMG signal correspond with the onset of muscle fatigue, despite no

objective loss of force presenting. This study maintained force constant across all experimental conditions. This was central to our hypothesis that low level force outputs are fatiguing after short periods, a phenomenon which is often un-appreciated where muscle performance is concerned. That low intensity contractions are fatiguing is of significance to people performing low intensity, repetitive manoeuvres on a daily basis. Oftentimes humans are not involved in maximal muscular efforts. Manual labour, sports performance and general physical activity engages muscles in low intensity and repetitive muscle actions which in and of themselves can present muscle pain, muscle fatigue and associated discomfort. The EMG signal seeks to detect intracellular changes in motor unit action potential associated with these low intensity contractions. Although no objective decrease in force was observed in our study, the maintenance of a relative 30% MVC by all subjects coinciding with significant changes in the EMG signal is strong evidence of the early onset of muscle fatigue in the muscles that were engaged here.

Conclusion

This study hypothesised that muscle fatigue could be demonstrated with EMG under conditions where low intensity loads were used for three minutes. We also hypothesised that muscle fatigue would correlate with the muscle tissue oxygen index, and would not correlate well with subjective perceptions of effort. In all subjects, median frequency declined significantly after three minutes of contractions. This decrease in median frequency was matched by an increase in mean power of the EMG signal, a strategy indicating an increase in motor unit recruitment to compensate for a reduction in motor unit action potential velocity, which in turn takes place due to reduced excitability of the muscle under low intensity loads. The relationship between tissue oxygen index and median frequency was strong. This observation was expected, and demonstrates the important of blood perfusion to the working muscle. The subjective perception of effort observed here is in agreement with a previous study where muscle fatigue as demonstrated (electro)-physiologically is not considered to be fatiguing on a subjective level. This may have implications for humans performing work at low intensity where signs of mild discomfort or stress are ignored. A further study is needed to determine if the observation made here that there is a relationship between oxygen desaturation and fatigue in males but not in females, and if the relationship is load-dependant.

Table 1

Anthropometric characteristics of subjects

	Males (n = 3)	**Females (n = 4)**	**Group (n = 7)**
Age (year)	24 ± 3.46	26 ± 1.83	25.14 ± 2.61
Weight (kg)	80.76 ± 7.96	66.93 ± 7.11	72.86 ± 10.05
Height (m)	1.80 ± 0.05	1.67 ± 0.06	1.72 ± 0.08
BMI	25.05 ± 2.82	23.98 ± 1.84	24.44 ± 2.16

Data are presented as mean ± SD

Table 2. Group force output measures with handheld trapezius elevation

	Force (Kg)		
TT_{di}	**Males (n = 3)**	**Female (n = 4)**	**Group (Kg)**
0.06	22.28 ± 5.73	8.27 ± 2.52	15.28 ± 4.13
0.12	22.89 ± 4.51	10.20 ± 1.47	16.55 ± 2.99
0.18	21.96 ± 3.93	10.44 ± 1.64	16.20 ± 2.79
0.24	22.37 ± 3.74	10.61 ± 1.87	16.49 ± 2.81
1.00 (MVC)	80.07 ± 15.08	37.08 ± 5.38	58.58 ± 10.23

Data are presented as mean ± SD. MVC, maximal voluntary contraction

Table 3. Group median frequency measures with handheld trapezius elevation

	Median Frequency (Hz)		
TT_{di}	**Males (n = 3)**	**Female (n = 4)**	**Group (n = 7)**
0.06	73.12 ± 10.66	71.49 ± 14.73	72.31 ± 12.70
0.12	70.61 ± 2.29	67.19 ± 16.84	68.90 ± 9.57
0.18	63.17 ± 7.92	65.85 ± 13.05	64.51 ± 10.49
0.24	64.15 ± 20.10	69.42 ± 18.61	66.79 ± 19.31

Data are presented as mean ± SD. Values for average median frequencies are presented in Hertz.
*One subject was unable to maintain the required force output during one contraction in minute two of TT_{di} 0.18, and for none of the contractions in minutes two and three in TT_{di} 0.24

