

Investigation of Localized Muscle Fatigue

A thesis submitted in fulfillment of the requirements for the
degree of Master of Engineering

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March 2010

Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

Vivek Yadav

March 31, 2010

Acknowledgements

I would like to express my appreciation and sincere gratitude to my supervisors, Dr. John Fang and Associate Professor Dinesh Kant Kumar for their valuable guidance, advice and encouragement throughout the course of this thesis. I thank them from the bottom of my heart. I express my deepest appreciation to them for their support, unlimited assistance, criticism and beneficial advice throughout my candidature at RMIT University.

I would like to thank Dr. Sridhar Arjunan for his constant support and suggestions to accomplish my research.

I would like to thank Dr. Vuk Vojisavljevic for his unconditional support as and when needed. Also I would like to extend my appreciation to my supervisors' fellow research students for helping me out whenever they could. Thanks and appreciations are due to Professor Ian Burnett, head of school for his unbiased advice and support throughout my candidature. I would like to thank all technicians, secretaries and personnel in the School of Electrical and Computer Engineering at RMIT University for their help and cooperation.

Without the participants who took part in this study I would have never been able to produce this work. So I salute all the participants who took out precious time from their everyday responsibilities for their participation in this research.

I wish to express my sincere gratitude to my family members and friends, for providing me with the encouragement to carry out research for the last two years.

Special thanks are due to my brother Vikas Yadav for his continuous support and encouragement in every possible way throughout my studies.

Last but by no means least; I would like to thank my dear parents, Sh. Dharam Pal and Smt. Sarla Devi. Nothing I can say can adequately express my gratitude for the adoration, support and encouragement they provided throughout my life. I am grateful to Omnipotent God for the gift of such caring parents.

Vivek Yadav

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Abstract

Muscle fatigue is a condition where the ability of the muscle to contract and produce force is reduced. Generally the result of prolonged, relatively strong muscle activity, localized muscle fatigue (LMF) occurs when a muscle or a group of muscles has reduced ability to contract and produce force despite neural stimulation. The causes of physical fatigue include poor workplace practices and lack of regular physical exercise. Signs of fatigue include reduced motivation, blurred vision, increased reflex time and poor concentration – all elements in fatigue-related accidents. Muscle fatigue is a leading cause of workplace and transport-related accidents, as well as work-related musculoskeletal disorders.

This thesis reports on an experimental study conducted to determine the effects of LMF on the physiological signals produced during voluntary isometric and cyclic muscle contraction. Surface electromyography (SEMG) was considered relevant for this research because it is the most practical and non-invasive technique for recording such physiological signals. Time and frequency domain responses were extracted from recorded signals and analyzed.

Statistical analysis on extracted data was carried out using analysis of variance (ANOVA) and non parametric (sign-test) analysis. Sign-test analysis shows a statistically significant change in root-mean-square (RMS) amplitude both before and after the onset of fatigue during cyclic contraction but no statistically significant change in median frequency (MDF). But for isometric contraction the results of sign-test show that there is a statistically significant change in both MDF and RMS before and after the onset of fatigue. Similarly,

ANOVA results suggest that for isometric contraction there is a statistically significant change in both MDF and RMS before and after the onset of fatigue. In addition, there is a statistically significant change in RMS amplitude before and after the onset of fatigue during cyclic contraction but no statistically significant change in MDF.

The results clearly demonstrate that while SEMG analysis is appropriate for muscular fatigue detection, the use of MDF alone does not provide a reliable and valid measure for LMF detection in real world applications where most tasks require a combination of both isometric and cyclic contractions.

Chapter 1

Introduction

Physical fatigue is a general phenomenon people experience at some stage in day to day activities characterized by drop in efficiency to perform physical work. Demanding physical exercise or prolonged physical work involving 30% to 40% of individual's maximal aerobic capacity induces muscle fatigue (Astrand and Rodahl, 1986). Individual's drowsiness usually followed by reduced alertness and unwillingness or dropped motivation towards assigned task are general signs of physical fatigue. Though advancement in manufacturing techniques and equipments has greatly reduced the heavy physical duties in industries and transportation, still frequent and repetitive activities at sub-maximal contraction level and incorrect posture leads to many disorders of muscles, tendons and nerves collectively classified as work-related musculoskeletal disorders (<http://www.ccohs.ca/oshanswers/diseases/rmirsi.html>). Prolonged abnormal posture and repetition of same task contributes to such disorders with common symptoms of pain in upper limbs and neck (Walker-Bone K. and Cooper C, 2005; Van et al, 2009). Fatigue related accidents are also major killers in transportation industry. Study suggests 25% of single vehicle accidents are direct result of driver's fatigue. In addition, it is reported that 39% commercial vehicle accidents are due to fatigue/drowsiness or inattention and accounts for 48% of accident-related fatalities worldwide (Sung, et al., 2005). Due to increase in such fatigue related accidents more emphasis on understanding of localized muscle fatigue (LMF) has been given in past decades partly due to its possible connection with

work-related musculoskeletal disorders (Baidya, K. N., and Stevenson, M. G., 1988). LMF is a gradual time dependent process defined as a reduction in muscle strength (Vollestad, N. K. 1997; De Luca, C.J., 1984).

Surface electromyogram (SEMG) is a signal which relates to the electrical activity of muscles. Muscles produce an electrical potential that is nonlinearly related to the amount of force produced in a muscle. Analyzing these signals and associating them with the state of the muscle has been an area of active research in the biomedical engineering for many decades. Muscle fatigue (i.e. the decrease in muscle performance during exercise) has been studied extensively using a variety of experimental paradigms. Based on the origin of fatigue, muscle fatigue can be divided into two types, namely central fatigue and peripheral fatigue (Fitts, R.H., 1996). Fatigue associated with the neural system is termed central fatigue. Peripheral fatigue originates from the processes occurring at neuromuscular junction and contractile elements involved directly in muscle contraction. Localized muscle fatigue generated due to physical over exertion or continued manual material handling tasks is associated to peripheral fatigue. There are two types of fatigue mechanisms based on isometric and cyclic contractions. Isometric contractions induce isometric fatigue with time while fatigue due to production of voluntary cyclic contractions is referred as cyclic or dynamic fatigue.

Most of the research in this field has been limited to study of isometric fatigue only (Lindström et. al, 1970; Viitasalo, J.H. and Komi, P.V., 1977; De Luca, C.J., 1984; Basmajian, J.V. and De Luca, C.J., 1985; Moritani et. al, 1986; Brody et. al, 1991; Merletti et. al, 1990; Wim et. al, 1993; Kleine et. al, 2001). Isometric fatigue is the result of isometric contraction exercise involving the static

contraction of a muscle without any noticeable change in the angle of the joint or length of muscle (Fleck, S. J., and Kraemer, W. J., 2004). Isometric contractions are performed by holding muscles and joint in a static position while opposed by resistance. Researchers have defined and correlated different measures of electromyography (EMG) with increase in onset of muscle fatigue. However there are different opinions for underlying mechanism related to decrease in MDF value and increase of RMS amplitude due to muscle fatigue. (Hagberg, M., 1981; Lindström et. al, 1970; Viitasalo, J.H. and Komi, P.V., 1977; De Luca, C.J., 1984; Basmajian, J.V. and De Luca, C.J., 1985; Moritani et. al, 1986; Brody et. al, 1991; Merletti et. al, 1990; Dimitrova, N.A. and Dimitrov, G.V., 2003; Wim et. al, 1993; Kleine et. al, 2001; Cifrek et al 2009).

During Dynamic fatigue contractions unlike isometric exercise, muscle length and angle at the joint changes and the force exerted changes markedly during the activation interval (Knaflitz, M. and Bonato P., 1999). Most of the every day routine tasks fall under this category. Recently there are a few researchers working in the field of dynamic fatigue (Cifrek, M., et al. 2000; Merletti R. and Parker. A. P., 2004; Bertolina et al., 2004; Farina et. al, 2004; Singh et. al, 2006; Dingwell et. al, 2008). A few researchers working in the field of dynamic fatigue contraction proposed a correlation of SEMG with fatigue but findings of other researchers (Singh et. al, 2006; Dingwell et. al, 2008) disagrees with findings of those who found a positive correlation between changes in SEMG spectrum due to fatigue with MDF shift towards lower frequency and increase in RMS (Cifrek, M., et al. 2000; Merletti R., Parker. A. P., 2004; Bertolina et al., 2004; Farina et. al, 2004).

1.1 Problem Statement

In order to analyze the localized muscle fatigue, there is a need of identifying the relationship between the change in the spectral and time domain parameters of SEMG. This thesis has analyzed the relationship between the fatigue and spectral parameters during isometric and cyclic contractions based on the following research questions:

- Are median frequency (MDF), a frequency domain parameter and root mean square (RMS), a time domain parameter reliable measures to analyse the changes in surface electromyography due to muscle fatigue?
- How the onset of localized muscle fatigue affects the RMS amplitude and MDF spectrum of SEMG during isometric and cyclic fatigue contractions?

1.2 Aim of the Research

The objective of this research is to study the effect of onset of physical fatigue/stress during isometric and dynamic contractions based on the changes in physiological signal i.e. SEMG.

Therefore, the intention of this present investigation is to assess the repeatability of common muscle fatigue measures, including amplitude and spectral measures of EMG and further, to determine the adequacy of different measures in detection of onset of localized muscle fatigue.

1.3 Outline of Thesis

This dissertation is organized into the following chapters, with additional detailed information included as appendices:

- Chapter 2 presents a review of existing literature on localized muscle fatigue and several measures used for detection of localized muscle fatigue.
- Chapter 3 describes the planning of the research project, participant's selection and experimental protocol as well as the theory of the various methods used in the project.
- Chapter 4 presents the results of experiments conducted, analysis of data and describes the findings of study in reference to the observation from analysis of experimental data.
- Chapter 5 briefly summarizes the main conclusions from this study and highlights additional research needs that were beyond the scope of this project.
- Questionnaire used to recruit the participants for this study is attached in Appendix A.
- Appendix B consist the summary of experimental procedures in plain language, given to the participants prior to experimentation.
- Sample of participant consent form to be signed by each participant prior to experimentation is attached in Appendix C.
- Appendix D contains the detailed results of experimental data analysis.
- Appendix E contains the publication.

Chapter 2

Background and Literature Review

2.1 Introduction

Muscle fatigue has been defined as “any exercise induced reduction in the ability to exert muscle force or power, regardless of whether or not the task can be sustained” (Taylor, J. L., and Gandevia, S. C., 2001). Over decades, researchers have explained different perspective of fatigue development with muscle contraction due to change in its biochemical properties, muscle fibre conduction velocity (MFCV), motor unit recruitment model and changes in synchronization pattern. Changes in muscle force produced over time are generally examined for measuring muscle fatigue. This change in muscle force comes with change in electrical activities of muscles.

Localized Muscle Fatigue (LMF) is caused by physiological and biochemical changes in muscle due to fatiguing contractions. Both prolonged isometric and repetitive dynamic contraction results in LMF. Currently there is no well recognized mechanism for development of muscle fatigue though based on several studies different models have been proposed. Localized Muscle Fatigue involves the processes occurring at neuromuscular junction and contractile elements also causing the general feeling of tiredness. LMF and different mechanisms for its generation are described by many researchers. Researchers (Vøllestad, N. K. 1997; Fitts, R. H., 1996) explained that a disproportion between Na^+ and K^+ ions disturbs the action potential propagation along muscle

membrane (sarcolemma). This action potential facilitates in depolarization of sarcolemma which in turn releases the Ca^{2+} ion its reticulum. This Ca^{2+} ion is responsible for contracting mechanism of myofibrils as explained in muscle filament contraction theory proposed by Hugh Huxley in 1954. A number of other factors can also disturb this process of Ca^{2+} release and pumping back to sarcolemma reticulum which results in reduced muscle contraction and lower power output due to reduced number of cross-bridges formation during contraction. Accumulation of metabolism by-products inside muscle cell especially phosphate ions is one of the main factors that reduces the affinity of Ca^{2+} , reducing muscle ability to contract resulting in LMF. LMF has also been associated with reduced oxygen supply to muscle due to ischemia during fatiguing contractions (Murthy, G., Hargens, A. R., Lehman, S., and Rempel, D. M. (2001). This causes the accumulation of lactic acid (metabolic by product). Lactic acid is removed by blood flow through muscle which is compromised at a stage when intramuscular pressure stops the blood flow to muscle. This increased lactic acid concentration changes sarcoplasm pH value resulting in muscle fatigue. Other researchers (Kahn, J. F., and Monod, H., 1989) have argued that although muscle ischemia induces LMF but instead of oxygen availability, accumulation of K^{+} ions results in failure of excitation-contraction coupling mechanism.

In summary, as muscle contraction is a long and complicated set of many processes, thus LMF may be a result of impaired processes at different points and multiple factors may be contributing to this impairment. Also both prolonged isometric contractions and repetitive/cyclic dynamic contractions can result in LMF, thus different mechanisms may be responsible for these two different types

of muscle fatigue. In general it is difficult to specify the single responsible factor for LMF and the precise mechanism of LMF is presently debatable.

Surface Electromyography (SEMG) has often been used for non-intrusive study of muscle functions, and changes in SEMG measures may indirectly indicate the progress of muscle fatigue (Piper, H., 1912; Cobb, S., Forbes, A., 1923; Knowlton, G.C., Bennett, R.L., McClure, R., 1951). Many researchers observed an increase in SEMG amplitude (Lindstrom et al., 1977; Kadefors, 1978; Duchene and Goubel, 1993) during fatiguing contractions. Researchers (Chaffin, 1973; Kadefors, 1978; Marras, 1990; Duchene and Goubel, 1993; De Luca, 1997) also observed a shift towards lower frequency in power density spectrum (PDS) of SEMG signal during isometric muscle contraction. Root mean square (RMS) of the signal has been generally used for representing SEMG magnitude while shift in the PDS of SEMG signal has often been indicated by median frequency (MDF).

2.1.1 Anatomy and Physiology of Muscle

A muscle is composed of bundles of specialized cells capable of contraction and relaxation. Muscle cell is the basic unit of human muscular system function to produce force and cause every motion in human body. All muscle cells consist of actin and myosin as myofilaments which move past each other to alter the muscle length (Merletti R. and Parker. A. P., 2004). The primary function of these specialized cells is to generate forces, movements and the ability to communicate such as speech, writing or other modes of expression. It has the ability to receive and respond to stimuli and can be shortened or contracted. Functional characteristics of muscles include excitability, contractility, extensibility and

elasticity. There are three types of muscles in human body namely skeletal, smooth and cardiac out of which only skeletal muscles are voluntary in nature. Smooth muscles create movements of internal organs while cardiac muscles are responsible for heart contraction. For all other conscious movements, skeletal muscles are responsible for producing great force by rapid and vigorous contractions and thus easily become fatigue. Skeletal muscle is a long thin striated cell consisting of myofibrils which are further composed of thick myosin and thin actin protein filaments. Arrangement of these protein filaments causes striations of skeletal muscle. Most popular theory of muscle contraction is sliding filament theory first proposed by Hugh Huxley in 1954 (Merletti R. and Parker. A. P., 2004). As per this theory sliding of thin actin myofilaments past thick myosin myofilaments causes muscle contraction and this sliding continues until overlapping of myosin and actin filaments is complete. Contraction of muscle starts on receiving a stimulus from motor neuron. One motor neuron along-with many skeletal muscle fibers it stimulates which then contracts simultaneously consists a motor unit. A whole muscle consists of many such motor units which can contract individually. With increase in stimulus, recruitment of motor units increases until all contracts together producing more power. Sustained contraction of muscle while at rest is important in maintaining posture and called muscle tone (Merletti R. and Parker. A. P., 2004). During muscle contraction, energy is released almost half of which is lost to heat helping body to maintain its body temperature to 37°c

Muscle contraction can be divided into two types and most of the routine movements involve both these contractions.

- Dynamic contraction - where muscle length shortens and its filaments move e.g. Flexion and extension of biceps brachii.
- Isometric contraction - where muscle length remains same and muscle taut e.g. Holding a weight in hand at some angle.

2.1.2 Motor Unit Action Potential (MUAP)

A motor unit (MU) is a basic unit of muscle fiber which produces contraction on receiving stimuli from central nervous system (CNS) (Basmajian, J.V., De Luca, C.J., 1985). A motor unit consists of a single motor neuron, its axon and all the muscle fibers attached to it (Merletti R., Parker. A. P., 2004). Number of muscle fibers attached in a motor unit varies depending on its function. As in case of eye muscles where very accurate and fine movement is needed, the number of muscle fibers in a motor unit can be as low as 3-10 while postural muscles can have over 500 muscle fibers in a single motor unit (Ottoson D., 1983). On receiving the stimulus from CNS motor unit contracts which results in generation of an electric field across the muscle fiber. This can be detected by skin surface electrodes located over the muscle; the resulting signal is called muscle fiber action potential. The summation of all the action potentials from the muscle fibers of a single motor unit is termed motor unit action potential (MUAP). The repetitive firing of a motor unit creates a series of impulses collectively called motor unit action potential train. The myoelectric signal of a muscle is then formed by summing up the electrical activity of all the active motor units. Representation of muscle electrical activity on a graph generates MUAP waveform.

2.1.3 Muscle Studied- Biceps Brachii

In this research, localized fatigue of skeletal muscles was analyzed via conducting experiments involving Biceps brachii. Biceps brachii is a fusiform, parallel anterior muscle of upper arm. Muscle consists of two muscle bundles individually originating from coracoid process of scapula and supraglenoid tubercle sharing a common insertion into radial tuberosity.

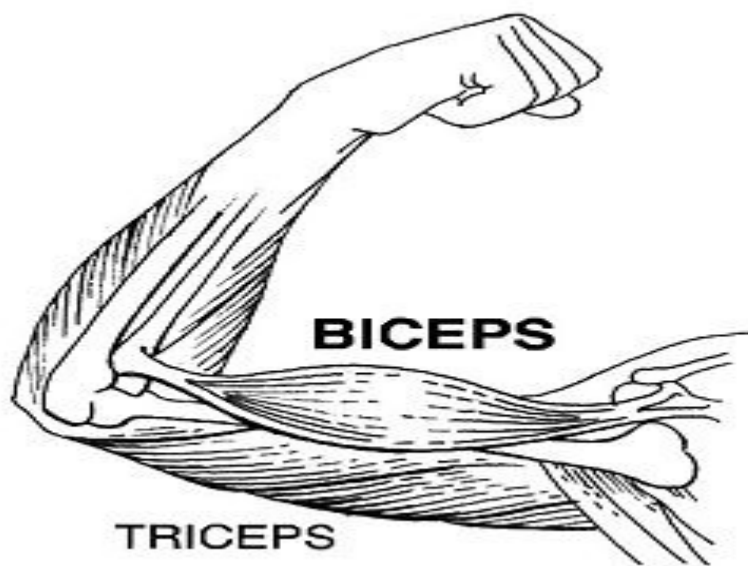


Figure 2- 1: Anatomy of Biceps Brachii

(orthopaedia, <http://www.orthopaedia.com/display/Main/Biceps+brachii>)

Biceps is the primary mover for flexion of elbow and supination/rotation of forearm. Blood flow to biceps muscle is supplied by brachial artery and is controlled by musculocutaneous nerve (C5-C7) originating from cervical region of spine. Located at back of the upper arm is triceps brachii which functions

antagonist to biceps brachii and responsible for extension of elbow/straightening of arm.

2.2 Electromyography (EMG)

EMG stands for electromyography. The EMG is applied to the study of skeletal muscle. The skeletal muscle tissue is attached to the bone and its contraction is responsible for supporting and moving the skeleton. The contraction of skeletal muscle is initiated by impulses in the neurons to the muscle and is usually under voluntary control. Skeletal muscle fibers are well-supplied with neurons for its contraction. This particular type of neuron is called a “motor neuron” and it approaches close to muscle tissue, but is not actually connected to it (Merletti R. and Parker. A. P., 2004). One motor neuron usually supplies stimulation to many muscle fibers. The human body as a whole is electrically neutral; it has the same number of positive and negative charges. But in the resting state, the nerve cell membrane is polarized due to differences in the concentrations and ionic composition across the plasma membrane. A potential difference exists between the intra-cellular and extracellular fluids of the cell. In response to a stimulus from the neuron, a muscle fiber depolarizes as the signal propagates along its surface and the fiber twitches. This depolarization, accompanied by a movement of ions, generates an electric field near each muscle fiber (Merletti R. and Parker. A. P., 2004). An EMG signal is the train of Motor Unit Action Potential (MUAP) showing the muscle response to neural stimulation. The EMG signal appears random in nature and is generally modeled as a filtered impulse process where the

MUAP is the filter and the impulse process stands for the neuron pulses, often modeled as a Poisson process (Raez et. al., 2006).

2.2.1 EMG – Anatomical and Physiological Background

EMG is the study of muscle electrical signals. EMG is sometimes referred to as myoelectric activity. Muscle tissue conducts electrical potentials similar to the way nerves do and the name given to these electrical signals is the muscle action potential. Surface EMG is a method of recording the information present in these muscle action potentials. When detecting and recording the EMG signal, there are two main issues of concern that influence the fidelity of the signal. The first is the signal-to-noise ratio. That is, the ratio of the energy in the EMG signals to the energy in the noise signal. In general, noise is defined as electrical signals that are not part of the desired EMG signal. The other issue is the distortion of the signal, meaning that the relative contribution of any frequency component in the EMG signal should not be altered. Two types of electrodes have been used to acquire muscle signal: invasive electrode and non-invasive electrode (Merletti R. and Parker. A. P., 2004). When EMG is acquired from electrodes mounted directly on the skin, the signal is a composite of all the muscle fiber action potentials occurring in the muscles underlying the skin. These action potentials occur at random intervals. So at any one moment, the EMG signal may be either positive or negative voltage. Individual muscle fiber action potentials are sometimes acquired using wire or needle electrodes placed directly in the muscle. The combination of the muscle fiber action potentials from all the muscle fibers of a single motor unit is the motor unit action potential (MUAP) which can be detected

by a skin surface electrode (non-invasive) located on skin surface near this field, or by a needle electrode (invasive) inserted in the muscle.

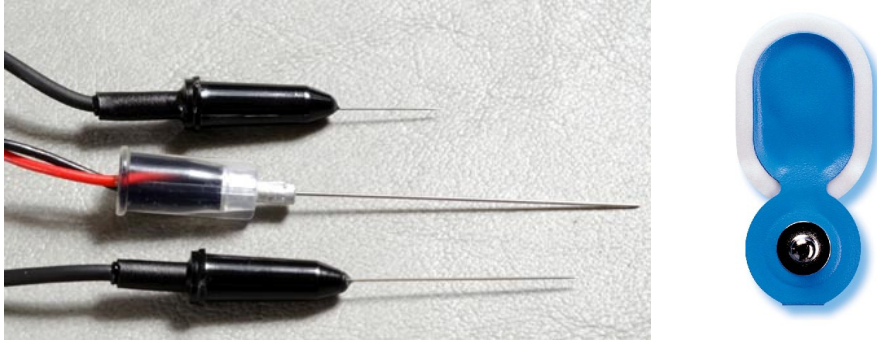


Figure 2-2 a Invasive Needle Electrode (source: Biopac Systems Inc.)