Table 4. Subjective Perception of Effort for each condition: Borg CR10 Scale

Subject	$TT_{di\ 0.06}$	TT_{di} 0.12	TT_{di} 0.18	TT_{di} 0.24
1	2	2	3	4
2	2.5	3	4	5
3	2.5	4	5	3
4	2	4	2	6
5	1	3	4	6
6	2.5	2.5	3	4
7	2.5	3	3	4
Mean ± SD	2.14 ± 0.56	3.07 ± 0.73	3.43 ± 0.98	4.57 ± 1.13

Subjective perception of effort rating was obtained immediately following each 3min condition

LIST OF MANUSCRIPT FIGURE LEGENDS

Figure 1 Average MVC % for each subject and all conditions. No significant differences demonstrated in MVC% between subjects. F (6, 18), = 0.896, $p > 0.05$

Figure 2 Average MF during minute one and minute three. No significant difference in MF across conditions for minute one. Significantly lower MF in minute three for TT_{di} 0.24 v TT_{di} 0.18, and TT_{di} 0.12 v TT_{di} 0.06. F (3, 15) = 4.483, $p < 0.05$

Figure 3 Average EMG mean power frequency during minute one and minute three. Significant increase in mean power in minute one between TT_{di} 0.24 v TT_{di} 0.18 F(3, 15) = 2.600, $p < 0.05$. In minute three, mean power significantly greater in TT_{di} 0.18 v TT_{di} 0.12, F (1, 11) = 0.243, $p < 0.05$

Figure 4 Linear regression analysis demonstrating a strong correlation between tissue oxygen index (TOI) and MF for fatiguing condition TT_{di} 0.24, (**Panel D**) $r^2 = 0.58$, F (1,51) = 70.440, $p < 0.05$, regression coefficients y = 0.7097x + 36.001. No significant correlation demonstrated between TOI and MF in conditions TT_{di} 0.06 (**Panel A,** r^2 = 3E-05, F (1, 52) = 0.001, $p > 0.05$), nor in condition TT_{di} 0.12 (**Panel B**, $r^2 = 0.0034$, F (1, 51) = 0.226, $p > 0.05$) or in condition TT_{di} 0.18 (**Panel C**, $r^2 = 0.0772$, F (1, 52) = 4.348, $p > 0.05$

Figure 5 Linear regression plotting EMG median frequency with values from the Borg CR10 scale, $r^2 = 0.038$, y = -0.0154x + 4.28