Figure 2-2 b Non-invasive Electrode (source: AMBU Inc.)

The signal is picked up at the electrode and amplified. Typically, a differential amplifier is used as a first stage amplifier. Additional amplification stages may follow. Before being displayed or stored, the signal can be processed to eliminate low-frequency ($<10\text{Hz}$) or high-frequency noise ($>\text{MHz}$), or other possible artifacts (50Hz). Consequently, the signal is frequently rectified and averaged in some format to indicate EMG amplitude (Merletti R. and Parker. A. P., 2004).

2.2.2 History of EMG

The development of EMG started with Francesco Redi's documentation in (Basmajian, J.V. and De Luca, C.J., 1985). The document informs that highly specialized muscle of the electric ray fish generates electricity. By 1773, Walsh had been able to demonstrate that Eel fish's muscle tissue could generate a spark

of electricity. In 1792, a publication entitled “De Viribus Electricitatis in Motu Musculari Commentarius” appeared, written by A. Galvani, where the author showed that electricity could initiate muscle contractions. Six decades later, in 1849, Dubios-Raymond discovered that it was also possible to record electrical activity during a voluntary muscle contraction. The first recording of this activity was made by Marey in 1890, who also introduced the term *electromyography*. In 1922, Gasser and Erlanger used an oscilloscope to show the electrical signals from muscles. Because of the stochastic nature of the myoelectric signal, only rough information could be obtained from its observation. The capability of detecting electromyographic signals improved steadily from the 1930s through the 1950s and researchers began to use improved electrodes more widely for the study of muscles. Clinical use of surface EMG for the treatment of more specific disorders began in the 1960s (Jeffery R. Cram, 2003). Hardyck and his researchers were the first (1966) practitioners to use SEMG. In the early 1980s, Cram and Steger introduced a clinical method for scanning a variety of muscles using an EMG sensing device. It is not until the middle of the 1980s that integration techniques in electrodes had sufficiently advanced to allow batch production of the required small and lightweight instrumentation and amplifiers. At present a number of suitable amplifiers are commercially available. In the early 1980s, cables became available which produce artifacts in the desired microvolt range. During the past 15 years, research has resulted in a better understanding of the properties of surface EMG recording. In recent years, surface electromyography is increasingly used for recording from superficial muscles in clinical protocols, where intramuscular electrodes are used for deep muscle only. There are many

applications for the use of EMG (Merletti R. and Parker. A. P., 2004). EMG is used clinically for the diagnosis of neurological and neuromuscular problems including muscular dystrophy, hereditary neuropathies, congenital myopathies, myasthenias, myotonic syndromes, metabolic myopathies (Negrin, P., Fardin, P., 1979; Han, et. al., 2005; Krocza et. al., 2009). EMG is also used in many types of research laboratories, including those involved in biomechanics, motor control, neuromuscular physiology, movement disorders, postural control, and physical therapy. An EMG is a complicated signal, which is controlled by the nervous system and is dependent on the anatomical and physiological properties of muscles. An EMG signal acquires noise while travelling through different tissues. Moreover, the EMG detector, particularly if it is at the surface of the skin, collects signals from different motor units at a time which may generate interaction of different signals (Merletti R. and Parker. A. P., 2004). Detection of EMG signals with powerful and advance methodologies is becoming a very important requirement in biomedical engineering. The main reason for the interest in EMG signal analysis is in clinical diagnosis and biomedical applications. The field of management and rehabilitation of motor disability is identified as one of the important application areas. The shapes and firing rates of Motor Unit Action Potentials (MUAPs) in EMG signals provide an important source of information for the diagnosis of neuromuscular disorders such as muscular dystrophy (Han, et. al., 2005). Once appropriate algorithms and methods for EMG signal analysis are readily available, the nature and characteristics of the signal can be properly understood.

2.2.3 Surface EMG (SEMG) Signal

SEMG (surface electromyography) is a non-intrusive technique of recording electrical activity of underlying motor units from skin surface. All voluntary muscle contractions are broadly divided into two categories: isometric contractions and non-isometric/dynamic contractions. During isometric contraction muscle generates force to maintain posture without changing its length while all other activities including most day to day activities falls into non-isometric category. During fatiguing muscle contractions, changes in myoelectric properties of muscles are reflected in SEMG patterns (Piper, H., 1912; Cobb, S., Forbes, A., 1923; Knowlton, G.C., Bennett, R.L., McClure, R., 1951). These changes in power density spectrum density have been analyzed to understand the relation between muscle fatigue and features of SEMG (Knowlton, G.C., Bennett, R.L., McClure, R., 1951; Kogi, K., Hakamada, T., 1962; De Luca, C.J., 1984; Basmajian, J.V., De Luca, C.J., 1985; Stulen, F.B., De Luca, C.J., 1982).

2.2.4 SEMG and Fatigue

Physiological inability of a muscle to contract is termed muscle fatigue. In general, localized muscle fatigue is a result of continual forced muscle contraction. Correlation between LMF during isometric and non-isometric fatiguing contractions and SEMG features has been reviewed. Effect of LMF on the classical indicators of muscle fatigue i.e. SEMG root mean square (RMS) amplitude and median frequency (MDF) have been observed (Lindström, L., Magnusson, R., Petersen, I., 1970; Viitasalo, J.H., Komi, P.V., 1977; (Moritani, T., Muro, M., Nagata, A., 1986). The median frequency is normally defined as the particular frequency that divides the power spectrum into two parts of equal area.

2.3 Muscle Fatigue Analysis

2.3.1 Effect of Fatigue on SEMG

2.3.1.1 Isometric contractions

Morphological change in EMG pattern during fatiguing isometric contraction were observed as early as in 1912 by Piper (Piper, H., 1912) and an increase in EMG amplitude due to prolonged isometric contraction was first noticed in 1932 by Cobb and Forbes (Cobb, S., Forbes, A., 1923) using simple laboratory equipments. Similar pattern of increase in EMG amplitude was rediscovered by Knowlton et al in 1951 using digital recording technique. Kogi and Hakamada in 1962 found shift of SEMG spectrum towards lower frequencies with development of fatigue condition (Kogi, K., Hakamada, T., 1962). Afterwards many researchers found the similar patterns and different explanations were proposed (De Luca, C.J., 1984; Basmajian, J.V., De Luca, C.J., 1985). Lindström et al., 1970 proposed a mathematical model to explain these patterns by relating SEMG power density spectrum (PDS) with muscle fiber conduction velocity (MFCV). Muscle fiber conduction velocity is the rate of propagation of action potential in muscle fiber with time. Shift of frequency spectrum towards lower frequencies under fatiguing isometric contraction was also observed by (Viitasalo, J.H. and Komi, P.V., 1977). Muscle fatigue is usually described in terms of MDF shift in PDS and SEMG RMS amplitude (Moritani et al., 1986). This change in PDS and SEMG RMS amplitude is due to biochemical and physiological changes in muscle fibers due to fatigue. Three possible explanations for the underlying mechanism for changes in EMG signals associated with fatiguing contractions

have been discussed in the literature, including changes in muscle fiber conduction velocity (MFCV), motor unit recruitment and motor unit synchronization (grouping). Biochemical and physiological changes inside skeletal muscles during fatiguing contractions are reflected in SEMG patterns. Muscle contractions result in accumulation of lactic acid in muscle fiber, concentration of which depends on various factors including muscle type, size, type of contraction (isometric or dynamic) and force level. Lactic acid is removed by blood flow through muscle which is compromised at a stage when intramuscular pressure stops the blood flow to muscle. This increased lactic acid concentration results in muscle fatigue due to change in its pH value. Change in intracellular pH decreases the conduction velocity (CV) of muscle fibers which results in change of motor unit action potential (MUAP) waveform, reflected into SEMG patterns (Basmajian, J.V. and De Luca, C.J., 1985). Brody et al relates the shift of MDF towards lower frequencies during fatigue condition with the decrease in muscle fiber CV (Brody et al., 1991). This is due to decrease in the intracellular pH value. Decrease in CV of muscle fiber also results in increased SEMG amplitude. This is explained as body tissue acts as a low-pass filter and allows more energy to reach to skin surface which results in increase in SEMG amplitude in after fatigue contraction due to decrease in muscle fiber CV (De Luca, C.J., 1984; Basmajian, J.V. and De Luca, C.J., 1985). Changes observed in power spectrum are often greater than expected due to decrease in muscle fiber CV.

Thus researchers (Merletti et al., 1990; Dimitrova, N.A., Dimitrov, G.V., 2003) suggested that these changes in shift of power spectrum cannot be

explained on basis of decrease in CV alone. Use of SEMG in detection of localized muscle fatigue due to shift in its power spectrum leads to development of specific analysers by many researchers for real time fatigue monitoring (Stulen, F.B., De Luca, C.J., 1982; Merletti et al., 1985; Kramer et al., 1987). Wim et al., 1993 describe firing rate, synchronization and recruitment pattern alongwith CV as indicator of localized muscle fatigue. More hypotheses were proposed to explain this shift in power spectrum. Change in observed signals due to remaining activity of the slow motor units, while the fast ones fatigue quickly and are switched off; as per time synchronization in the activity of particular motor units (Cifrek et al 2009). Moritani et al in 1986 observed activity of underlying MU (a motor neuron and all muscle fibers associated with that neuron) is reflected in EMG amplitude collected from skin surface (Moritani et al., 1986). They observed a change in SEMG RMS amplitude with increase in number of motor units during sub-maximal isometric contractions. Recently researchers (Lowery, et al. 2000; Lowery et al. 2001) have proposed a correlation between MU firing rate and their recruitment pattern with change in SEMG RMS amplitude.

Many models have been developed to explain the strategies of motor unit recruitments. It is well established that during muscle contraction, motor units are activated pseudo randomly to ensure smooth generation of force. As muscle force increases, the number of active motor units increases, referred to motor unit recruitment. Recruitment of motor units depends on current fatigue status of the muscle and the load to be supported. This brings a time dependency in the SEMG signal as muscle loading progresses. Large inter-subject variance in recruitment strategy is due to difference in tissue thickness, electrode location and distribution

of the motor unit conduction velocities (Farina, D., Merletti, R., and Enoka, R. M., 2004). Muscle fatigue has been described in terms of motor unit recruitment patterns (Kleine, B. U. et. al., 2001). As per motor unit synchronisation theory, the recruitment pattern of motor units appears to become synchronized with the onset of localized muscle fatigue. Modelling studies have found that the shift of PDS and MDF towards lower frequencies is countered by a decline in the CV (Stegeman D. F. and Linssen, W., 1992). During low-level bicep voluntary contractions, MDF decreases but the CV remains the same. Kleine posits that changes in the firing pattern, particularly synchronization, must be responsible for the spectral shift to lower frequencies not attributable to a conduction velocity change (Kleine, B. U., Stegeman, D. F., Mund, D., and Anders, C., 2001). During fatigue, the motor unit firing patterns become more synchronized when motor unit fires in approximately identical fashion than is expected by chance. In the fatigue state, the central drive to a muscle has to increase, leading to synaptic input that is common to more than one neuron. This leads to increased synchronicity (Naik et. al., 2009).

2.3.1.2 Cyclic / Dynamic contractions

Practicing movement and exercise usually results in localised muscle fatigue which are examples of cyclic dynamic contractions. Most of the work done towards quantifying fatigue from SEMG signals involved isometric contractions due to complication in accurately recording dynamic movements and their mathematical analysis (Cifrek et al 2009). Thus more work needs to be done for accurately detection of fatigue during cyclic dynamic contraction as most of routine fatiguing movements and exercises are cyclic dynamic in nature. Merletti

and Parker explain that for non-isometric contractions, unwanted signals due to movement of electrodes and cables are a major source of so called motion artifacts (Merletti R. and Parker. A. P., 2004). Difficulty in eliminating these artifacts from raw signal is another issue as some good data may be lost. Other issues faced during non-isometric data collection includes pulling on electrodes due to movement and sweating causing change in electrode-skin impedance due to prolonged fatiguing exercises (Merletti R. and Parker. A. P., 2004). Scope of many alternate methods proposed for non-isometric SEMG analysis is quite limited due to underlying assumptions (Merletti R. and Parker. A. P., 2004) and conclusions drawn based on them will not be accurate and reliable.

Recently a few researchers have worked on analysis of cyclic dynamic contractions for detection of onset of muscle fatigue. Cifrek et al conducted experiments on leg-extension training device and used MDF as indicator of muscle fatigue (Cifrek, M., et al. 2000). MDF results were interpreted with percentage increase in heart rate but no consistent changes were reported. Later Bertolina et al in 2004 observed no consistent change in either time domain or frequency domain parameters of SEMG during controlled long duration dynamic fatiguing contractions (Bertolina, M. V. et al. 2004). Similar results for long duration cyclic dynamic exercise were reported by Singh et al with no significant relation between muscle fatigue and SEMG features (Singh et. al, 2006).

In 2004, Farina et al found a positive correlation between CV and SEMG recorded during fast cyclic dynamic contractions (Farina et. al, 2004). They observed a decrease in CV during fast fatiguing dynamic contractions as measured by SEMG. More recently Dingwell et al in 2008 studied the effect of

muscle fatigue on SEMG and reported a mixed set of results (Dingwell et. al, 2008). Non-stationary changes in SEMG MDF pattern and inter-subject variability were observed. Based on the decrease in MDF value; fatigue was observed in 68% cases of total muscles studied though reverse trend of increase in MDF was also observed in a few cases.

In summary, a shift of the median frequency towards a lower frequency and an increase in SEMG amplitude during fatiguing isometric contractions are well established though the underlying mechanisms for these changes have been explained differently in literature. Researchers have observed a decrease in MDF with no change in CV which counters the theory that MDF shift to lower frequencies is due to the decrease in MFCV caused by LMF. Motor unit recruitment and synchronization theory explains the MDF shift and increased SEMG amplitude for isometric contractions but is at odds while explaining results of cyclic dynamic exercise. In recent study for cyclic dynamic contractions, Dingwell et al observed no clear shift of MDF after the onset of fatigue with large inter subject variability (Dingwell et. al, 2008). Thus no general conclusion can be drawn as a few researchers have reported the significant change in SEMG features during fatiguing cyclic dynamic contractions which is in contradiction with findings of other researchers.

As there is a gap in literature on the use of SEMG as a reliable source for fatigue analysis, thus the purpose of this research is to bridge this gap by conducting experiments involving isometric and controlled cyclic dynamic contractions to verify whether SEMG RMS amplitude and MDF can characterize onset of LMF. Experimental protocol for this study has been designed following

guidelines for collection of SEMG data during isometric and non-isometric contraction as described in electromyography (Merletti R., Parker. A. P., 2004) to prevent motion artifact, cross-talk and noise. SEMG data from isometric and cyclic contractions from 20 participants was collected as per guidelines of RMIT University Ethics Committee for Human Experiments. Collected SEMG signals were analysed in both time domain and frequency domain for extracting SEMG features i.e. PDS, MDF and RMS amplitude. The results were reported for both isometric and cyclic dynamic contractions. Statistical tools were used to validate the results of time and frequency domain analysis by means of ANOVA and sign test.

By conducting experiments for isometric and cyclic dynamic contractions, the purpose of this study was to investigate whether changes in SEMG RMS amplitude and MDF spectrum shift can differentiate between two types of fatiguing contractions. This study also reports the effect of LMF on SEMG RMS amplitude and MDF spectrum under isometric and cyclic dynamic fatiguing contractions. The outcomes of this study will clear the doubt whether SEMG features can be used as a reliable source for detection of localized muscle fatigue using classical indicators of fatigue. In particular, this research will contribute to the original body of knowledge for detection of LMF using SEMG features by providing experimental evidence using existing methodologies.

2.3.2 Analysis of SEMG

SEMG recorded from skin surface can be analyzed to monitor muscle activity and fatigue. Normally an expert physician can detect the changes in EMG pattern by eyeballing the data while physically calculating EMG amplitude, frequency and

duration of muscle activity. But the method is restricted by the experience of the examiner and is apparently limited only to expert physicians. Thus a more reliable, accurate and reproducible technique of EMG analysis is needed for objective evaluation of muscle fatigue. Such demand can be fulfilled by using a mathematical signal processing technique. As electromyography is a continuous representation of signal strength with time i.e. analog in nature; these signals are converted into digital form using an analog-digital convertor (Hussain, Z., M., 2003) before further processing. Signal processing involves the extraction of the required features from the signal. Different signal processing techniques can be used depending on signal type and the nature of information to be extracted. Thus, signal processing is concerned with the mathematical treatment of the signal and feature extraction by carrying out algorithmic operations on the signal (Salivahanan, S., et al, 2000). Biosignals are usually processed using two major techniques of time domain and frequency domain analysis. Time and frequency domains can be related using an appropriate transformation e.g. Fourier Transform (Hussain, Z., M., 2003). These methods of signal processing are explained in the following sections.

2.3.3 Frequency Domain Analysis

Frequency spectrum of a signal is a function of signal amplitude or phase plotted against frequency. Amplitude and phase frequency spectrum of a signal encloses the same information as the original signal but are represented in a different domain (Salivahanan, S., et al, 2000). Frequency domain analysis is a method of analyzing a mathematical function of a signal with respect to frequency by

plotting its amplitude against frequency. Generally signal information is hidden in its component sinusoids. In frequency domain analysis, the frequency, phase and amplitude of the component sinusoids are of key importance and not the shape of the signal in its original time domain (Smith, S., W., 1997). Generally Fourier transform is used to convert signals from time domain to frequency domain (Salivahanan, S., et al, 2000). In recent past, researchers have used some new frequency domain analysis methods like instantaneous median frequency calculated using continuous wavelet transform on SEMG analysis. The results of such study were then compared with MDF calculated using fast Fourier transform. However most of the work has been done on isometric contractions only where results from both methods were reported reliable (Coorevits et. al., 2008; Coorevits et. al., 2008). The frequency domain analysis technique used in this study for calculation of MDF is discussed in detail in next chapter.

2.3.4 Time Domain Analysis

EMG signals are continuous-time signals as they are defined as a continuous function in the time domain (Salivahanan, S., et al, 2000). Time domain analysis is based on the amplitude of the signal, which is a function of the power contained in the signal. The amplitude of EMG signals oscillates between positive and negative values, so its average is close to zero. Therefore analysis of such signals normally uses rectified or squared signals (Basmajian, J.V. and DeLuca, C. J., 1985). The most common time-domain analysis methods of bio-signal are: Root Mean Square (Vrms), Envelope of rectified signal, Zero Crossing, Phase Count and Area under the curve. Power spectral density estimation of SEMG signals for

the fatigue analysis has been done by researchers using different models. Again most of the work undertakes only data collected during isometric contraction. Recently, relatively new models like time-varying auto regressive were proposed and reported their results in comparison to conventional PSD method (Zhang et. al., 2010). The time domain analysis technique used in this study for RMS calculation is discussed in detail in next chapter.

Chapter 3

Methodology

The objective of this research is to investigate the effect of localized muscle fatigue on EMG patterns to see the feasibility of using EMG in detecting localized muscle fatigue. To achieve this, experiments on 20 participants were conducted where two-channel EMG was recorded. Standard non-invasive technique of surface EMG (SEMG) was used throughout the experiments for collecting bio-signals. Participants performed two sessions of 3-minutes each for both isometric and cyclic contractions with an interval of 1 hour. After attaching the electrodes in place, a 5-minute resting period was allowed for participants to relax. The participant's EMG was recorded for both 3-minute sessions of cyclic and isometric contractions with other conditions (e.g. laboratory temperature) remaining unchanged.

The EMG data collected from participants was preprocessed individually using signal filtering before feature extraction processes to reduce noise and movement artifact. Same feature extraction methods were used for both cyclic and isometric EMG data. Then statistical analysis was performed on extracted features to achieve the research outcome.

This chapter is divided into three sections namely *Experimental Methodology*, *Data Analysis Methodology* and *Statistical Analysis*. *Experimental Methodology* includes selection of participants, equipments and software, fixed weights for isometric and cyclic contraction exercise and procedure used for recording of

EMG signals. Details of signal processing technique, feature extraction methods of SEMG for fatigue detection are covered under *Data Analysis Methodology* section while statistical analysis method are detailed in the section titled *Statistical Analysis*.

3.1 Experimental Methodology

3.1.1 Participant Selection

Volunteers aged 18 or over were selected by responding to posters advertised in and around RMIT University. Twenty male participants were selected for this study. More detailed physical description of the participants is given in Table 2-1. Participants selected for this research fit into the selection criteria of having no history of myo or neuro-pathological disorder and/or any abnormal motion restriction. Participants selected for this study were not on any medication and advised not to have caffeine, alcohol and nicotine 24 hours prior to experiments. Experiments were conducted after receiving approval from RMIT University Ethics Committee for Human Experiments. Each participant was preaddressed 'in plain language' an oral and written summary of the experiment protocol and study purpose. Participants were made familiar with equipments used and a written consent form was signed by each participant prior to experiment procedure. A copy of consent form and screening questionnaire is attached in Appendix A and C.

Table 2- 1: Participants descriptive data

	Age (years)	Stature (cm)	Body Mass (kg)
Mean	26.2	176.4	76.1
Standard Deviation	2.6	6.0	12.5
Range	22 - 30	167 - 187	62-104

3.1.2 Equipment and Software

For collecting bipolar EMG data from participant's skin surface (SEMG), BIOPAC EMG100C amplifier and 20mm disc electrodes (Blue Sensor Ag/AgCl) were used with a highly conducting wet gel. The SEMG signals collected while performing isometric and cyclic contraction exercise with 8 lb dumbbell weight in the right hand, were preamplified (x2000), bandpass filtered (10 Hz – 500 Hz) and sampled at 1500 Hz for off-line analysis. The Bipolar SEMG was recorded using AcqKnowledge 3.8.1 (BIOPAC) software.

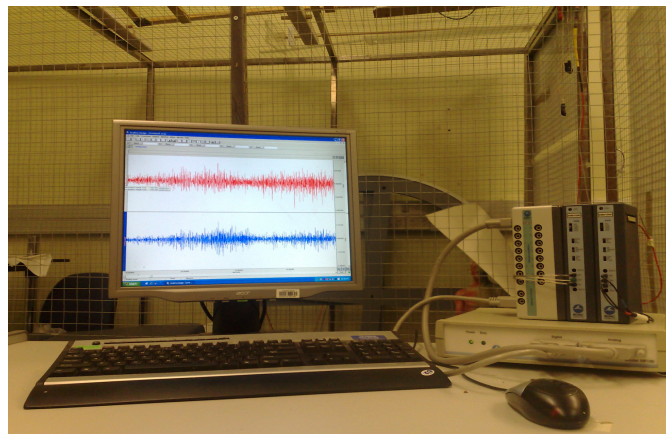


Figure 3- 1: BIOPAC EMG100C acquisition system recording SEMG signals using AcqKnowledge 3.8.1 software.

3.1.3 Experimental Protocol

The experiments were conducted in accordance with approval from the RMIT University Ethics Committee for Human Experiments. At first, participants were informed that they can withdraw their participation from study at any time without giving any reason and all data and information collected previously would be destroyed and would not be used. In plain language, participants were given an oral and a written statement explaining experiment procedure and purpose of the study. The participants were encouraged to familiar themselves with laboratory and equipments used prior to the experiment. A copy of the statement given to participants is included in the Appendix B.

The experiments were carried out during RMIT University normal working hours at Biomedical Engineering Laboratory, School of Electrical and Computer Engineering, RMIT University city campus in the presence of a third party. This was to ensure that immediate action can be taken in the event of an emergency. Before the experiments, all participants and third parties present in the experiments were briefed on how to remove the electrodes in the case of an emergency and isolate themselves from the testing equipment used. The air-conditioned laboratory maintained temperature between 20⁰C to 22⁰C throughout the experiments. The equipments were tested to ensure reproducibility of results. To minimize the motion artefacts, participants were requested to minimize movements other than isometric or cyclic biceps brachii muscle contractions of right hand during the EMG recording sessions.

To start with experiment session, participants were asked to remove any watch or jewellery from their wrist before preparing the upper arm skin area

around biceps muscle and elbow of opposite hand by cleaning with warm water and alcohol swabs. Participants sat down relaxing in a chair while disposable Ag/AgCl electrodes were attached to their right hand biceps muscle.

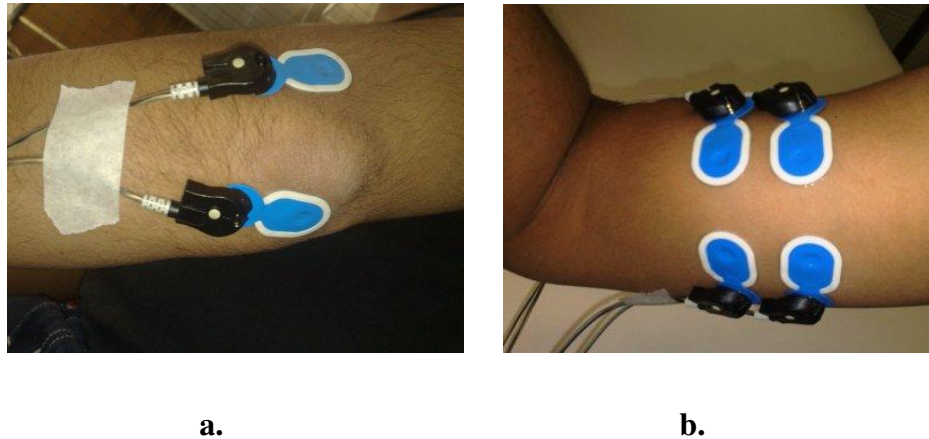


Figure 3- 2: a) Electrodes placement on biceps brachii muscle. b) Location of GND/reference electrode at elbow.

Reference electrodes were attached at elbow of opposite hand. For bipolar EMG recording, two electrodes were attached on either side of biceps muscles. Distance between centers of two electrodes on either side was kept around 25mm as shown above in Figure 3-2.

Reference electrodes were connected to GND (ground) sockets of BIOPAC EMG modules 1 and 2 via connecting cables. Electrodes from either side of biceps brachii muscle were connected to BIOPAC modules 1 and 2 via connecting cables. First and second modules were set to channel 1 and 2 respectively from the switch on top of the EMG modules. Connection of electrodes to BIOPAC EMG modules and their setting are shown in figure 3. For

all experiments following values were set for listed parameters on front of EMG modules:

Gain: 1000 (± 5 mV)

Low Pass Filter: 500 Hz

High Pass Filter: 10 Hz

Notch Filter: 50 dB @ 50 Hz



a.



b.

Figure 3- 3: a) Connection of electrodes to BIOPAC acquisition system. b) Setting of EMG modules for SEMG recording.

On computer attached to BIOPAC system, AcqKnowledge software was used to record EMG data after selecting these file settings: A1 and A2 were selected as channel 1 and 2 respectively and sampling frequency was set to 1500 for recording duration of 3-minutes. Now participants were asked to stand straight without any support and hands relaxed.

3.1.3.1 Isometric Contractions

The recording was started on Acqknowledge software and participants were asked to lift fixed weight of 8 lb in their right hand. Then participants were instructed to produce voluntary isometric contractions by holding the weight at 45 degree elbow angle between biceps brachii muscle and lower arm. Integrated signal traces were checked for clear visibility on Acqknowledge recording window, if clear traces were not visible then recording was stopped and y-axis scaling was adjusted to get the clearly visible traces of EMG.

The isometric contractions were recorded until muscle fatigue was achieved or 3-minutes elapsed, whichever falls earlier.

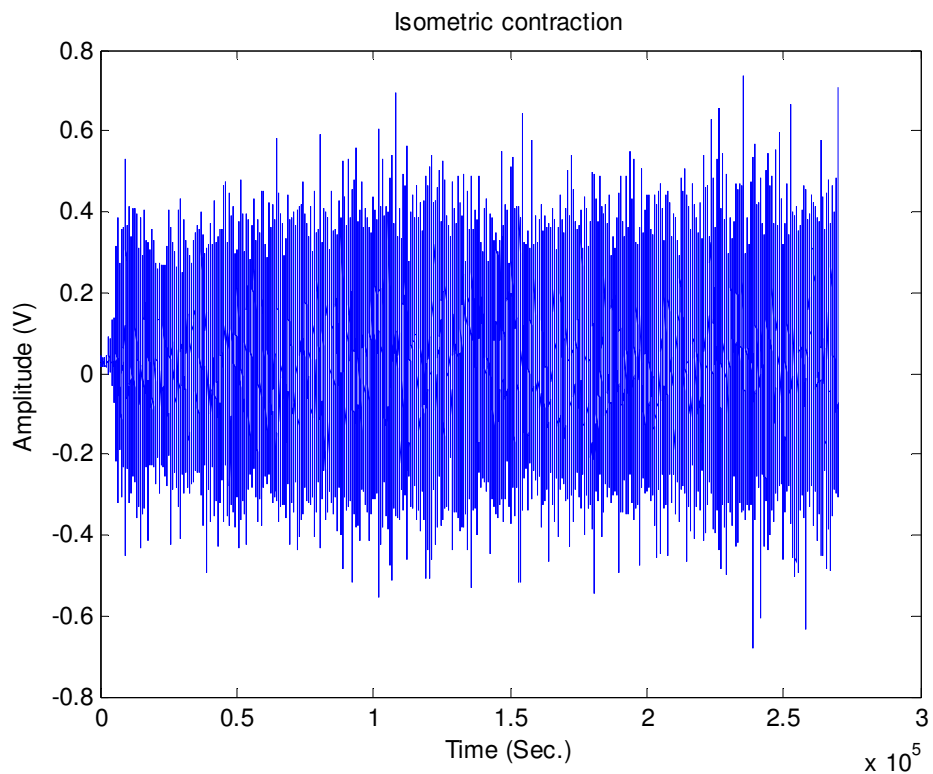


Figure 3- 4: Isometric SEMG recorded over 3-minutes.

The recordings were saved as .mat (MATLAB files) files for further processing and later offline analysis using MATLAB. At the end of this session participants were allowed to relax for an hour to get their muscles relaxed to normal.

3.1.3.2 Cyclic Contractions

The second session of EMG recording of cyclic contractions was started after relaxation of an hour. All steps of electrode attachment were completed as before with all other conditions and settings remained unchanged. Participants were asked to stand straight without any support and hands relaxed before recording was started on Acqknowledge software and participants were asked to lift fixed weight of 8 lb in their right hand. Then participants were instructed to produce repeated voluntary cyclic contractions and relaxation using biceps brachii muscle. At first participants were advised to keep the constant speed of approximately 7-8 seconds for one cycle of contraction and relaxation. Integrated signal traces were checked for clear visibility on Acqknowledge recording window, if clear traces were not visible then recording was stopped and y-axis scaling was adjusted to get the clearly visible traces of EMG. The cyclic contractions were recorded until muscle fatigue was achieved or 3-minutes whichever falls earlier.

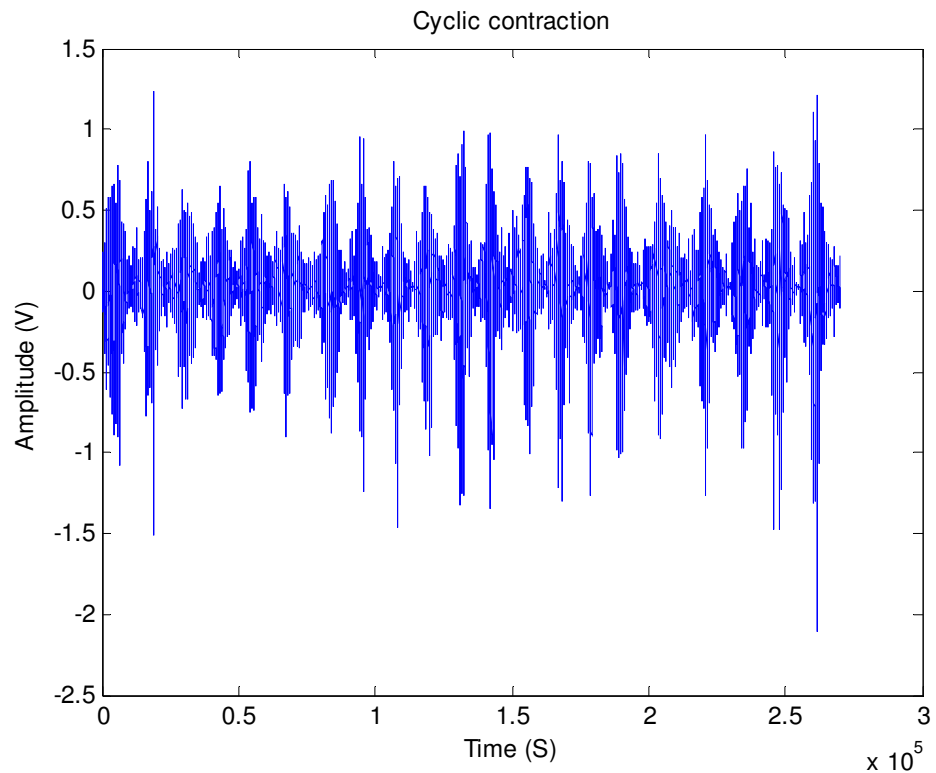


Figure 3- 5: Cyclic SEMG recorded over 3-minutes.

The recordings were saved as .mat (MATLAB files) files for further processing and later offline analysis using MATLAB.

3.2 Data Analysis

To remove the artifacts from raw SEMG collected during cyclic and isometric contraction exercises, signals were processed before feature extraction. The key factor affecting the feature extraction process is the presence of noise such as electrical noise and artefacts from other biological signals in raw signal. Following subsections explain the Signal Processing and Feature Extraction techniques used in this research.

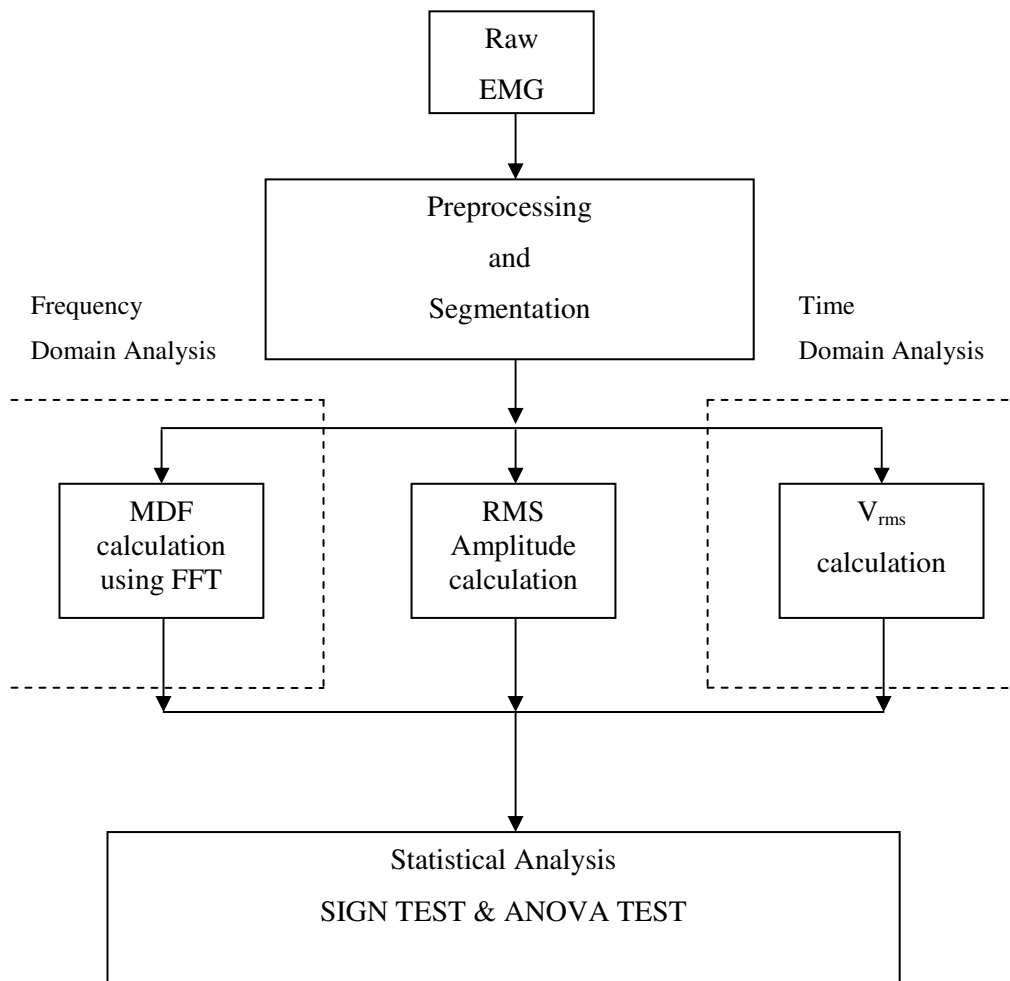


Figure 3- 6: Data Analysis Flow-chart.

The flow chart above explains the analysis of recorded SEMG data in order to get experimental results. The raw EMG signal is first filtered using inbuilt notch filter to minimize noise. The output signal is band-passed to remove artifacts and unwanted frequencies. This filtered output is segmented using different window sizes as needed for further analysis. Window size selected for MDF analysis is 50ms and 100ms in case of cyclic contractions and 10s in case of isometric contraction (Singh et. al, 2006). Two window sizes are selected to confirm the

non-stationary nature of spectrum in case of MDF analysis. In case of Vrms calculation, window size of 1s for isometric and 100ms for cyclic are selected. Window sizes selected are same as advised and evidenced in literature as (Singh et. al, 2006).

3.2.1 Signal Preprocessing

In order to remove noise from raw signal, Figure 3-7 explains the steps involved before the feature extraction process. Raw signals were filtered through a low-pass filter of cut-off frequency 500 Hz. The signals were then filtered through high-pass filter with filtering frequency over 10 Hz. Values selected for filters are as suggested by the BIOPAC literature for recording of SEMG signals (Macy A. and Dimov A., 2009). The output signal was differentiated and squared before further analysis. BIOPAC SYSTEMS have an in built system to reduce the noise by using a notch filter.

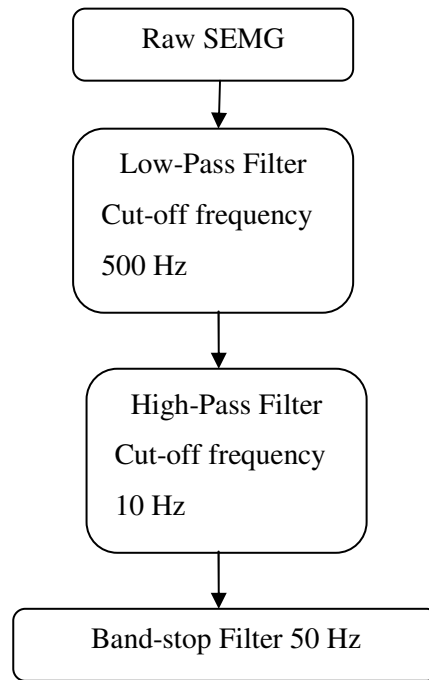


Figure 3- 7: Preprocessing of raw SEMG signal.

3.2.2 Frequency Domain Analysis

In the frequency domain analysis, required measures are calculated from power spectrum of preprocessed EMG signal. Median frequency (MDF) is the most important parameter used for detection of onset of muscle fatigue. The frequency domain is explained later in next section. MDF extraction from the power spectrum of SEMG involves the following steps: Fast Fourier Transform (FFT) of SEMG signal, squaring of FFT generated, integration and normalization. Now as by definition, MDF is the frequency at which 50% of total power within the epoch is reached.

3.2.2.1 Median Frequency (MDF) analysis

To process an analog signal, it is essential to follow the sampling technique. Sampling is the process of taking values of a continuous-time (analog) signal $[x(t)]$ at specific (or selected) time intervals that can be used for analysis. The resulting signal is called discrete-time signal that can be digitized and then processed using digital systems (like the computer) (Salivahanan, S., et al, 2000, Hussain Z., M., 2003). It is only possible to reconstruct the original signal with the use of the sampled points only if sampling theorem is satisfied:

"For a continuous signal that contains no frequency higher than F_c , the original signal can be recovered without distortion if it is sampled at a rate of at least $2F_c$ samples per second." (Rabiner, L. R., and B. Gold., 1975, Salivahanan, S., et al, 2000, Cosic, I., 2003.). A sampling frequency of twice the highest frequency present in the signal is called Nyquist frequency. Spectral analysis could be studied using the Discrete Fourier Transform (DFT). DFT is one of the most important tools in digital signal processing. It is used in three common ways. First, the DFT can calculate a signal's frequency spectrum. This is a direct examination of information encoded in the frequency, phase, and amplitude of the component sinusoids. Second, the DFT can find a system's frequency response from the system's impulse response, and vice versa. Third, the DFT can be used as an intermediate step in more elaborate signal processing techniques (Smith, S., W., www.dspguide.com/specanal.htm).

Fourier Transform (FT): Assuming that a discrete non-periodic signal is a sequence of data sampled from an analogue signal with sampling period T and

frequency $1/T$ ($\omega = 2\pi/T$) then the Fourier transformation $X(\omega)$ of a signal $x(n)$ is defined as follows:

$$X(\omega) = \sum_{n=0}^{n=\infty} x(n) \times e^{-j\omega nT} \quad (3-1)$$

It is an important property of the Fourier transform that it is repetitive at intervals of sampling frequency in both positive and negative direction. In practice normalized frequencies are used, i.e. $T=1$:

$$X(k) = \sum x(n) \cdot e^{-j\omega nT} \quad (3-2)$$

Discrete Fourier Transform (DFT): DFT refers to the calculation of the FT for a discrete period of time of the signal under analysis. This transform evaluates only a finite number of complex coefficients, when the total number N being equal to the original number of data points in one period of the original signal (Salivahanan, S., et al, 2000, Cosic, I., 2003):

$$X(k) = \sum_{n=0}^N x(n) \times e^{-j\omega nT} \quad (3-3)$$

Fast Fourier Transform (FFT): Computation of FT was time consuming, so it was a big barrier in applied signal processing. In 1995, an efficient algorithm was proposed to compute the DFT in a reasonably easier way. The name of Fast Fourier Transform (FFT) is applied to this computational algorithm, which is used for faster computation of DFT coefficient. (Salivahanan, S., et al, 2003; Hussain, Z., M., 2003).

3.2.3 Time Domain Analysis

Modulation of the amplitude due to muscular effort and/or fatigue represents the dominant change of SEMG signal in the time domain. According to Clancy (Clancy et. al, 2002) the amplitude of the single channel SEMG signal can be estimated using cascade of five sequential processing stages: noise rejection/filtering, whitening, amplitude demodulation, smoothing and re-linearization.

3.2.3.1 Root Mean Square (Vrms) analysis

The root mean square or (RMS) is a statistical measure of the magnitude of a varying quantity. It can be calculated for a series of discrete values or for a continuously varying function. The name comes from the fact that it is the square root of the mean of the squares of the values (Clancy et. al, 2002).

The RMS for a collection of N values $\{X_1, X_2, \dots, X_N\}$ is:

$$x_{rms} = \sqrt{\frac{1}{N} \sum_{i=1}^N x_i^2} = \sqrt{\frac{x_1^2 + x_2^2 + \dots + x_N^2}{N}} \quad (3-4)$$

and the corresponding formula for a continuous function $f(t)$ defined over the interval $T_1 \leq t \leq T_2$ is:

$$x_{rms} = \sqrt{\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} [f(t)]^2 dt} \quad (3-5)$$

In both equations

X_i is the i th sample of a signal and

N is the number of samples in the epoch.

The RMS is one of the most commonly used methods that measures the amplitude of a bio-signal. The amplitude of a bio-signal expresses the magnitude of the energy (or power) of that particular signal (Basmajian, J.Y. and C. J. Deluca, C., Y., 1985; Cram, J.R., et al, 1998). Measurement of RMS in different conditions affecting a biological system can give an index of the changes related to that particular effect, which can be used in EMG signal analysis.

3.3 Statistical Analysis

To understand the relationship between physical measures and physiological mechanisms, results of experiment conducted under cyclic and isometric conditions are interpreted to investigate the effect of reduction in force of contraction due to localized muscle fatigue on physical measures. Surface EMG data recorded from Biceps Brachii muscle from 20 male subjects are analyzed to show the onset of muscle fatigue during both cyclic and isometric conditions.

3.3.1 Sign Test

Sign test is used to test the hypothesis that there is no difference between the continuous distributions of two variables X and Y. For recorded set of data, Sign test has been used to perform a paired, two-sided sign test of the null hypothesis that data in the vector x-y comes from a continuous distribution with zero median, against the alternative that the distribution does not have zero median. Vectors x and y have same length which satisfies sign-test condition.

$$[p, h] = \text{signtest}(x, y) \quad (3-6)$$

P = probability

h = indicator of rejection of null hypothesis

h = 0 indicates failure of rejection of null hypothesis

h = 1 indicates rejection of null hypothesis

3.3.2 ANOVA Test

ANOVA stands for 'analysis of variance'. This is a statistical model for comparing the means of two or more groups in order to determine whether a significant difference exist between the groups. The purpose of a one-way ANOVA is to find out whether data from several groups have a common mean. That is, to determine whether the groups are actually different in the measured characteristic.

One-way ANOVA is a simple special case of the linear model. The one-way ANOVA form of the model is

$$y_{ij} = \alpha_j + \epsilon_{ij} \quad (3-7)$$

where:

- y_{ij} is a matrix of observations in which each column represents a different group.

- α_j is a matrix whose columns are the group means. (The "dot j " notation means that α applies to all rows of column j . That is, the value α_{ij} is the same for all i .)
- ε_{ij} is a matrix of random disturbances.

The model assumes that the columns of y are a constant plus a random disturbance.

3.3.3 Reporting Results and Terminology

The result of one way ANOVA performed is displayed in table format. One of the results is displayed below as an example only from one set of readings:

Table 3- 1: Example of ANOVA table generated using MATLAB.