Figure 6 Borg CR10

Figure 1

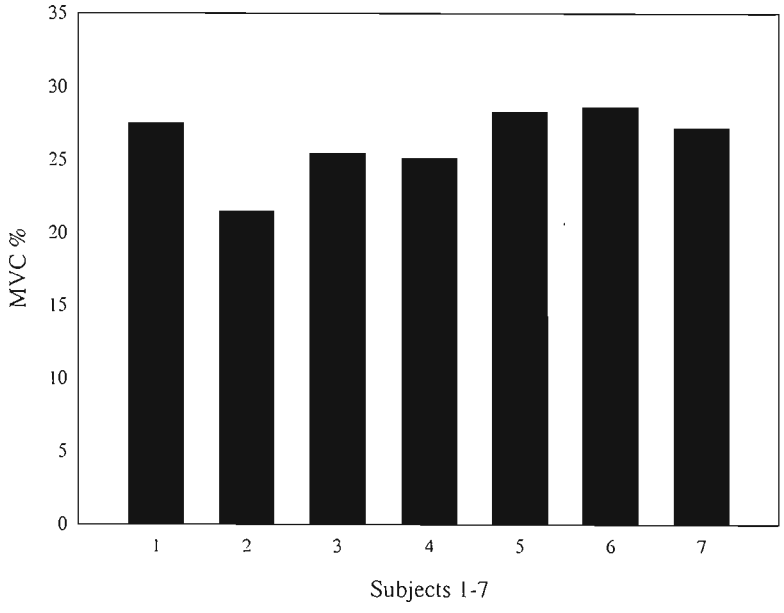

Figure 2

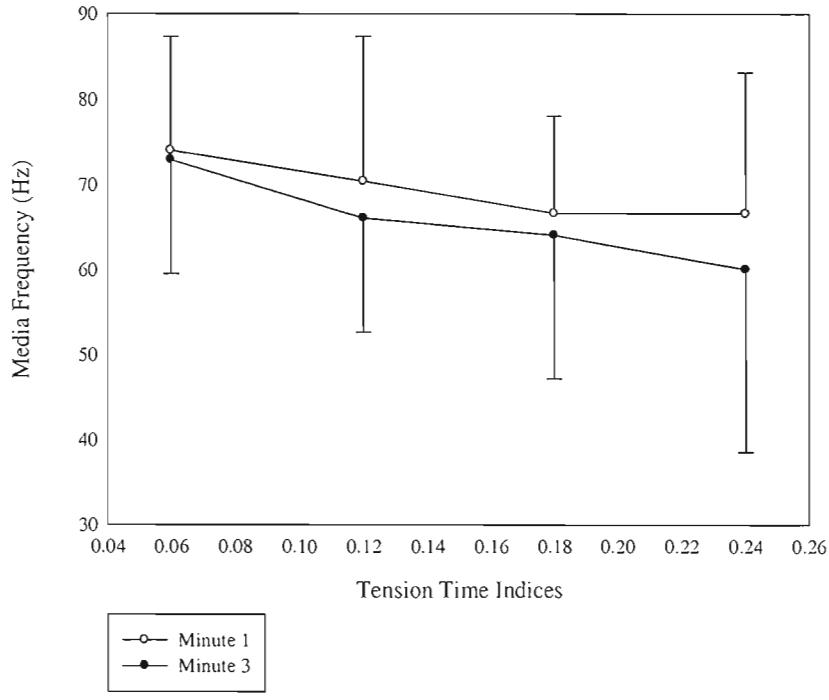

Figure 3

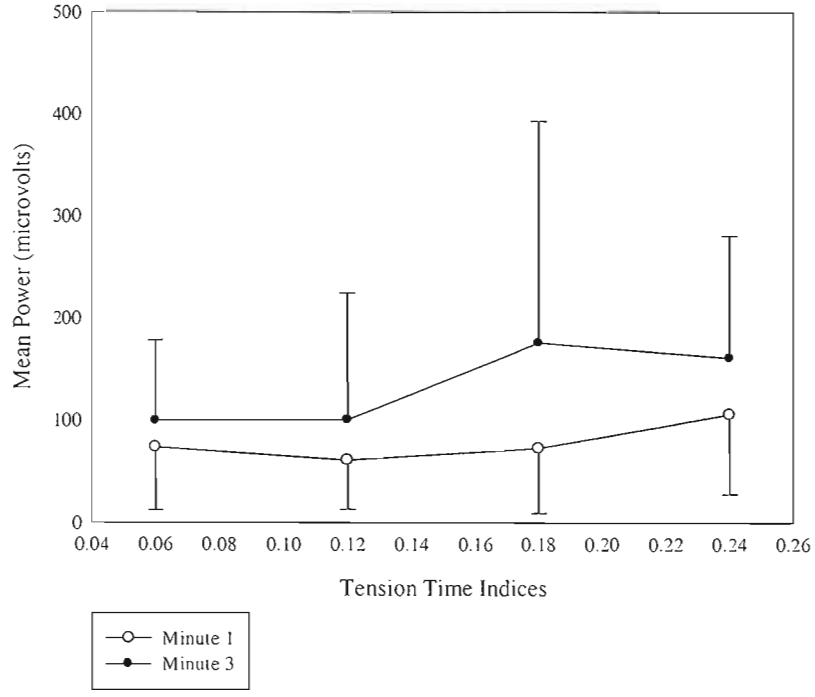

Figure 4

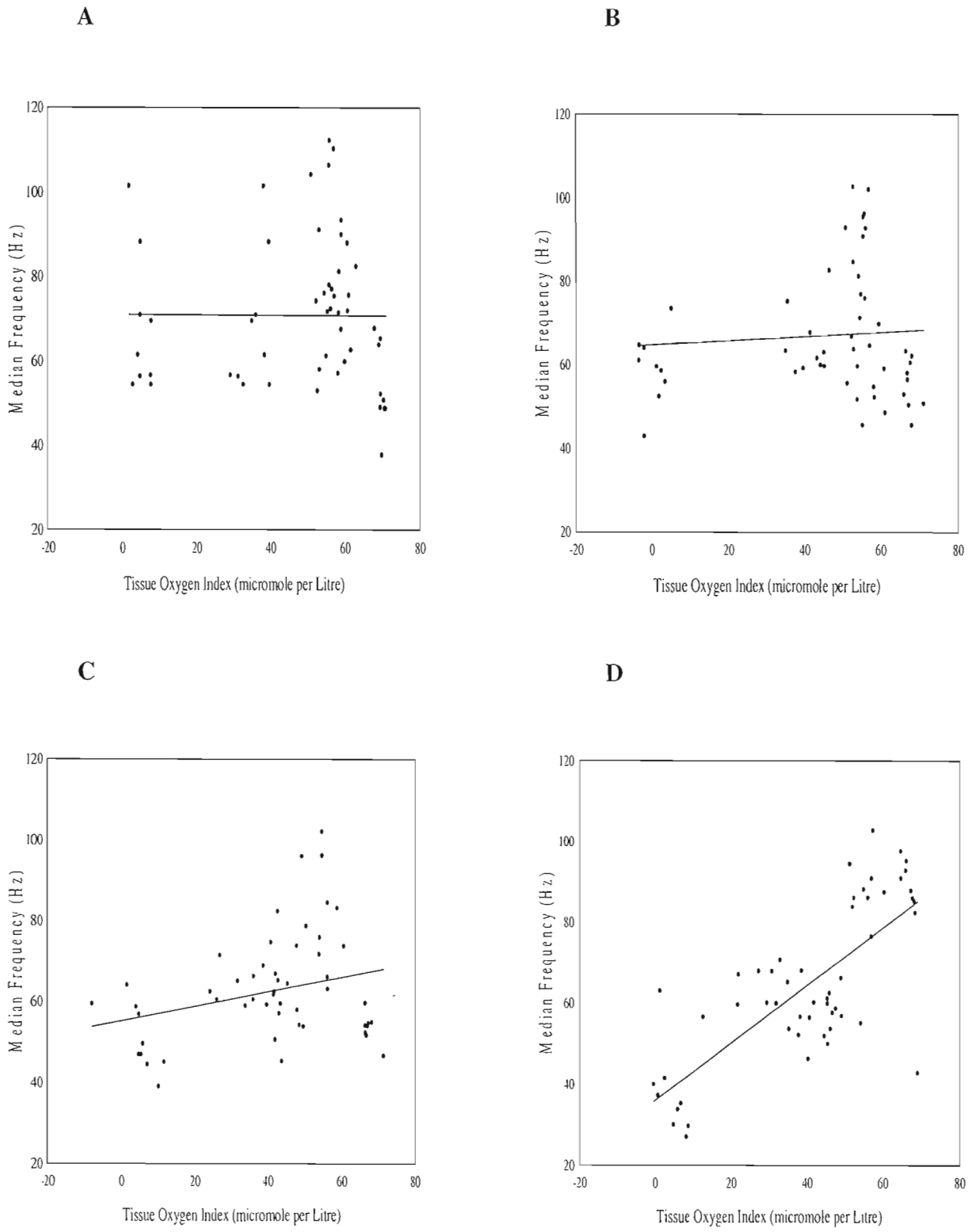
A
B
C
D