ANOVA Table					
Source	SS	df	MS	F	Prob>F
Columns	0.0785	1	0.0785	10.7	0.0023
Error	0.27882	38	0.00734		
Total	0.35732	39			

The following terminologies refer to ANOVA table:

- **Model:** An ANOVA model is a mathematical equation that relates the measured response of the elements to the sources of variation using a number of assumptions.
- **Sum of Squares:** Term refers to a sum of squares numbers. For example, in the calculation of variance (s^2) of a sample of n independent observations (Y_1, Y_2, \dots, Y_n)

$$s^2 = \frac{\sum_{i=1}^n (Y_i - Y_x)^2}{n - 1} \quad (3-8)$$

Where the numerator of s^2 is a sum of squares the squares of the differences between the observed values (Y_i) and the sample mean (Y_x). In ANOVA, the sum of squares of a source of variation is a measure of variability due to that source. Sum of squares is denoted as SS.

- Degree of freedom: the degree of freedom refers to the number of independent observations that are calculated in the sum of squares (SS). It is denoted as df.
- Mean squares: The mean square of a source of variation is its sum of squares divided by its associated degrees of freedom. It is denoted as MS.
- F / F_{obtained} : F ratio value calculated from data used for ANOVA
- $\text{Prob}>F / F_{\text{critical}}$: F value found on F table to make decision about rejecting the Null hypothesis.

The ANOVA analysis was performed as explained above on the recorded data set. The results of ANOVA test has been reported and explained in chapter 4.

Chapter 4

Fatigue Analysis using SEMG - Results and Discussion

In this chapter, the outcomes of this research which investigates the effect of localized muscle fatigue are detailed along-with observations and discussion. This chapter is subtitled into three segments namely *Frequency Domain Analysis*, *Time Domain Analysis* and *Statistical Analysis*. In frequency-domain analysis, SEMG feature extraction was performed using Fourier transform and median frequency (MDF) was calculated and discussed. Time-domain analysis covers the SEMG feature extraction by plotting amplitude over time and Vrms (Root Mean Square voltage) calculation and discussion. In statistical analysis, sign-test and ANOVA test were used to test whether there is a statistically significant difference between the before and after fatigue values calculated using frequency and time domain analysis.

4.1 Feature Extraction of SEMG - Frequency Domain Analysis

The results of the median frequency (MDF) computed from the power density spectrum (PDS) of Surface electromyography (SEMG) recorded from 20 subjects have been tabulated here in Table 4-1 to Table 4-3. Table 4-1 presents the results for isometric contraction while Table 4-2 and Table 4-3 present the results from cyclic contraction exercise.

4.1.1 Isometric Contraction

In Table 4-1, MDF value of each subject at three points i.e. before fatigue, at half-time and after fatigue during isometric contractions have been tabulated along-with before to after fatigue ratio.

From table 4-1, it is observed that there is a noticeable decrease in the MDF of all but 1 subject for channel 1. For channel 2, MDF decrease with onset of muscle fatigue for all 20 subjects. This observation is synonymous with the hypothesis proposed based on current literature.

Figure 4-1 shows the average median frequency (MDF) of all participants for both channel 1 and 2 with their respective standard deviation for before and after fatigue condition during isometric contraction (window size: 10s). Detailed plots for individual participant value for both channels are included in Appendix D. Figure 4-2 presents the after to before (A/B) MDF ratio for all participants for both channels with their corresponding standard deviation value during isometric contraction (window size: 10s). Detailed plot with individual value for each participant is included in Appendix D.

Table 4- 1: MDF (Hz) of subjects during isometric contractions.

Subject	Before Fatigue		After Fatigue		Fatigue at Half-Time		After to Before Fatigue Ratio (A/B)	After to Before Fatigue Ratio (A/B)
	Channel 1	Channel 2	Channel 1	Channel 2	Channel 1	Channel 2	Channel 1	Channel 2
1	98.69	86.79	101.44	78	98.79	80.11	1.027865	0.898721
2	65.1	72.97	61.15	62.44	63.99	67.75	0.939324	0.855694
3	68.85	69.67	62.71	60.24	63.63	61.16	0.910821	0.864648
4	106.29	98.42	98.24	84.32	99.88	88.72	0.924264	0.856736
5	103.55	97.5	97.6	93.84	98.1	97.69	0.94254	0.962462
6	60.7	64	56.3	61.62	56.95	64.27	0.927512	0.962813
7	81.21	89.36	74.71	78.74	75.07	84.67	0.919961	0.881155
8	83.95	81.39	76.63	74.89	78	77.82	0.912805	0.920138
9	90	100.9	82.31	96.67	85.24	99.15	0.914556	0.958077
10	79.93	86.33	76.72	78.1	78.64	78.92	0.95984	0.904668
11	92.83	84.5	81.02	68.48	88.99	75.26	0.872778	0.810414
12	85.78	80.75	81	77.71	82.58	79.38	0.944276	0.962353
13	91.46	86.51	76.26	71.69	82.58	75.81	0.833807	0.82869
14	94.57	93.57	80.75	88.71	83.31	89.81	0.853865	0.94806
15	89.1	82.58	74.34	71.77	81.21	76.72	0.834343	0.869097
16	84.5	90.73	82.49	78.64	83.4	81.48	0.976213	0.866747
17	97.14	86.88	86.7	82.12	91.1	83.95	0.892526	0.945212
18	101.72	87.89	87.89	72.51	93.57	76.45	0.864039	0.825009
19	92.1	90.64	90.17	84.87	90.73	85.97	0.979045	0.936342
20	99.79	81.57	93.57	69.76	93.48	75.71	0.937669	0.855216

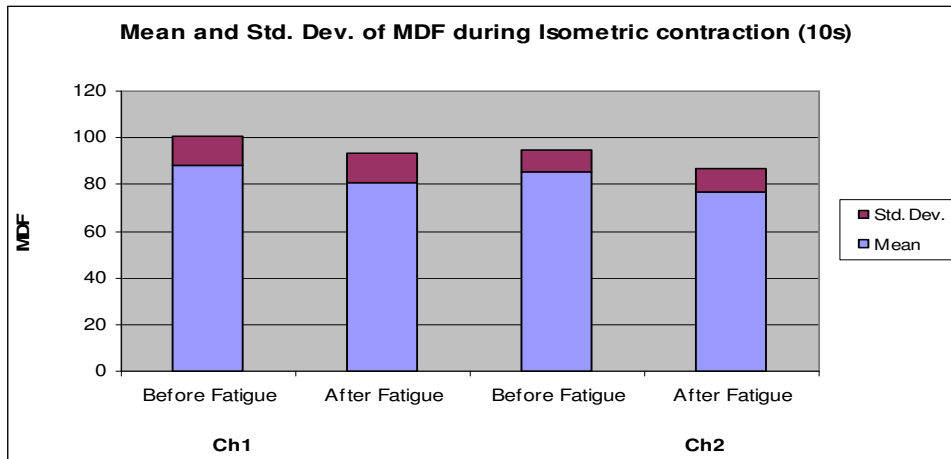


Figure 4- 1: MDF Isometric Contraction (10s)

From Figure 4-1, it is observed that for channel 1 mean MDF decreases from 88.36 (\pm SD12.52) to 81.1 (\pm SD12.14) and for channel 2 mean MDF decreases from 85.65 (\pm SD9.25) to 76.76 (\pm SD9.98). Also it is observed that Mean of MDF decreases after fatigue condition for both channels.

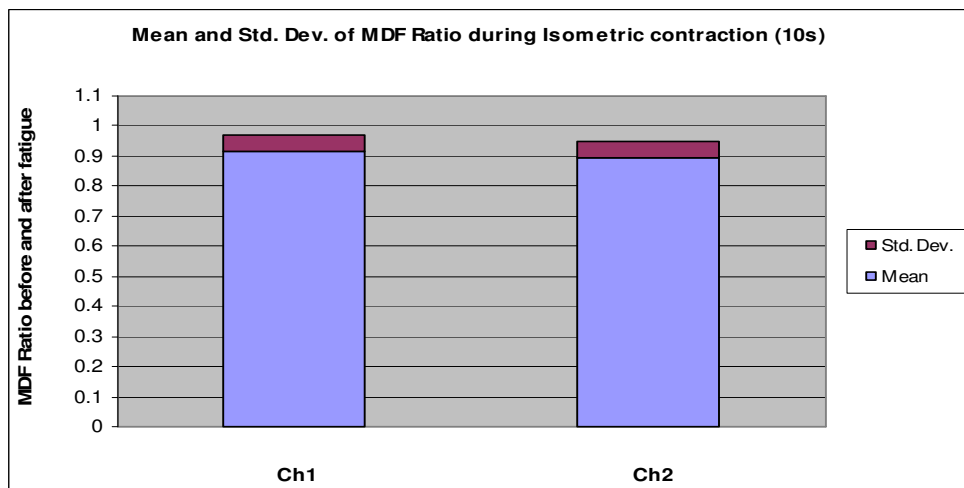


Figure 4- 2: MDF Isometric Contraction (10s)

From Figure 4-2, it is observed that for channel 1 the mean of ratio of MDF for after fatigue to before fatigue condition is 0.918 (\pm SD0.05) and for

channel 2 mean of ratio of MDF for after fatigue to before fatigue condition is 0.896 (\pm SD0.05). Also it is observed that the Mean of ratio of MDF for after fatigue to before fatigue condition for both channels lies below 1 indicating a decrease in MDF after fatigue condition for both channels.

The results suggest that the ratio of the MDF between before and after fatigue indicates the presence of fatigue in both the channels during isometric contraction. From the tables shown above, it can be observed that the mean MDF decreases during the after fatigue contraction due to onset of localized muscle fatigue.

4.1.2 Cyclic Contraction

The results when subjects performed cyclic contractions have been tabulated in Table 4-2 and 4-3. Table 4-2 contains the MDF value of each subject calculated with 100ms time window at three points i.e. before fatigue, at half-time and after fatigue during cyclic contractions while with time window of 50ms have been tabulated in table 4-3.

From table 4-2, it is observed that for both channels 1 and 2, 30% of subjects show clear shift in PDS towards lower frequencies as evident by A/B MDF ratio while 15% subjects show reversed trend for both channels of PDS shift. One of subjects show no change in MDF for either channel while the rest of the subjects provide no clear result where one of the channels shows no MDF change on onset of fatigue or shows reverse trend of PDS shift compared to another channel.

Table 4- 2: MDF (Hz) of subjects during cyclic contractions.

Subject	Before Fatigue		After Fatigue		Fatigue at Half-Time		After to Before Fatigue Ratio (A/B)	After to Before Fatigue Ratio (A/B)
	Channel 1	Channel 2	Channel 1	Channel 2	Channel 1	Channel 2	Channel 1	Channel 2
1	58.59	70.31	29.3	58.59	41.02	52.73	0.500085	0.83331
2	52.73	64.45	46.88	76.17	41.02	46.88	0.889057	1.181846
3	64.45	82.03	64.45	64.45	76.18	52.73	1	0.785688
4	52.73	58.59	70.31	58.59	41.02	52.73	1.333397	1
5	52.73	46.88	46.88	41.02	52.73	46.88	0.889057	0.875
6	52.73	52.73	41.02	58.59	41.02	52.73	0.777925	1.111132
7	76.17	52.73	64.45	58.59	64.45	64.45	0.846134	1.111132
8	41.02	35.16	58.59	46.88	35.16	41.02	1.428328	1.333333
9	82.03	76.17	52.73	64.45	52.73	64.45	0.642814	0.846134
10	46.88	70.31	52.73	70.31	52.73	70.31	1.124787	1
11	52.73	58.59	52.73	58.59	58.59	64.45	1	1
12	70.31	46.88	87.89	64.45	87.89	82.03	1.250036	1.374787
13	46.88	52.73	41.02	58.59	46.88	46.88	0.875	1.111132
14	46.88	70.31	58.59	64.45	41.02	64.45	1.249787	0.916655
15	70.31	76.17	58.59	52.73	70.31	46.88	0.83331	0.692267
16	52.73	70.31	41.02	46.88	52.73	70.31	0.777925	0.666761
17	41.02	46.88	52.73	64.45	58.59	64.45	1.285471	1.374787
18	64.45	52.73	41.02	46.88	41.02	52.73	0.636462	0.889057
19	64.45	58.59	58.59	52.73	64.45	64.45	0.909077	0.899983
20	70.31	58.59	64.45	46.88	46.88	58.59	0.91665	0.800137

Table 4- 3: MDF (Hz) of subjects during cyclic contractions using 50ms time window.

Subject	Before Fatigue		After Fatigue		Fatigue at Half-Time		After to Before Fatigue Ratio (A/B)	After to Before Fatigue Ratio (A/B)
	Channel 1	Channel 2	Channel 1	Channel 2	Channel 1	Channel 2	Channel 1	Channel 2
1	46.88	82.03	46.88	46.88	35.16	46.88	1	0.571498
2	58.59	70.31	46.88	58.59	46.88	46.88	0.800137	0.83331
3	58.59	58.59	46.88	58.59	93.75	46.88	0.800137	1
4	58.59	82.03	58.59	70.31	46.88	70.31	1	0.857125
5	70.31	58.59	70.31	70.31	82.03	46.88	1	1.200034
6	58.59	70.31	35.16	70.31	59.59	58.59	0.600102	1
7	82.03	58.59	46.88	46.88	58.59	46.88	0.571498	0.800137
8	46.88	46.88	82.03	58.59	35.16	58.59	1.749787	1.249787
9	58.59	70.31	58.59	46.88	58.59	58.59	1	0.666761
10	82.03	58.59	58.59	70.31	58.59	70.31	0.714251	1.200034
11	58.59	46.88	70.31	58.59	46.88	58.59	1.200034	1.249787
12	70.31	46.88	105.47	70.31	93.75	93.75	1.500071	1.499787
13	93.75	82.03	46.88	58.59	46.88	46.88	0.500053	0.714251
14	46.88	70.31	70.31	82.03	58.59	70.31	1.499787	1.16669
15	82.03	93.75	70.31	70.31	82.03	46.88	0.857125	0.749973
16	46.88	58.59	46.88	46.88	46.88	58.59	1	0.800137
17	105.47	58.59	70.31	58.59	70.31	70.31	0.666635	1
18	70.31	46.88	58.59	46.88	58.59	70.31	0.83331	1
19	70.31	70.31	58.59	58.59	70.31	58.59	0.83331	0.83331
20	93.75	82.03	70.31	46.88	58.59	58.59	0.749973	0.571498

From Table 4-3, it is observed that for both channels 1 and 2, no clear shift in PDS towards lower frequencies is observed as evident by A/B MDF ratio. In 23% cases no change in MDF value was observed between before and after fatigue values. Similar to Table 4-2, no clear visible pattern is observed.

Figure 4-3 shows the average median frequency (MDF) of all participants for both channel 1 and 2 with their respective standard deviation for before and after fatigue condition during cyclic contraction (window size: 100ms). Detailed plots for individual participant value for both channels are included in Appendix D. Figure 4-4 presents the after to before (A/B) MDF ratio for all participants for both channels with their corresponding standard deviation value during cyclic contraction (window size: 100ms). Detailed plot with individual value for each participant is included in Appendix D.

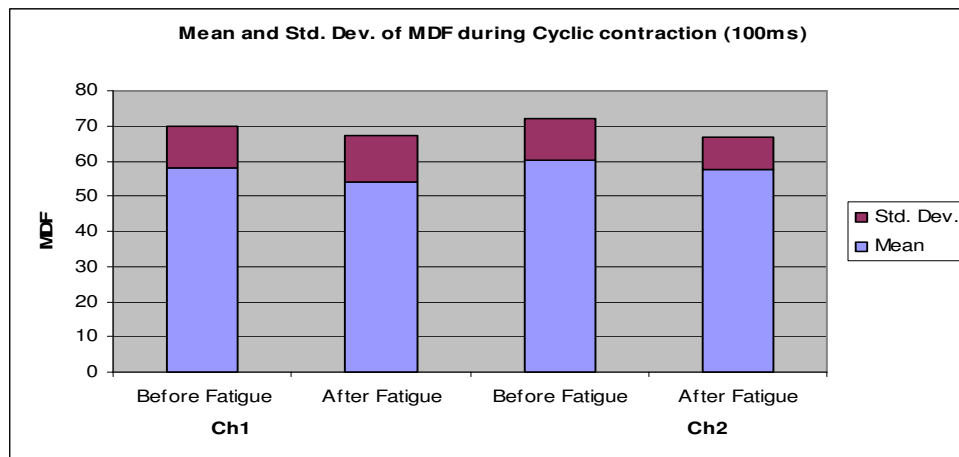


Figure 4- 3: MDF Cyclic Contraction (100ms)

From Figure 4-3, it is observed that for channel 1 mean MDF decreases from 58.01 (\pm SD11.7) to 54.2 (\pm SD13.01) and for channel 2 mean MDF decreases from 60.06 (\pm SD12.15) to 57.71 (\pm SD8.97). Also it is

observed that Mean of MDF decreases slightly in after fatigue condition for both channels.

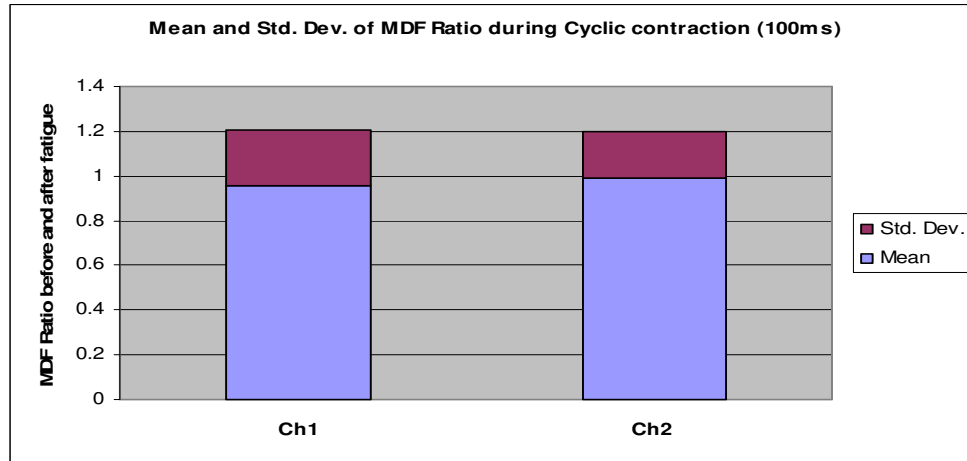


Figure 4- 4: MDF Cyclic Contraction (100ms)

From Figure 4-4, it is observed that For channel 1 mean of ratio of MDF for after fatigue to before fatigue condition is 0.96 (\pm SD0.25) and for channel 2 mean of ratio of MDF for after fatigue to before fatigue condition is 0.99 (\pm SD0.21). Also it is observed that Mean of ratio of MDF for after fatigue to before fatigue condition for both channels lies just below 1 indicating a little decrease in MDF in after fatigue condition for both channels.

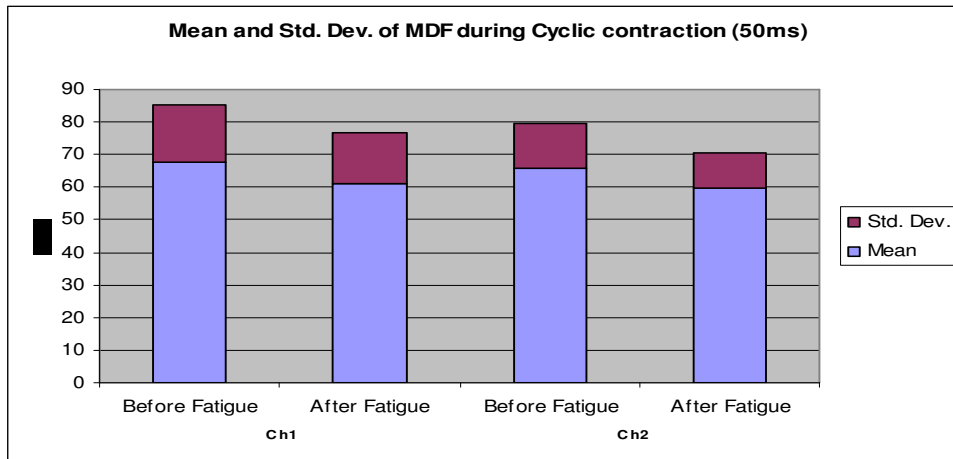


Figure 4- 5: MDF Cyclic Contraction (50ms)

Figure 4-5 shows the average median frequency (MDF) of all participants for both channel 1 and 2 with their respective standard deviation for before and after fatigue condition during cyclic contraction (window size: 50ms). Detailed plots for individual participant value for both channels are included in Appendix D.

From Figure 4-5, it is observed that for channel 1 mean MDF decreases from 67.97 (\pm SD17.26) to 60.93 (\pm SD15.95) and for channel 2 mean MDF decreases from 65.62 (\pm SD13.92) to 59.77 (\pm SD10.68). Also it is observed that Mean of MDF decreases in after fatigue condition for both channels.

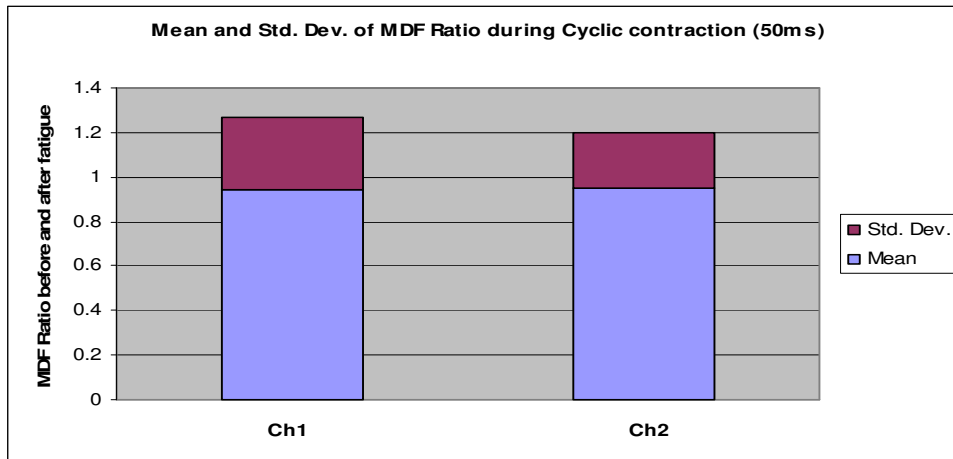


Figure 4- 6: MDF Cyclic Contraction (50ms)

Figure 4-6 presents the after to before (A/B) MDF ratio for all participants for both channels with their corresponding standard deviation value during cyclic contraction (window size: 50ms). Detailed plot with individual value for each participant is included in Appendix D.

From Figure 4-6, it is observed that for channel 1 mean of ratio of MDF for after fatigue to before fatigue condition is 0.94 (\pm SD0.33) and for channel 2 mean of ratio of MDF for after fatigue to before fatigue condition is 0.95 (\pm SD0.25). Also it is observed that Mean of ratio of MDF for after fatigue to before fatigue condition for both channels lies below 1 indicating decrease in MDF in after fatigue condition for both channels.

The results suggest that the ratio of the MDF between before and after fatigue does not indicate the presence of fatigue in both the channels during cyclic contraction. From the tables above, it can be observed that the mean MDF does not show any noticeable decreases during the after fatigue contraction due to onset of localized muscle fatigue.

4.2 Feature Extraction of SEMG - Time Domain Analysis

The results of the root mean square (V_{rms}) computed from the amplitude of Surface electromyography recorded from 20 subjects have been tabulated.

4.2.1 Isometric Contraction

The results of the root mean square (V_{rms}) calculated for isometric contractions have been tabulated in Table 4-4.

From Table 4-4, it is observed that in all cases V_{rms} value increases towards the end of isometric contraction as clearly visible from the table. No reverse trend is observed. Increase of V_{rms} value in after fatigue condition is observed more strongly for channel 2 than channel 1.

Figure 4-7 shows the average root-mean-square value (V_{rms}) of all participants for both channel 1 and 2 with their respective standard deviation for before and after fatigue condition during isometric contraction. Detailed plots for individual participant value for both channels are included in Appendix D. Figure 4-8 presents the after to before (A/B) V_{rms} ratio for all participants for both channels with their corresponding standard deviation value during isometric contraction. Detailed plot with individual value for each participant is included in Appendix D.

Table 4- 4: Vrms (mV) of subjects during isometric contractions.

Subject	Before Fatigue		After Fatigue		After to Before Fatigue Ratio (A/B) of Channel 1	After to Before Fatigue Ratio (A/B) of Channel 2
	Channel 1	Channel 2	Channel 1	Channel 2		
1	0.0626	0.1446	0.1111	0.4348	1.77476	3.006916
2	0.0977	0.1007	0.1563	0.4349	1.599795	4.318769
3	0.1679	0.1464	0.2157	0.1567	1.284693	1.070355
4	0.0888	0.1232	0.1591	0.2908	1.791667	2.36039
5	0.0434	0.046	0.0743	0.083	1.711982	1.804348
6	0.2858	0.1222	0.4137	0.4574	1.447516	3.743044
7	0.1061	0.0664	0.138	0.1169	1.30066	1.760542
8	0.1592	0.1824	0.2191	0.2431	1.376256	1.332785
9	0.2229	0.1198	0.29	0.3348	1.301032	2.794658
10	0.0971	0.0771	0.1415	0.1781	1.457261	2.309987
11	0.0656	0.0908	0.0869	0.1451	1.324695	1.598018
12	0.1364	0.0827	0.1802	0.2021	1.321114	2.443773
13	0.0875	0.1141	0.1421	0.2003	1.624	1.755478
14	0.1242	0.1408	0.1543	0.2218	1.242351	1.575284
15	0.0807	0.1061	0.1538	0.2045	1.905824	1.927427
16	0.0613	0.0538	0.0766	0.1612	1.249592	2.996283
17	0.0622	0.0956	0.0783	0.1392	1.258842	1.456067
18	0.0835	0.0449	0.1296	0.1598	1.552096	3.55902
19	0.0851	0.1243	0.144	0.2248	1.692127	1.808528
20	0.1011	0.0663	0.2163	0.1308	2.139466	1.972851

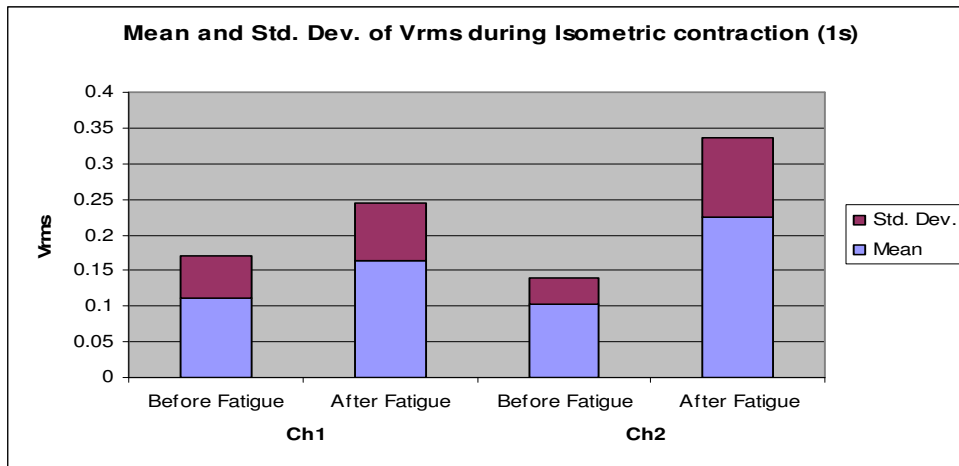


Figure 4- 7: Vrms Isometric Contraction (1s)

From Figure 4-7, it is observed that for channel 1 mean Vrms increases from 0.11 (\pm SD0.059) to 0.164 (\pm SD0.08) and for channel 2 mean Vrms increases from 0.102 (\pm SD0.037) to 0.227 (\pm SD0.11). Also it is observed that Mean of Vrms increases in after fatigue condition for both channels.

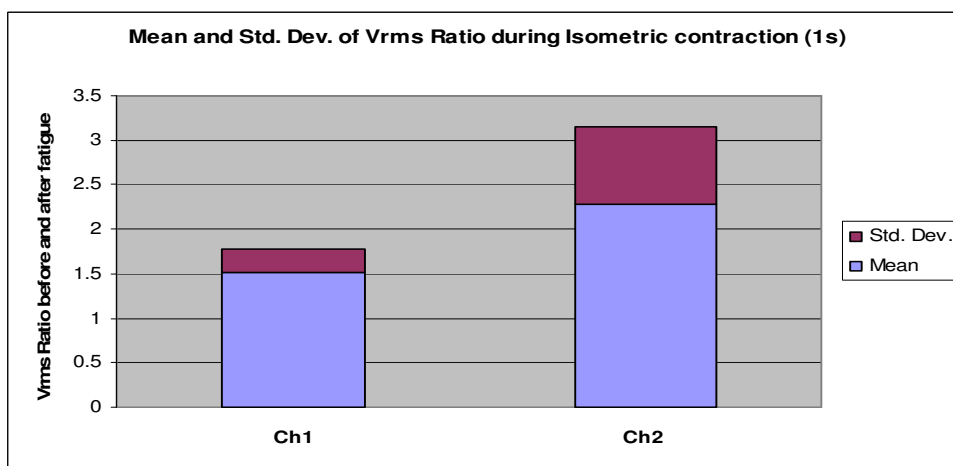


Figure 4- 8: Vrms Isometric Contraction (1s)

From Figure 4-8, it is observed that for channel 1 mean of ratio of Vrms for after fatigue to before fatigue condition is 1.52 (\pm SD0.25) and for channel 2 mean of ratio of Vrms for after fatigue to before fatigue condition is 2.28 (\pm SD0.87). Also it is observed that Mean of ratio of Vrms for after fatigue to

before fatigue condition for both channels lies well above 1 indicating significant increase in Vrms in after fatigue condition for both channels.

The results suggest that the ratio of the Vrms between before and after fatigue indicates the presence of fatigue in both the channels during isometric contraction. The ratio was high in the channel 2 which shows the muscle activation at the distal end had more effect due to fatigue. From the Figure 4- 7 above, it can be observed that the mean Vrms increases during the fatigue stage and it is sustained towards the end of the fatigue state.

4.2.2 Cyclic Contraction

The results of the Vrms calculated for cyclic contractions have been tabulated in Table 4-5. From Table 4-5, it is observed that after fatigue Vrms value is greater than before fatigue values in all cases as clearly visible from the table. Again as in Table 4-4, increase of Vrms value in after fatigue condition is observed more strongly for channel 2 than channel 1.

Figure 4-9 shows the average root-mean-square value (Vrms) of all participants for both channel 1 and 2 with their respective standard deviation for before and after fatigue condition during cyclic contraction (window size: 100ms). Detailed plots for individual participant value for both channels are included in Appendix D. Figure 4-10 presents the after to before (A/B) Vrms ratio for all participants for both channels with their corresponding standard deviation value during cyclic contraction (window size: 100ms). Detailed plot with individual value for each participant is included in Appendix D.

Table 4- 5: Vrms (mV) of subjects during cyclic contractions.

Subject	Before Fatigue		After Fatigue		After to Before Fatigue Ratio (A/B) of Channel 1	After to Before Fatigue Ratio (A/B) of Channel 2
	Channel 1	Channel 2	Channel 1	Channel 2		
1	0.15	0.2463	0.2243	0.439	1.495333	1.782379
2	0.1046	0.1877	0.1232	0.2164	1.17782	1.152904
3	0.1385	0.1552	0.2088	0.2454	1.507581	1.581186
4	0.2047	0.3824	0.2489	0.4592	1.215926	1.200837
5	0.1087	0.1292	0.1462	0.1739	1.344986	1.345975
6	0.3919	0.1889	0.497	0.2842	1.268181	1.5045
7	0.1174	0.1289	0.1628	0.1516	1.386712	1.176106
8	0.2684	0.2666	0.3427	0.351	1.276826	1.316579
9	0.2322	0.2796	0.3348	0.4378	1.44186	1.565808
10	0.1014	0.1146	0.1624	0.2397	1.601578	2.091623
11	0.0694	0.1029	0.1164	0.1561	1.677233	1.517007
12	0.217	0.2148	0.3441	0.3595	1.585714	1.67365
13	0.1342	0.194	0.1465	0.2208	1.091654	1.138144
14	0.1817	0.1699	0.2998	0.3179	1.649972	1.871101
15	0.1334	0.1468	0.2112	0.2989	1.583208	2.036104
16	0.134	0.1185	0.137	0.2074	1.022388	1.750211
17	0.1037	0.0913	0.1515	0.1623	1.460945	1.777656
18	0.1121	0.1107	0.1539	0.1691	1.372881	1.527552
19	0.1374	0.1861	0.2117	0.2542	1.540757	1.365932
20	0.2477	0.1931	0.2804	0.2351	1.132015	1.217504

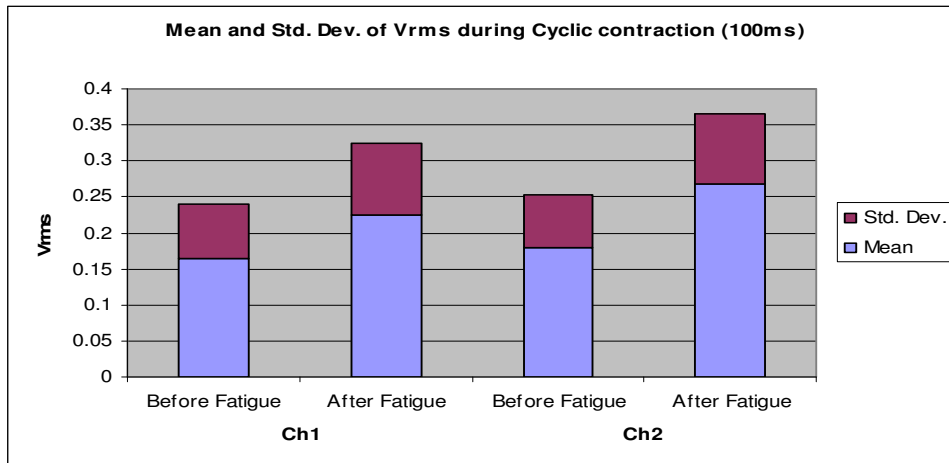


Figure 4- 9: Vrms Cyclic Contraction (100ms)

From Figure 4-9, it is observed that for channel 1 mean Vrms increases from 0.164 (\pm SD0.077) to 0.225 (\pm SD0.098) and for channel 2 mean Vrms increases from 0.18 (\pm SD0.072) to 0.27 (\pm SD0.097). Also it is observed that Mean of Vrms increases in after fatigue condition for both channels.

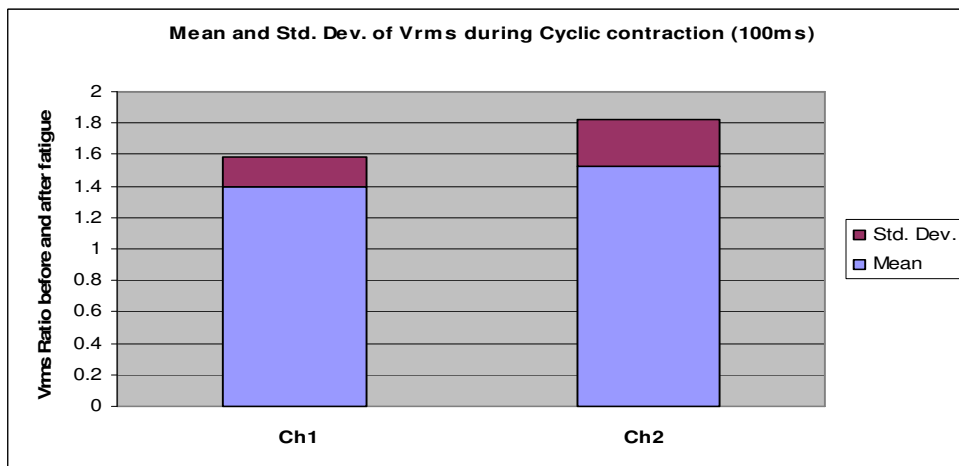


Figure 4- 10: Vrms Cyclic Contraction (100ms)

From Figure 4-10, it is observed that for channel 1 mean of ratio of Vrms for after fatigue to before fatigue condition is 1.4 (\pm SD0.19) and for channel 2 mean of ratio of Vrms for after fatigue to before fatigue condition is 1.53

(\pm SD0.29). Also it is observed that Mean of ratio of Vrms for after fatigue to before fatigue condition for both channels lies well above 1 indicating significant increase in Vrms in after fatigue condition for both channels.

The results suggest that the ratio of the Vrms between before and after fatigue indicates the presence of fatigue in both the channels during cyclic contraction. From the tables above, it can be observed that the mean Vrms increases during the fatigue stage and this suggest that there is an increase in the level of the muscle activation and it is sustained during the fatigue state.

4.3 Statistical Analysis – Sign-test

Sign-test is used to test the hypothesis that whether there is a difference between the continuous distribution of two variables X and Y. Results of sign-test are presented here, first for MDF during both isometric and cyclic contraction; and then for Vrms during both types of contraction.

4.3.1 Sign-test Results for MDF

Table 4- 6: Sign-test Results for MDF

Contraction type (Time window)		P	h
Cyclic Contractions (50ms)	Channel 1	0.1185	0
	Channel 2	0.4545	0
Cyclic Contractions (100ms)	Channel 1	0.2379	0
	Channel 2	0.6291	0
Isometric Contractions (10s)	Channel 1	4.0054e-005	1
	Channel 2	1.9073e-006	1

From Table 4-6, it is observed that for cyclic contraction (50ms), for both channels value of P is 0.1185 and 0.4545 respectively (closer to 1) and value of $h = 0$ which indicates a failure to reject the null hypothesis at the 5% significance level. Also it is observed that at default 5% significance level, the test fails to reject to the null hypothesis of zero median in the difference.

For cyclic contraction (100ms), for both channels value of P is 0.2379 and 0.6291 respectively (closer to 1) and value of $h = 0$ which indicates a failure to reject the null hypothesis at the 5% significance level. Also it is observed that at default 5% significance level, the test fails to reject to the null hypothesis of zero median in the difference.

For isometric contraction (10s), for both channels value of P is 4.0054e-005 and 1.9073e-006 respectively (closer to 0) and value of $h = 1$ which indicates rejection of null hypothesis at the 5% significance level. Also it is observed that at default 5% significance level, the test rejects the null hypothesis of zero median in the difference.

4.3.2 Sign test Results for Vrms

Results of sign-test performed over Vrms value for both isometric and cyclic contractions are presented here.

Table 4- 7: Sign-test Results for Vrms

Contraction type (Time window)		P	h
Cyclic (100ms)	Channel 1	1.9073e-006	1
	Channel 2	1.9073e-006	1
Isometric (1s)	Channel 1	1.9073e-006	1
	Channel 2	1.9073e-006	1

4.3.2.1 Observation

From Table 4-7, it is observed that for cyclic contraction (100ms), for both channels value of P is 1.9073e-006 (closer to 0) and value of $h = 1$ which indicates rejection of null hypothesis at the 5% significance level. Also it is observed that at default 5% significance level, the test rejects the null hypothesis of zero median in the difference.

For isometric contraction (1s), for both channels value of P is 1.9073e-006 (closer to 0) and value of $h = 1$ which indicates rejection of null hypothesis at the 5% significance level. Also it is observed that at default 5% significance level, the test rejects the null hypothesis of zero median in the difference.

4.3.2.2 Discussion

The statistical sign test shows the significance of separation of the feature vectors between normal and fatigue condition. The results suggest that the Vrms is highly significant in separation between fatigue and non-fatigue state during cyclic contraction (100ms) and isometric contraction (1 s).

4.4 Statistical Analysis – ANOVA Test

One way analysis of variance is performed on extracted features of SEMG for before and after fatigue conditions values to check whether a statistically significant difference exists between two sets of values. Statistically, one way ANOVA is a technique used for numerical data analysis to compare ‘means’ of two or more samples.

4.4.1 ANOVA Results for MDF

Results of one way ANOVA performed on isometric and cyclic MDF values are presented below.

Table 4- 8: ANOVA Results for MDF

Source	F	Prob.
Cyclic (50ms) Ch1	1.79	0.1888
Cyclic (50ms) Ch2	2.23	0.1436
Cyclic (100ms) Ch1	0.95	0.3367
Cyclic (100ms) Ch2	0.48	0.492
Isometric (10s) Ch1	3.51	0.0688
Isometric (10s) Ch2	9.08	0.0046

4.4.1.1 Observation

From Table 4-8, it is observed that for cyclic contractions (50ms), probability values for both channels are statistically non significant (closer to 1). Also it is observed that statistically there is not much change between before and after fatigue values.

Also it can be seen that for cyclic contractions (100ms), probability values for both channels are statistically non significant (closer to 1). It is observed that these values are even closer to 1 than cyclic contraction with a time window of 50ms and that statistically there is not much change between before and after fatigue values.

For isometric contractions (10s), probability values for both channels are statistically significant (closer to 0). Also it is observed that statistically there is change between before and after fatigue values.

4.4.1.2 Discussion

The statistical ANOVA analysis shows the significance of separation of the feature vectors between normal and fatigue condition. The results suggest that the MDF is not significant in separation between fatigue and non-fatigue state during cyclic contraction (50 ms and 100ms), but the MDF during isometric contraction (10s) is highly significant in separation between the two states.

4.4.2 ANOVA Results for Vrms

Results of one way ANOVA performed on isometric and cyclic Vrms values are presented in Table 4- 9.

Table 4- 9: ANOVA Results for Vrms

Source	F	Prob.
Cyclic (100ms) Ch1	4.74	0.0357
Cyclic (100ms) Ch2	10.7	0.0023
Isometric (1s) Ch1	5.66	0.0225
Isometric (1s) Ch2	22.67	2.8e- 005

4.4.2.1 Observation

From Table 4-9, it is observed that for cyclic contractions (100ms), probability values for both channels are statistically significant (closer to 0). Also that statistically there is change between before and after fatigue values.

For isometric contractions (10s), probability values for both channels are statistically significant (closer to 0). Also it is observed that statistically there is change between before and after fatigue values.

4.4.2.2 Discussion

The statistical ANOVA analysis shows the significance of separation of the feature vectors between normal and fatigue condition. The results suggest that the Vrms is NOT significant in separation between fatigue and non-fatigue state during cyclic contraction (50 ms and 100ms), but the Vrms during isometric contraction (10s) is highly significant in separation between the two states.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

This thesis reports the experimental study conducted to investigate the effect of localized muscle fatigue on the surface electromyogram. Two separate sets of fatigue contraction exercise were studied that addressed research issues relevant to the onset of localized muscle fatigue. The effect of localized muscle fatigue was studied during isometric and cyclic fatigue contractions. To understand the influence of localized muscle fatigue on surface electromyogram signal, controlled experiments were conducted on twenty participants. The processing and extraction of features from the raw data was done offline. The extracted features were then subjected to statistical analysis (sign-test and ANOVA) to establish the effect of isometric and cyclic fatiguing exercise on the surface electromyogram due to onset of localized muscle fatigue. The conclusions of the experimental study are given below.

5.1.1 Effect of Localized Muscle Fatigue on Isometric Contraction

During isometric fatigue contractions there is an apparent decrease in MDF values and an increase in Vrms values after the onset of localized muscle fatigue. These changes in MDF and Vrms are statistically verified by sign-test and ANOVA. The changes in MDF and Vrms are due to change in recruitment pattern of muscle

fibers after onset of fatigue . This change in recruitment pattern due to onset of muscle fatigue has been observed in various research studies []

5.1.2 Effect of Localized Muscle Fatigue on Cyclic Contraction

During cyclic fatigue contractions there is no considerable change in MDF values (for either window size) after the onset of localized muscle fatigue. This is statistically verified by sign-test and ANOVA.

Unlike MDF, there is significant increase in Vrms values after the onset of localized muscle fatigue during cyclic fatigue contractions. This is also statistically confirmed by sign-test and ANOVA.

Changes in MDF and Vrms values during cyclic fatiguing contractions differ from isometric contractions probably due to different underlying muscle recruitment mechanisms.

5.2 Summary and Future Work

This study is concluded as follows

1. It is concluded that MDF values alone should not be used to detect the onset of localized muscle fatigue during cyclic fatigue.
2. It is concluded that MDF and Vrms does not provide a reliable and valid measure for cyclic fatigue contraction.
3. It is evident that isometric and cyclic fatigue contractions involve different underlying mechanisms for muscle recruitment and thus could not be analysed using similar analytical techniques.
4. It is apparent that Vrms and MDF can be used as good measures of onset of localized muscle fatigue during isometric contractions.

The present work was an initial step towards understanding localized muscle fatigue and the processes and mechanisms involved in it. Due to practical constraints, a number of other research issues such as muscles crosstalk and the effects of motor unit synchronisation were not addressed in this study, which could be part of further study. The development of muscle fatigue is presumably task dependent thus various types of tasks involving arm/shoulder activities are worth examining. One more research problem that is significantly important is onset of muscle fatigue during more complex and dynamic contraction as compared to isometric contraction, significantly different muscle requirement patterns are involved thus muscle fatigue onset could also be noticeably different. Specific to the use of EMG, further studies can be directed towards establishment of reliable measures for muscle fatigue. The present study has shown that a few EMG-based fatigue measures such as RMS and MDF could potentially be used to evaluate fatigue during dynamic contractions, but more studies definitely required for authenticating their effectiveness.

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Appendix A Questionnaire

Questionnaire

INVESTIGATION OF LOCALIZED MUSCLE FATIGUE

INITIAL PARTICIPANT QUESTIONNAIRE

Date:

Investigator:

To be done over the phone at time of first contact with potential participant: "I need to ask you a number of questions in order to determine your suitability as a participant in this study. It will take five minutes to complete and when we finish I will be able to tell you if you are suitable to be tested and we can organise a time for you to come in. Is this a convenient time?"

1. ID: _____

2. Gender: Male Female

3. Age: _____

4. Height: _____cm Weight: _____kg

5. Have you ever suffered from joint problems such as osteoarthritis, rheumatoid arthritis, or any other form of arthritis?

Yes No

If answer 'Yes', please answer the following question

What type of arthritis were you diagnosed with?

6. Do you have any pain in your upper limbs?

Yes No

If answer 'Yes', please answer the following question

In which part of your arm/s do you have pain?