Median Frequency (Hz)
Tissue Oxygen Index (micromole per Litre)
120
100
80
60
40
20
-20
0
20
40
60
80

Figure 5

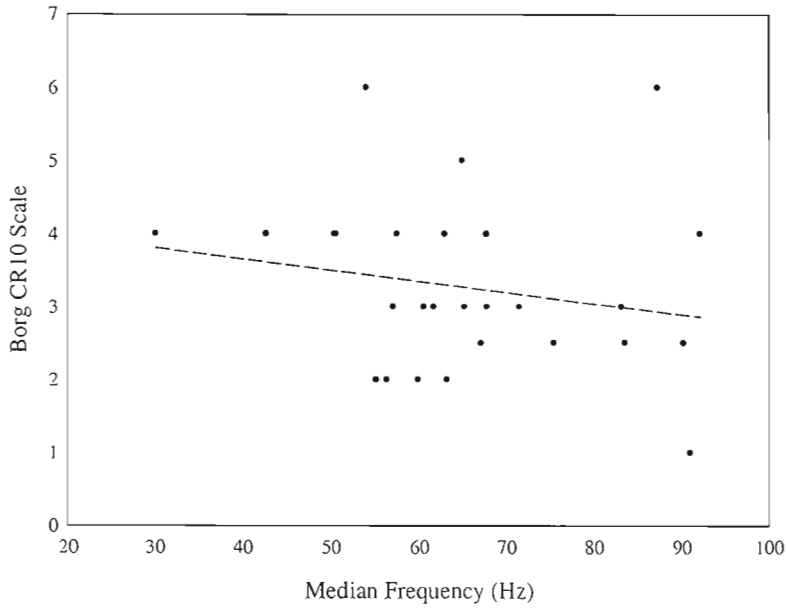
Borg CR10 Scale
0
1
2
3
4
5
6
7
20
30
40
50
60
70
80
90
100
Median Frequency (Hz)

Figure 6

RATING OF PERCEIVED EXERTION

Borg CR10 Scale

0	Nothing at all	How you feel when lying in bed or sitting down
0.3		
0.5	Extremely Weak	
0.7		
1	Very Weak	Little or no effort.
1.5		
2	Weak	Target range: how you should feel with exercise
2.5		or physical activity.
3	Moderate	
4		
5	Strong	
6		
7	Very Strong	How you felt doing the hardest work you've
8		ever done
9		
10	Extremely Strong	
•	Absolute Maximum	Do not work this hard

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CHAPTER IV

PROJECT CONCLUSION

4.1 General Conclusion

This project attempted to demonstrate muscle fatigue in the trapezius at low intensity loads by recording electromyographical signals, and correlating these signals with tissue oxygen index levels in the muscle and also subjective perceptions of effort. The finding of this study that low intensity loads can elicit muscle fatigue is in agreement with other studies that have demonstrated the same. The results of this project are also in agreement with studies demonstrating that while physiological fatigue occurs in the muscle, subjective ratings of effort do not match well with this; in that subjects often perceive their work as weak to moderate when the onset of muscle fatigue is occurring. This is an important observation as people may continue to work under low intensity loads where the intracellular environment is changing over time and physiological fatigue occurring. The effect of repeated patterns of fatiguing, low intensity contractions taking place during functional movements in the work place has implications for the tolerance of muscles to the stresses which are put on them, and may alter the joint mobility or rhythm of a muscle over time if it is subjected to repetitive work. This effect is described in the literature. This project also demonstrated a strong relationship between the (electro)-physiological signals emanating from the fatiguing muscle with levels of tissue oxygen index which occurred during contractions. A further investigation with a larger sample size and control group is warranted to determine if this effect is reproducible.

The limitations of this study were presented in chapter 1. In addition to these limits, alternative protocols may elicit similar or more pronounced results to those found here. This study used four experimental conditions with a different duty cycle per condition. An inherent weakness in using the duty cycle *per se* is that it does not consider the absolute time of contraction/relaxation but only the ratio between the two. This has implications particularly for the relaxation phase of a contracting muscle. For example, this study utilised a duty cycle of 0.4 where contraction took place for eight seconds, and relaxation for 12 seconds. Over **two minutes** this could amount to a total of 48s of work, with 72s of relaxation. However, a duty cycle of 0.8 where contraction/relaxation phases lasted for eight seconds and two seconds respectively would equally

produce 48s of work in **one minute**, however relaxation would total 12s. Though the absolute time of work is similar in both cycles, the longer relaxation phase in the 0.4 cycle provides for increased relaxation time between contractions, and consequently continuous muscle perfusion. The much shorter relaxation phase in the 0.8 duty cycle limits muscle relaxation and perfusion between contractions. It is reasonable to propose, albeit preliminarily, that the shorter relaxation phase following contraction outlined here could provide a mechanism to elicit muscle fatigue while at the same time limiting muscle perfusion.

The relative load used in this study was chosen to be 30% MVC, which has been shown to elicit muscle fatigue. Greater relative loads have been reported in the literature and should not be ruled out for a further study. Loads of up to 60% have been reported in the literature review of this project, and while not correlated to muscle desaturation in the literature, would surely provide for greater desaturation levels than observed here. Similarly, the experimental conditions employed here were relatively short i.e. 3min, and perhaps not entirely representative of loading patterns used across a variety of professions or in terms of muscle work performed over greater periods of time. Repetitive typewriting and lifting occurs over longer periods of time than three minutes, and perhaps experimental conditions of longer duration would be more representative of the stress undergone by muscles habitually.

In summary, muscle fatigue is observed at low intensity loads where contraction-relaxation phases favour longer contractions and short relaxation periods. Oxygen desaturation in the muscle is implicated in muscle fatigue. Muscle fatigue as measured with surface electromyography does not correlate well to subjective perceptions of effort.

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