7. Please tick a box on the check list for neuromuscular disorders

Yes: You have currently this problem.

Ever: You have ever had this problem.

Never: You have never had this problem.

Unknown: You do not know whether you have had ever this problem or not.

Check list for neuromuscular disorders

- | | | | | | | | |
|-------------------------|-----|--------------------------|------|--------------------------|-------|--------------------------|---------|
| a) Meningitis | Yes | <input type="checkbox"/> | Ever | <input type="checkbox"/> | Never | <input type="checkbox"/> | Unknown |
| | | <input type="checkbox"/> | | | | | |
| b) Trauma | Yes | <input type="checkbox"/> | Ever | <input type="checkbox"/> | Never | <input type="checkbox"/> | Unknown |
| | | <input type="checkbox"/> | | | | | |
| c) Seizure disorders | Yes | <input type="checkbox"/> | Ever | <input type="checkbox"/> | Never | <input type="checkbox"/> | |
| Unknown | | <input type="checkbox"/> | | | | | |
| d) Sleep disorders | Yes | <input type="checkbox"/> | Ever | <input type="checkbox"/> | Never | <input type="checkbox"/> | |
| Unknown | | <input type="checkbox"/> | | | | | |
| e) Stoke | Yes | <input type="checkbox"/> | Ever | <input type="checkbox"/> | Never | <input type="checkbox"/> | Unknown |
| | | <input type="checkbox"/> | | | | | |
| f) Brain tumour | Yes | <input type="checkbox"/> | Ever | <input type="checkbox"/> | Never | <input type="checkbox"/> | |
| Unknown | | <input type="checkbox"/> | | | | | |
| g) Fibromyalgia | Yes | <input type="checkbox"/> | Ever | <input type="checkbox"/> | Never | <input type="checkbox"/> | |
| Unknown | | <input type="checkbox"/> | | | | | |
| h) Neurological deficit | Yes | <input type="checkbox"/> | Ever | <input type="checkbox"/> | Never | <input type="checkbox"/> | |
| Unknown | | <input type="checkbox"/> | | | | | |

8. Do you have any other known condition affecting your musculoskeletal or nervous system not in a list of question 7 a) to h) above?

Yes No

If you answered 'Yes' to this question, please provide your condition

9. Have you had ever any other known condition affecting your musculoskeletal or nervous system not in a list of question 7 a) to h) above?

Yes No

If you answered 'Yes' to this question, please provide your condition

"Now I am going to tally up your answers and see whether you are suitable to participate.... "

EXCLUDE? Yes No

"Okay, I have looked over all of your answers and unfortunately you are unable to participate in the current study. This is not due to one particular answer you have given, rather the overall profile".

OR

"Okay, I have looked over all of your answers and you do meet the criteria for participation.

The next step is to organise a session time for you....."

Would you like to book in? Y N

****mention length of session and basic protocol****

What is your full name?

What is your phone number?

Do you have an email address that I can use?

What is your postal address?

When you like to book in?

Monday	Morning (9:30am) Afternoon (1:30pm)
Tuesday	Morning (9:30am) Afternoon (1:30pm)
Wednesday	Morning (9:30am) Afternoon (1:30pm)
Thursday	Morning (9:30am) Afternoon (1:30pm)
Friday	Morning (9:30am) Afternoon (1:30pm)

NOTE:

* Finally, we do have to let you know that participants will be excluded if they have used any illicit drug within one week of testing

* We ask that you do not consume alcohol within 24 hours of testing

Appendix B

Plain Language Statement

INVITATION TO PARTICIPATE IN A RESEARCH PROJECT

PROJECT INFORMATION STATEMENT

Investigation of Localized Muscle Fatigue

Investigators:

- Mr. Vivek Yadav (Masters by Research candidate SECE, RMIT University, 9925-3025) vivek.yadav@student.rmit.edu.au
- Dr. John Fang (Project Supervisor SECE, RMIT University, 9925-1954) john.fang@rmit.edu.au
- A/Prof. Dinesh Kumar (Co-Supervisor SECE, RMIT University, 9925-2432) dinesh@rmit.edu.au

Dear Participants,

You are invited to participate in a biomedical research project being conducted by RMIT University. This information sheet describes the project in a simple language. Please read this sheet carefully and be confident that you understand its contents before deciding whether to participate. If you have any questions about the project, please ask one of the investigators. You are able to withdraw from this study at any time, if you feel so, without obligations.

Who is involved in this research project? Why is it being conducted?

- My Name is Vivek Yadav. I am conducting research in Bio-Medical Lab. of the School of Electrical and Computer Engineering, RMIT University. This research project is part of my Masters by Research thesis. Myself as the primary investigator and my supervisors are involved in this research project.
- This research project has been approved by the RMIT Human Research Ethics Committee.
- This research is being conducted because the scientific community has not been able to deduce yet whether localized muscle fatigue can be detected using muscle activity signals collected from skin surface. Upon successful completion, it will contribute to the scientific

knowledge of this area and will serve as a step further into detecting localized muscle fatigue.

Why have you been approached?

You have been approached because you have expressed interest for participation in this study through an advertisement that circulated in RMIT University campus. Your contact details have been supplied to the researcher by your self through email or telephone.

What is the project about? What are the questions being addressed?

This project is concerned with the effects of fatigue on muscle activity. The proposed research will assess issues concerning the reliability of using the electrical activity of the muscles from skin surface (called SEMG) for detecting localized muscle fatigue.

We aim to detect changes in muscle activity at the onset of localized muscle fatigue.

This project will try and identify possible effects arising from muscle fatigue by measuring the muscle activity of subjects under the condition of isometric and cyclic contraction. Participants will be asked to perform cyclic and isometric muscle contractions with a fixed load in hand.

The research questions that we aim to answer are:

- How the localized muscle fatigue influence muscle activity. This will be studied under isometric and cyclic conditions.
- Whether this influence can be detected using the electrical activity of the muscles from skin surface (called SEMG).
- What are the observed changes and differences and how significant are they?
- Are the changes classified as adverse, insignificant, or positive?

Up to 20 participants will be involved in this study.

If I agree to participate, what will I be required to do?

You will be asked to follow the procedure that is outlined below. All necessary safety measures have been taken to ensure your safety. If you are in discomfort or pain at any stage during the experiment, please let me know and I will discontinue the test. Participation in this research is voluntary and you may withdraw at anytime without giving me the reason or notice. If you decide to withdraw, any information that has already been provided will not be used.

Procedure: you will be asked to remove any watch or jewellery and skin will be cleaned using mild soap. 5-6 self-adhesive electrodes will be placed in close proximity to muscles on skin. Prior to recordings, the participants will be encouraged to familiarise themselves with the experimental protocol and the equipments.

During the first set of exercise, you will be asked to perform isometric muscle contraction using fixed standard load. Data will be recorded throughout the experiment until muscle fatigue is achieved. During the second set of exercise, you will be asked to perform repeated muscle contraction and relaxation holding a fixed standard load in hand. Each contraction cycle will be about 7-8 seconds. You will have to spend at least 30 minutes if you decide to proceed with experiments (muscle activity recording) with fixed and minimal movements.

What are the risks or disadvantages associated with participation?

There are no direct known risks or disadvantages associated with such experiments.

- However in rare cases, electrodes applied to the skin may cause rash and/or an itchy sensation during or after experiment. For this reason, using mild soap the skin surface will be cleaned before and after experiment.
- The collected data/signals will not be medically assessed.

What are the benefits associated with participation?

There are no direct benefits to the participant arising from this project. However, as a participant,

- You will have the opportunity to observe how and with what equipment muscle activity measurements are taken.

What will happen to the information I provide?

- The data collected will be analysed for my thesis and the results may appear in publications. The results will be reported in a manner that does not enable you to be identified. Thus the reporting will protect your anonymity.
- The collected data will be retained for a maximum of 5 years period, after which it will be destroyed. During this period the information will be kept under strict security (inside a locked cabinet in lockable office) and will be only accessible by my supervisors.

- Any information that you provide can be disclosed only if (1) it is to protect you or others from harm, (2) a court order is produced, or (3) you provide the researchers with written permission.

What are my rights as a participant?

Participants in the study will have the following rights:

- The right to withdraw their participation at any time, without prejudice.
- The right to have any unprocessed data withdrawn and destroyed, provided it can be reliably identified, and provided that so doing does not increase the risk for the participant.
- The right to have any questions answered at any time.
- The right to access your collected data upon request.

Whom should I contact if I have any questions?

For any enquiries please do not hesitate to contact us:

- Mr. Vivek Yadav (Masters by Research candidate SECE, RMIT University, 9925-3025) vivek.yadav@student.rmit.edu.au
- Dr. John Fang (Project Supervisor SECE, RMIT University, 9925-1954) john.fang@rmit.edu.au
- A/Prof. Dinesh Kumar (Co-Supervisor SECE, RMIT University, 9925-2432) dinesh@rmit.edu.au

What other issues should I be aware of before deciding whether to participate?

- At the end of the data collection a printed copy of your muscle activity will be provided to you as a record. The printed record will also contain information about how the data were collected.

Yours sincerely

Vivek Yadav B. Tech. (Bio-Medical Eng.)

John Fang BSc (Electrical Eng.), PhD

Dinesh Kumar B.Eng. (Hons), PhD

Appendix C

Participant Consent Form

Prescribed Consent Form for Persons Participating In Research Projects Involving Tests and/or Medical Procedures

Portfolio	Science Engineering and Technology	
School of	Electrical and Computer Engineering	
Name of participant:		
Project Title:	Investigation of localized muscle fatigue	
Name(s) of investigators:	Vivek Yadav	Phone: 03 99253025
(1)		
(2)	Dr. John Fang	Phone: 03 99252432
(3)	A/Prof. Dinesh Kant Kumar	Phone: 03 99251954

1. I have received a statement explaining the tests/procedures involved in this project.
2. I consent to participate in the above project, the particulars of which - including details of tests or procedures - have been explained to me.
3. I authorise the investigator or his or her assistant to use with me the tests or procedures referred to in 1 above.
4. I acknowledge that:
 - (a) The possible effects of the tests or procedures have been explained to me to my satisfaction.
 - (b) I have been informed that I am free to withdraw from the project at any time and to withdraw any unprocessed data previously supplied (unless follow-up is needed for safety).
 - (c) The project is for the purpose of research and/or teaching. It may not be of direct benefit to me.
 - (d) The privacy of the personal information I provide will be safeguarded and only disclosed where I have consented to the disclosure or as required by law.

- (e) The security of the research data is assured during and after completion of the study. The data collected during the study may be published, and a report of the project outcomes will be provided to John Fang, Science Engineering and Health College and School of Electrical and Computer Engineering (researcher to specify). Any information which will identify me will not be used.

Participant's Consent

Participant: _____ Date: _____
(Signature)

Witness: _____ Date: _____
(Signature)

Participants should be given a photocopy of this consent form after it has been signed.

Appendix D

Detailed Results

MDF Results for Isometric Contraction

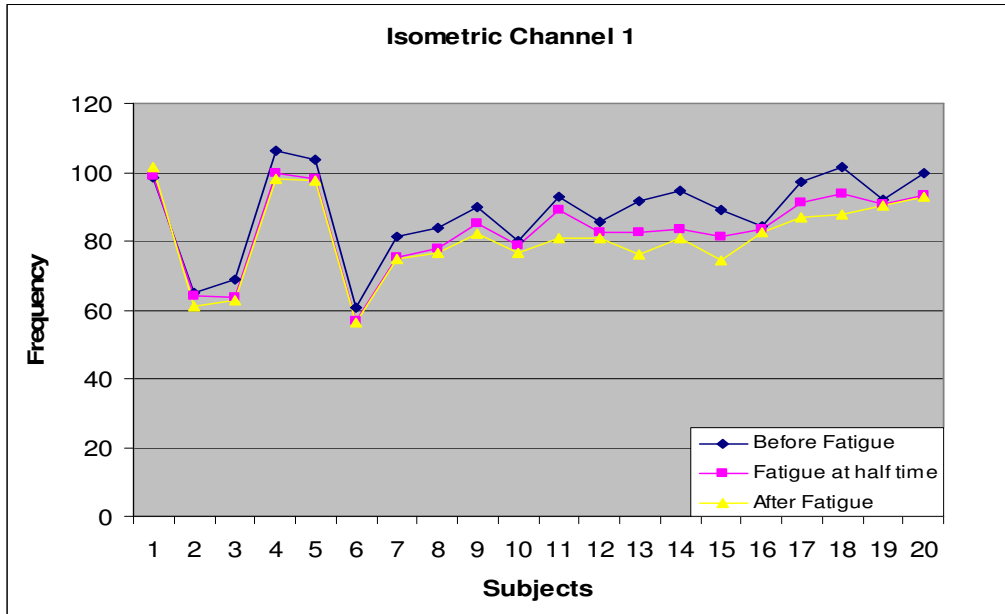


Figure 1: MDF (Hz) of each subject under isometric contraction for channel 1 using 10sec time window.

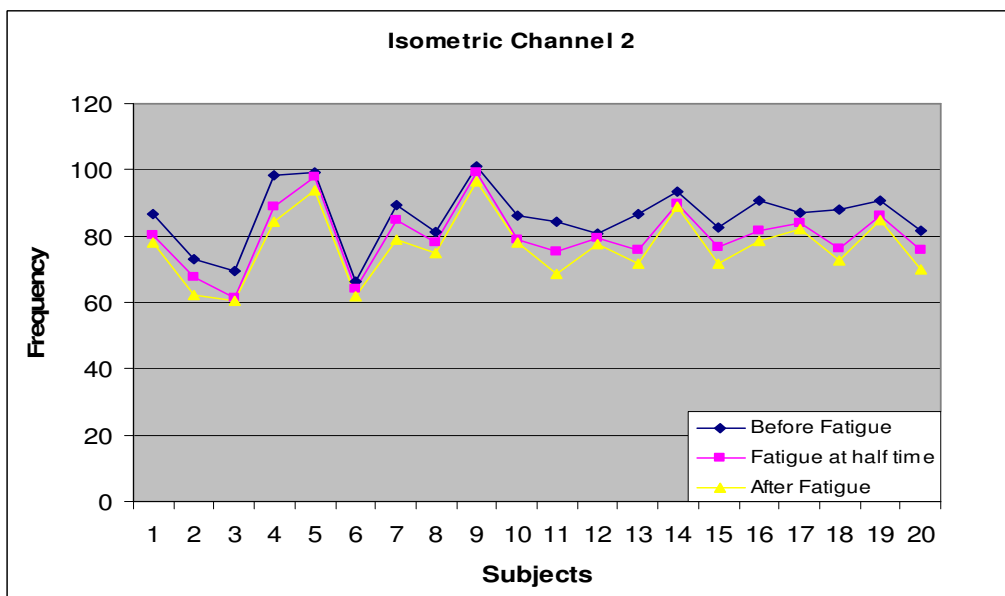


Figure 2: MDF (Hz) of each subject under isometric contraction for channel 1 using 10sec time window.

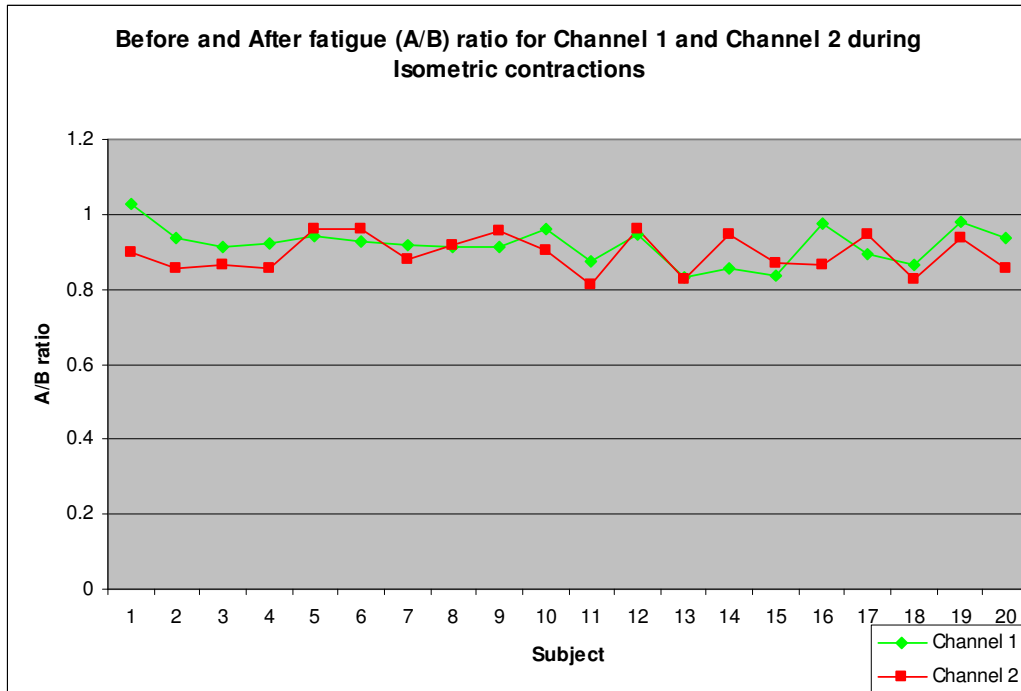


Figure 3: After to Before (A/B) fatigue ratio of each subject under isometric contraction for channel 1 and channel 2.

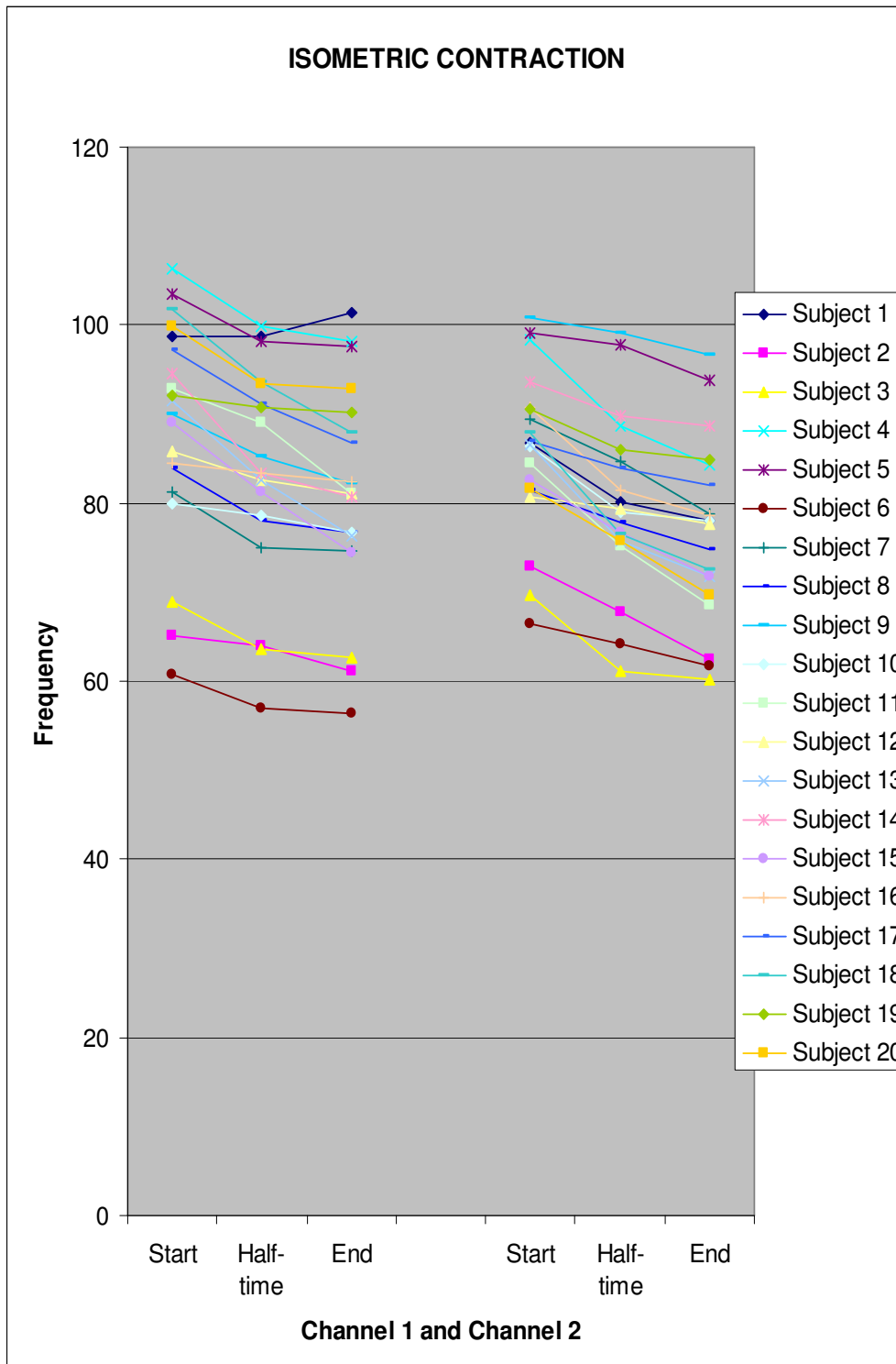


Figure 4: MDF (Hz) of each subject during isometric contraction using 100ms time window.

MDF Results for Cyclic Contraction

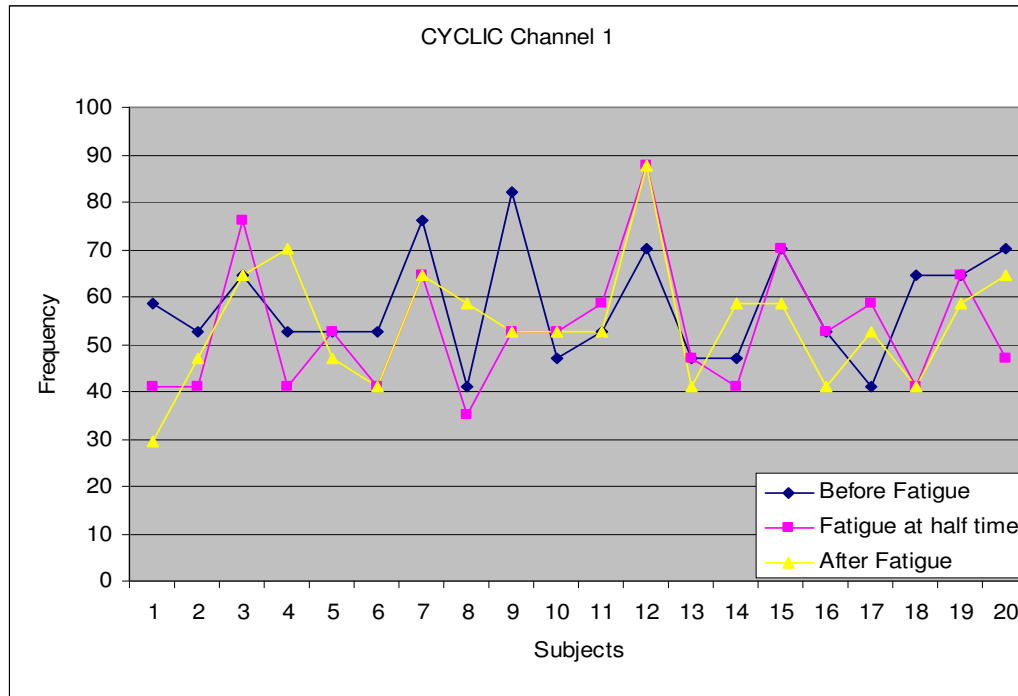


Figure 5: MDF (Hz) of channel 1 for each subject during cyclic contraction using 100ms time window.

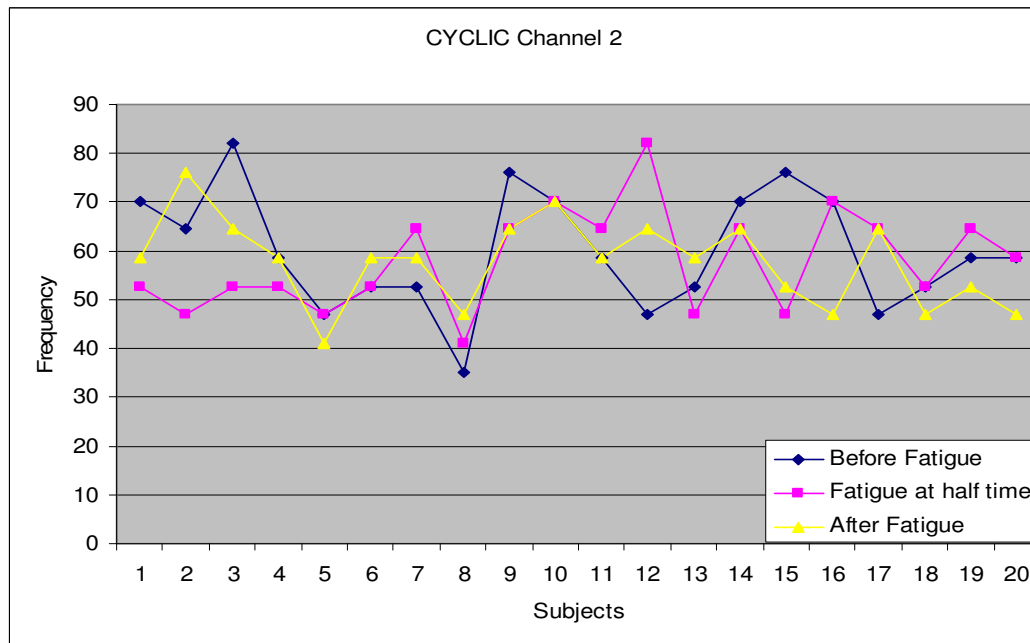


Figure 6: MDF (Hz) of channel 2 for each subject during cyclic contraction using 100ms time window.

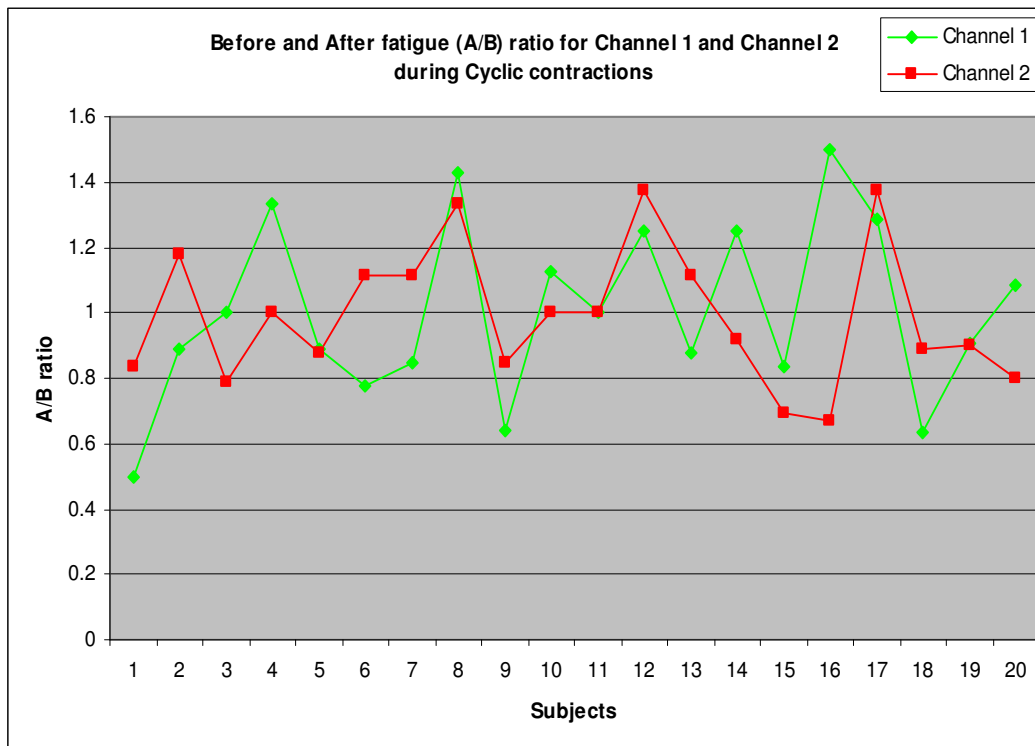


Figure 7: After to Before (A/B) fatigue ratio of each subject under cyclic contraction for channel 1 and channel 2 using 100ms time window.

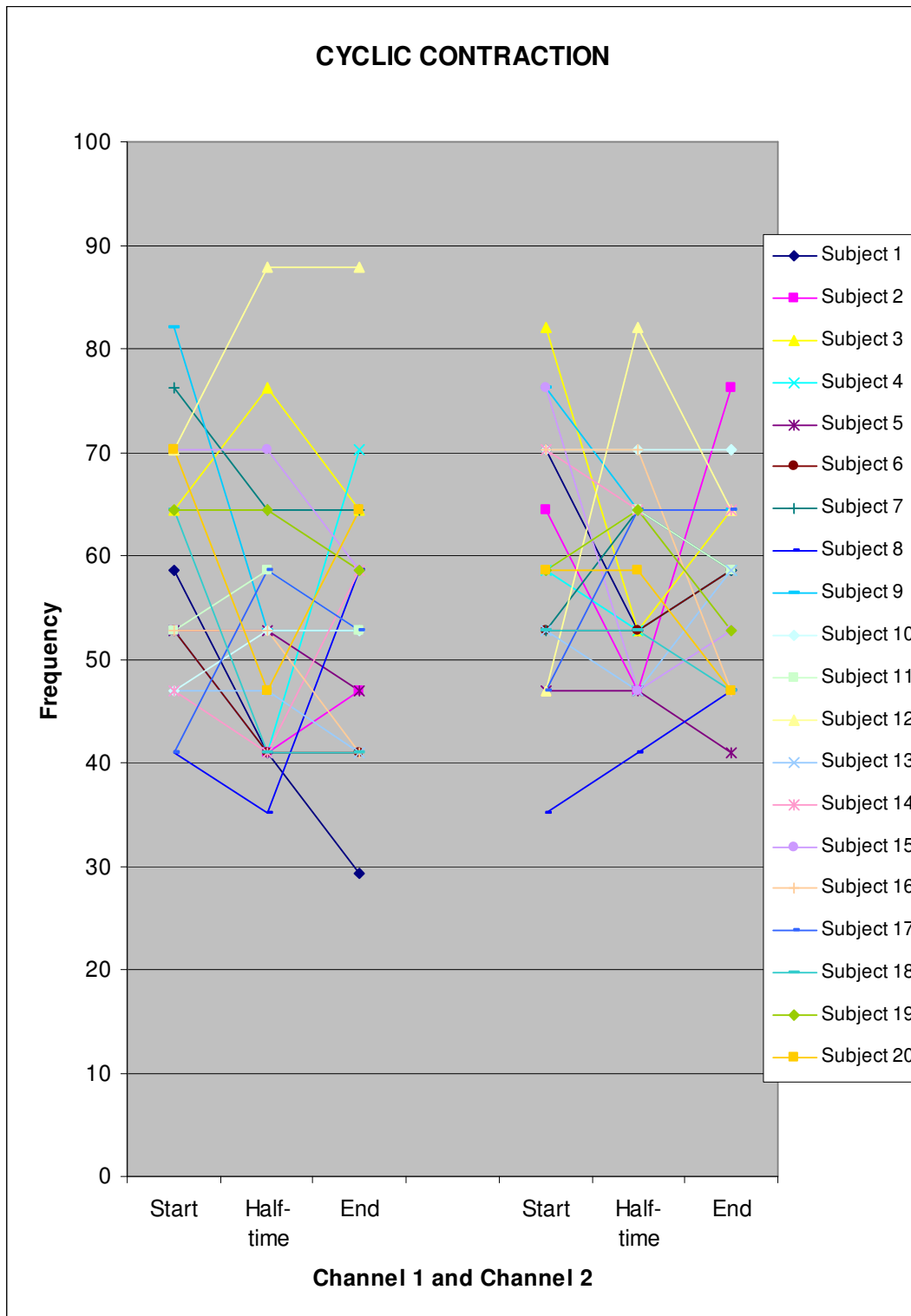


Figure 8: MDF (Hz) of each subject during cyclic contraction using 100ms time window.

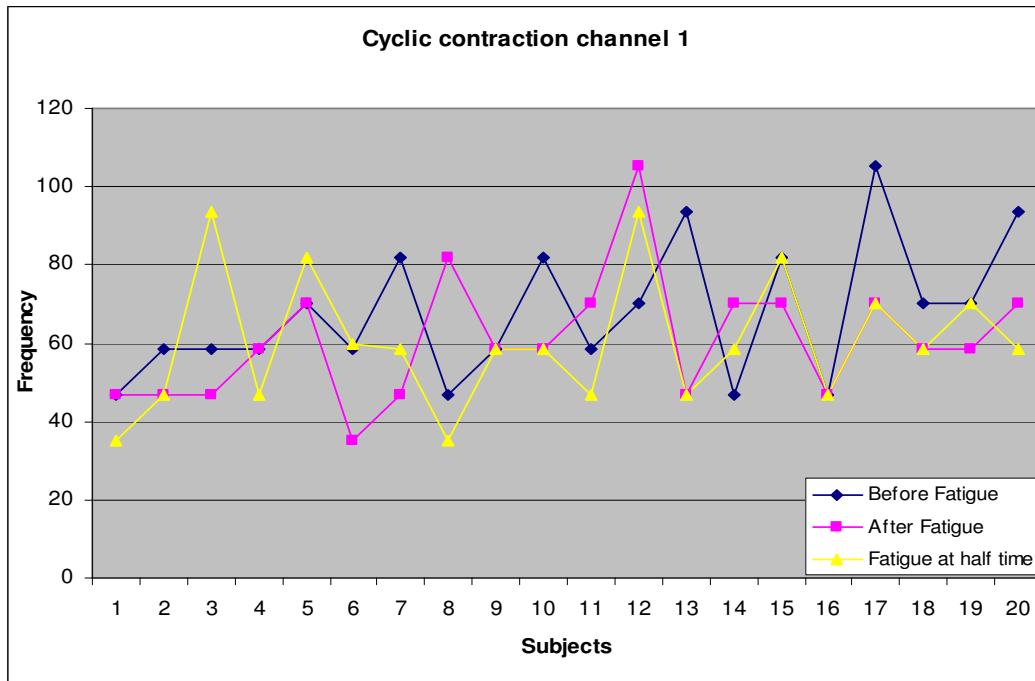


Figure 9: MDF (Hz) of channel 1 for each subject during cyclic contraction using 50ms time window.

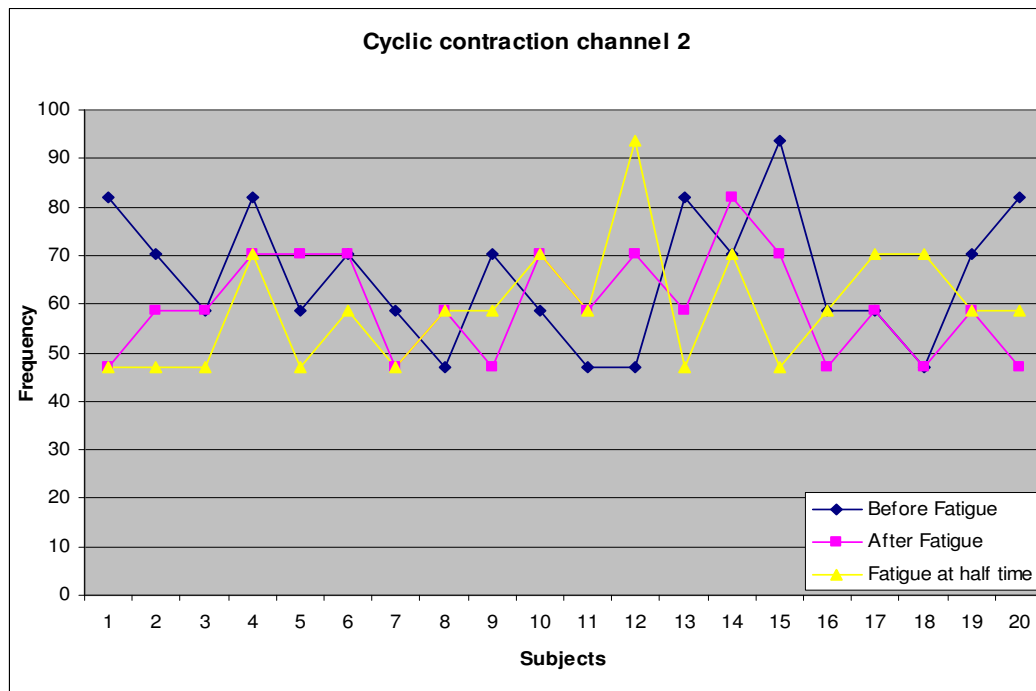


Figure 10: MDF (Hz) of channel 2 for each subject during cyclic contraction using 50ms time window.

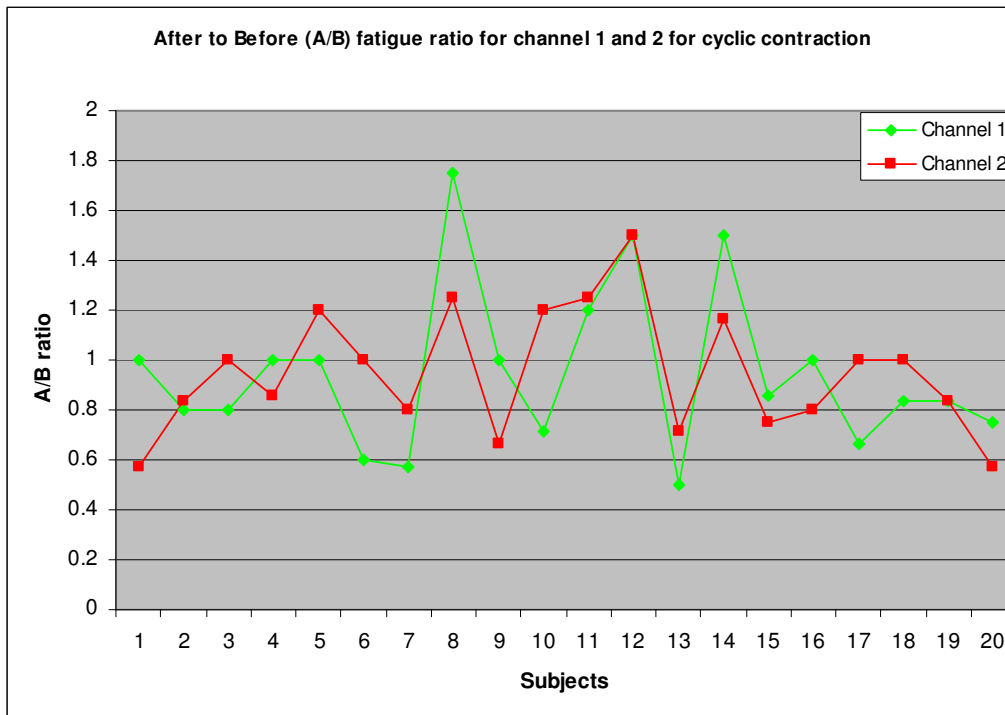


Figure 11: After to Before (A/B) fatigue ratio of each subject under cyclic contraction using 50ms time window for channel 1 and channel 2.

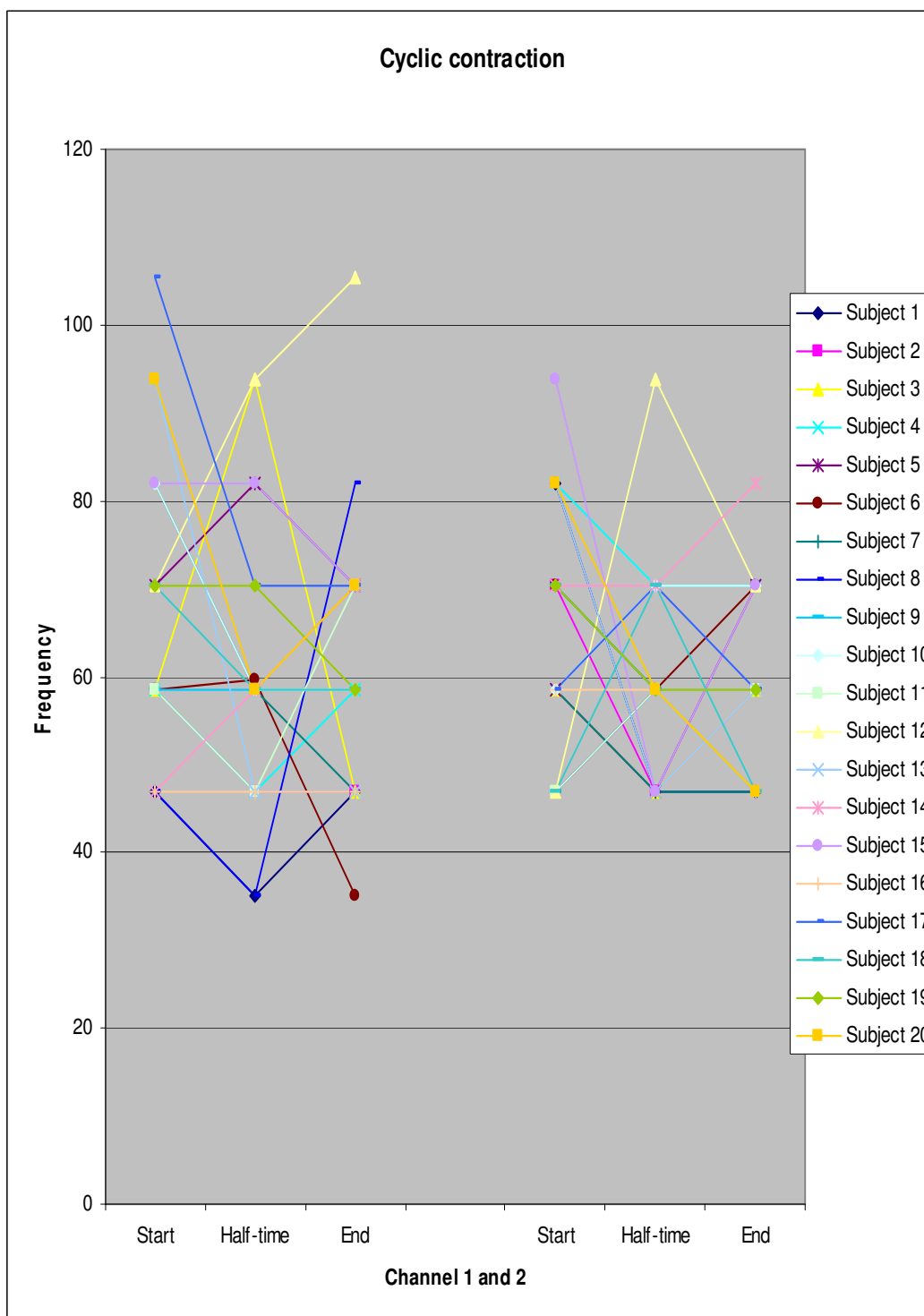


Figure 12: MDF (Hz) of each subject during cyclic contraction using 50ms time window.

Vrms Results for Isometric Contraction

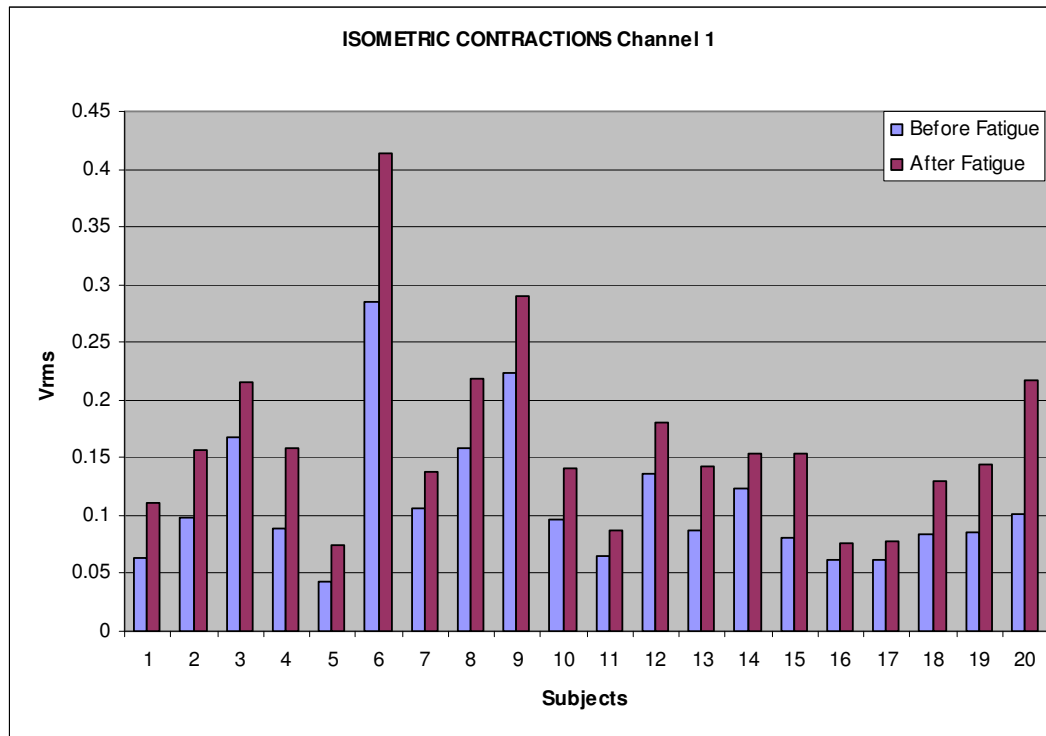


Figure 13: Vrms (mV) of each subject for channel 1 during isometric contraction.

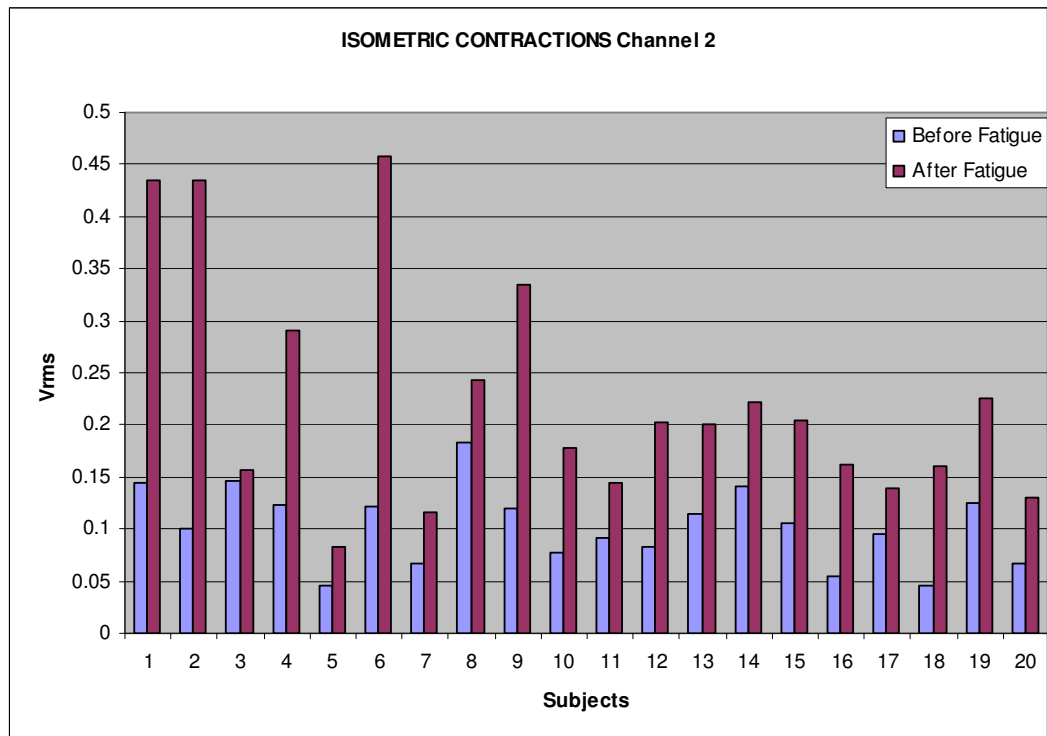


Figure 14: Vrms (mV) of each subject for channel 2 during isometric contraction.

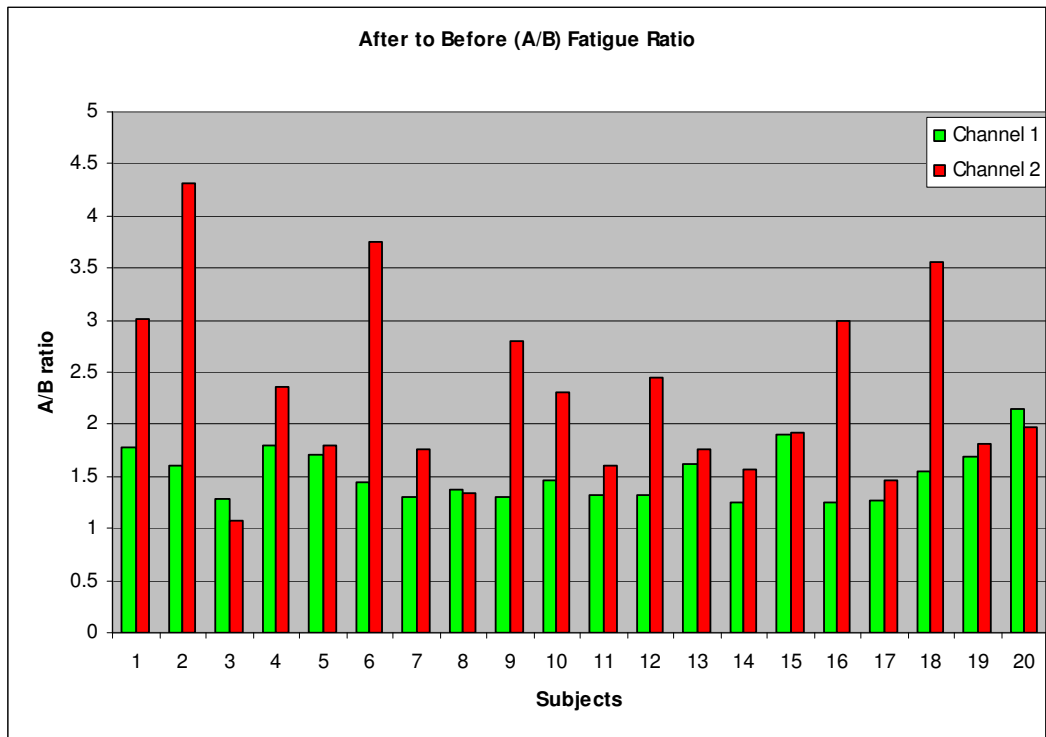


Figure 15: After to before fatigue ratio (A/B) of V_{rms} (mV) of each subject for both channels during isometric contraction.

Vrms Results for Cyclic Contraction

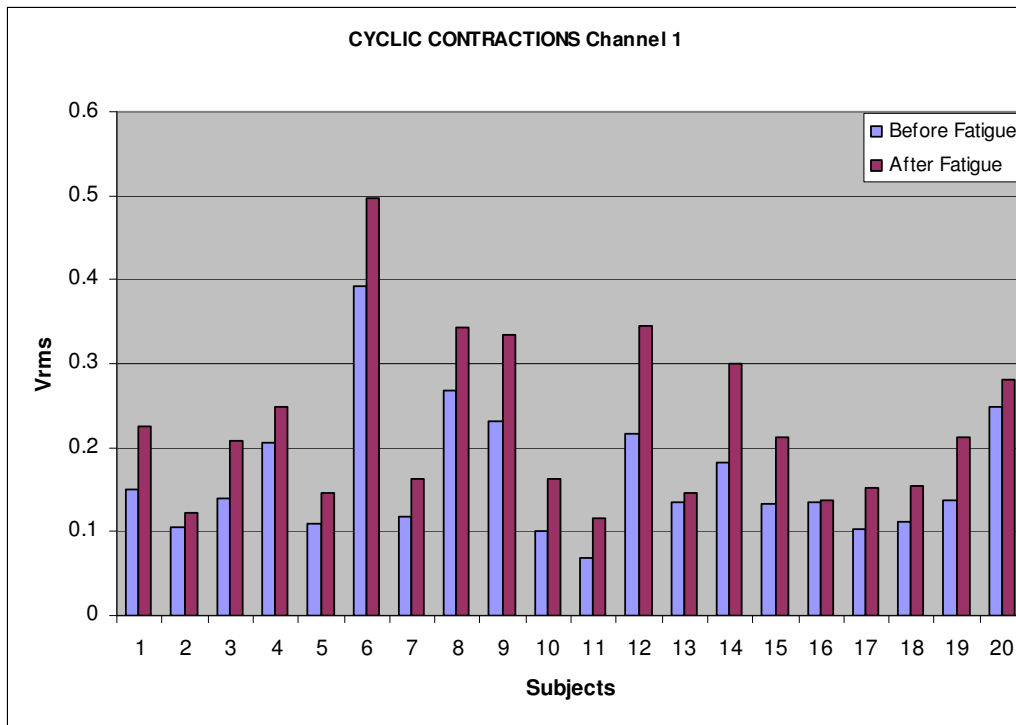


Figure 16: Vrms (mV) of each subject for channel 1 during cyclic contraction.

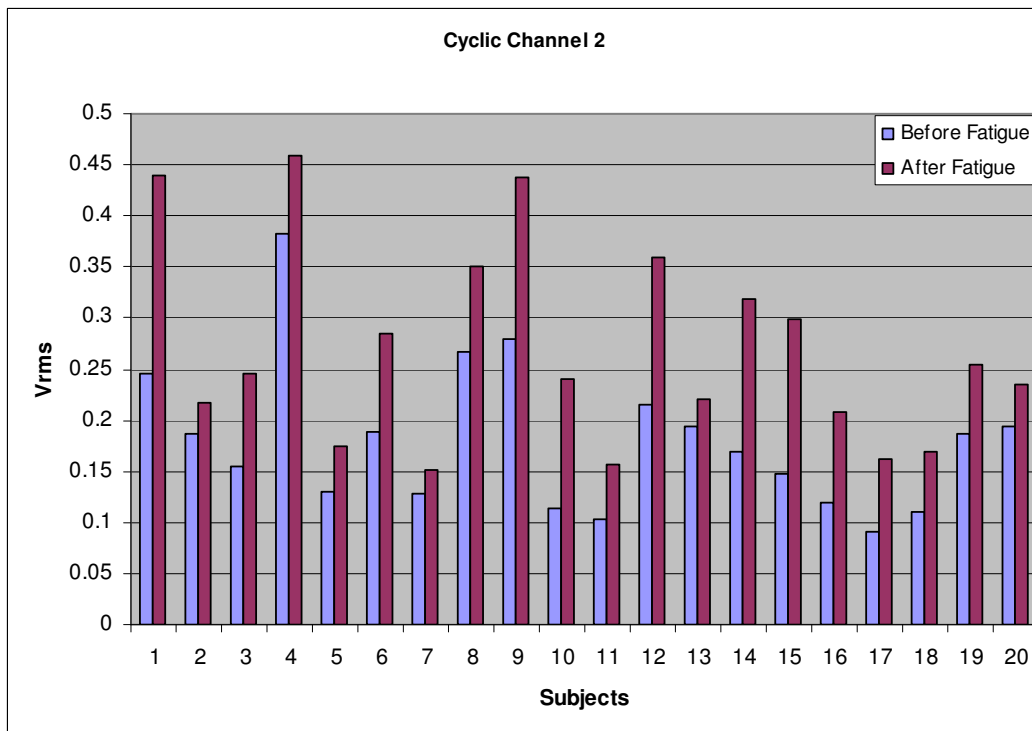


Figure 17: Vrms (mV) of each subject for channel 2 during cyclic contraction.

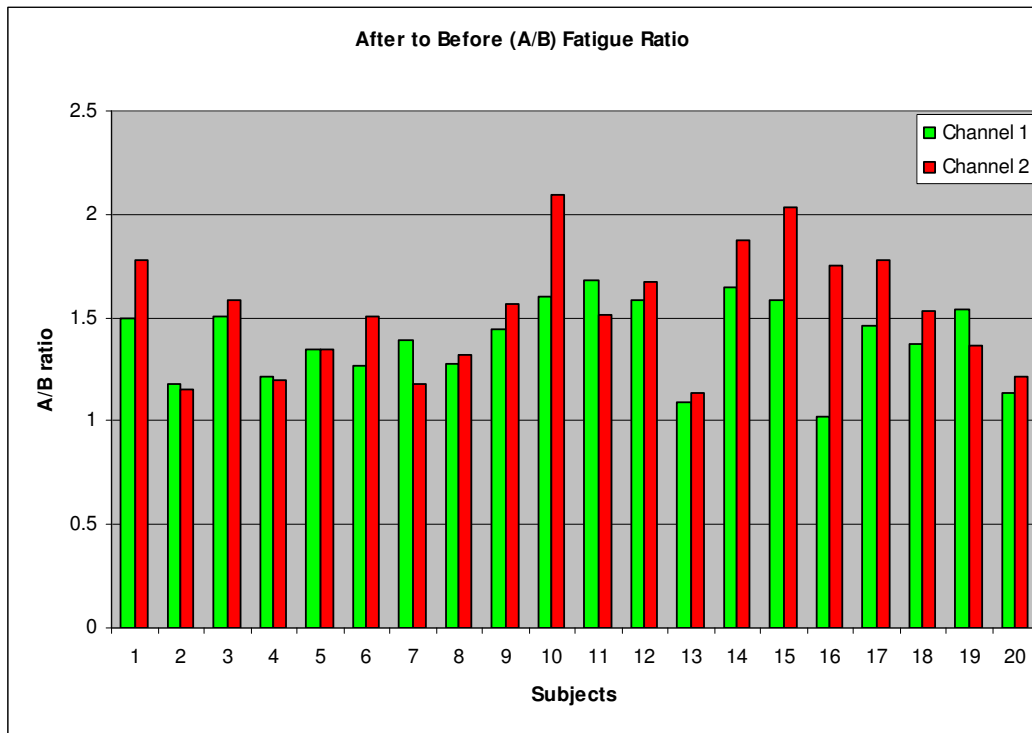


Figure18: After to before fatigue ratio (A/B) of Vrms (mV) of each subject for both channels during cyclic contraction.

ANOVA Results for MDF-Isometric Contraction

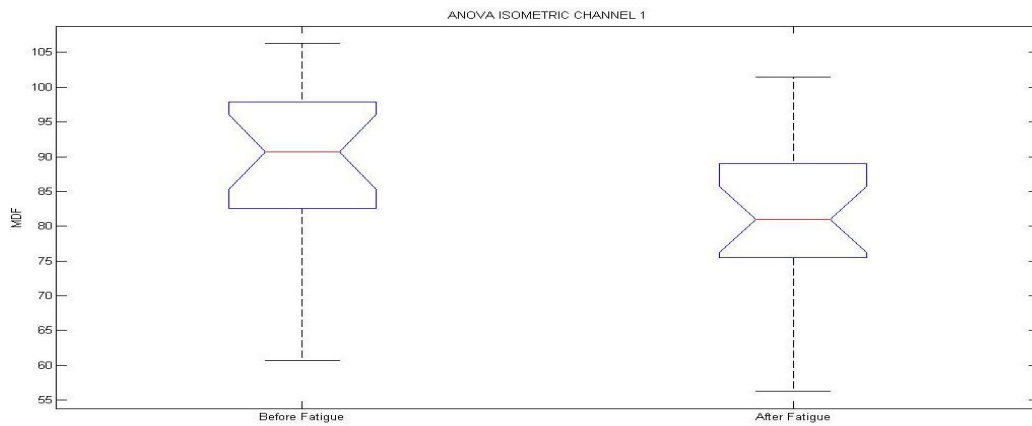


Figure: ANOVA plot for channel 1 MDF (Hz) during isometric contraction.

Table: ANOVA table of result for channel 1 MDF (Hz) during isometric contraction.

ANOVA Table					
Source	SS	df	MS	F	Prob>F
Columns	532.17	1	532.17	3.51	0.0688
Error	5763.76	38	151.678		
Total	6295.93	39			

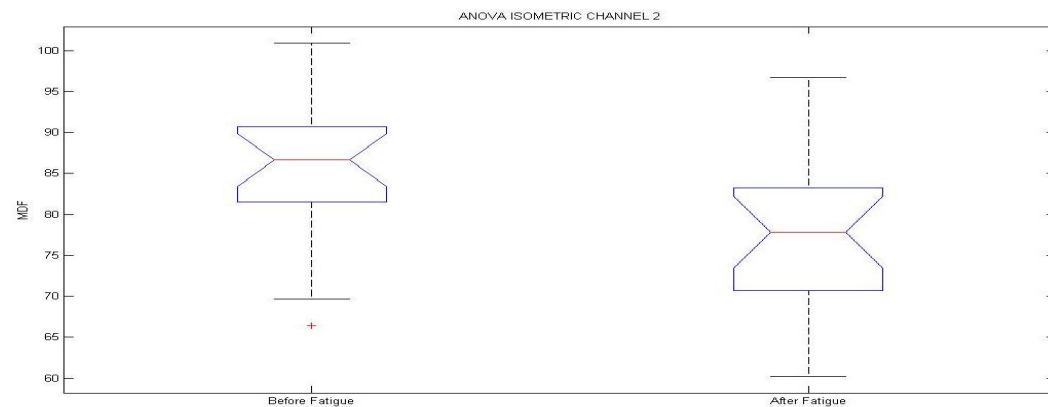


Figure: ANOVA plot for channel 2 MDF (Hz) during isometric contraction.

Table: ANOVA table of result for channel 2 MDF (Hz) during isometric contraction.

ANOVA Table					
Source	SS	df	MS	F	Prob>F
Columns	826.37	1	826.372	9.08	0.0046
Error	3460.22	38	91.058		
Total	4286.59	39			

ANOVA Results for MDF-Cyclic Contraction

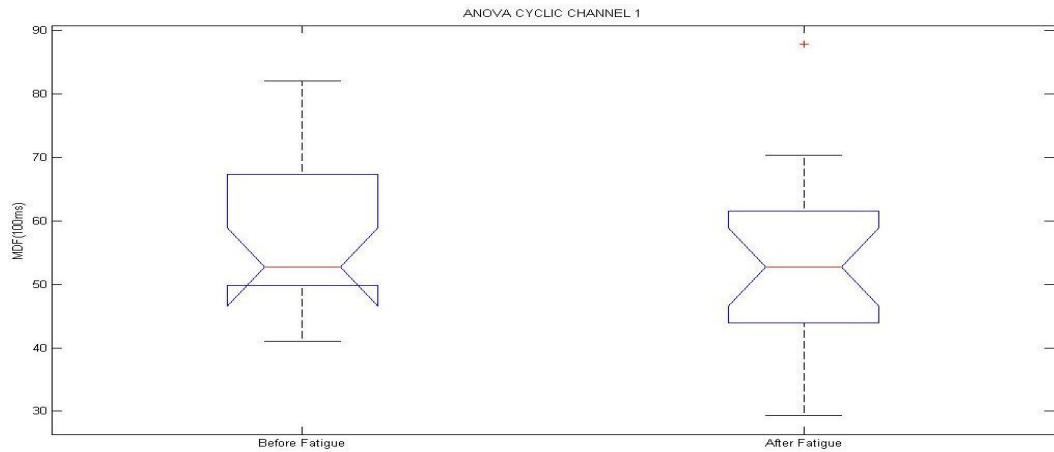


Figure: ANOVA plot for channel 1 MDF (Hz) during cyclic contraction (100ms).

Table: ANOVA table of result for channel 1 MDF (Hz) during cyclic contraction (100ms).

ANOVA Table					
Source	SS	df	MS	F	Prob>F
Columns	145.01	1	145.009	0.95	0.3367
Error	5819.09	38	153.134		
Total	5964.09	39			

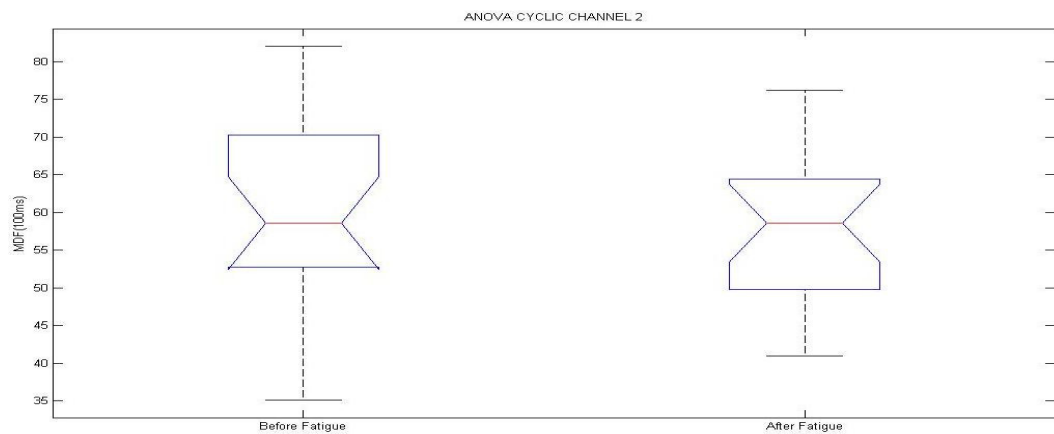


Figure: ANOVA plot for channel 2 MDF (Hz) during cyclic contraction (100ms).

Table: ANOVA table of result for channel 2 MDF (Hz) during cyclic contraction (100ms).

ANOVA Table					
Source	SS	df	MS	F	Prob>F
Columns	54.92	1	54.92	0.48	0.492
Error	4334.6	38	114.068		
Total	4389.52	39			

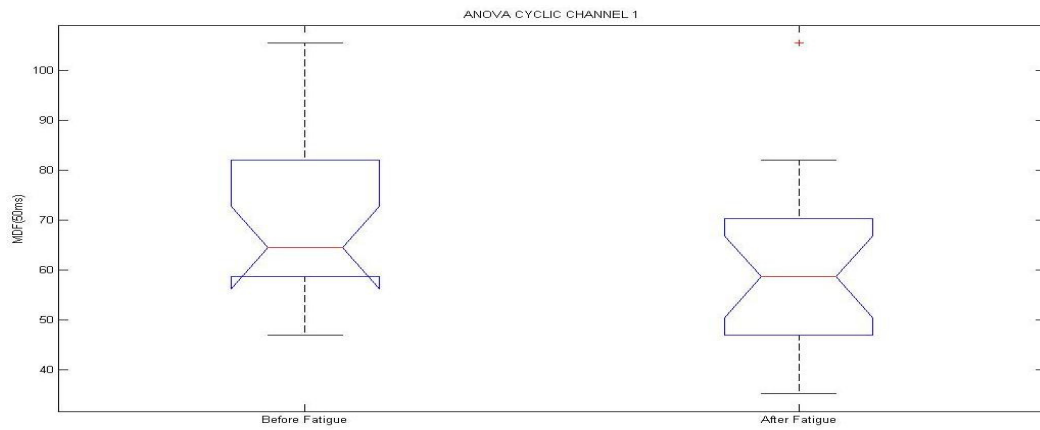


Figure: ANOVA plot for channel 1 MDF (Hz) during cyclic contraction (50ms).

Table: ANOVA table of result for channel 1 MDF (Hz) during cyclic contraction (50ms).

ANOVA Table					
Source	SS	df	MS	F	Prob>F
Columns	494.3	1	494.279	1.79	0.1888
Error	10490.3	38	276.06		
Total	10984.6	39			

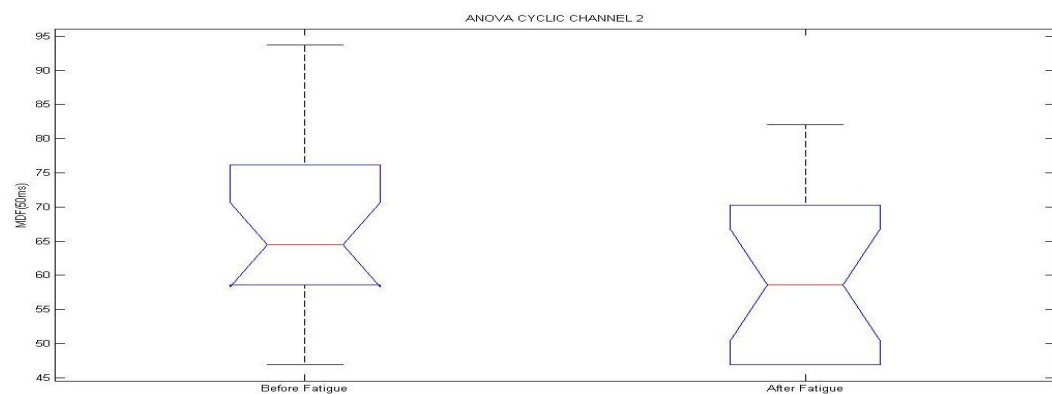


Figure: ANOVA plot for channel 2 MDF (Hz) during cyclic contraction (50ms).

Table: ANOVA table of result for channel 2 MDF (Hz) during cyclic contraction (50ms).

ANOVA Table					
Source	SS	df	MS	F	Prob>F
Columns	343.28	1	343.279	2.23	0.1436
Error	5848.42	38	153.906		
Total	6191.7	39			

ANOVA Results for Vrms-Isometric Contraction

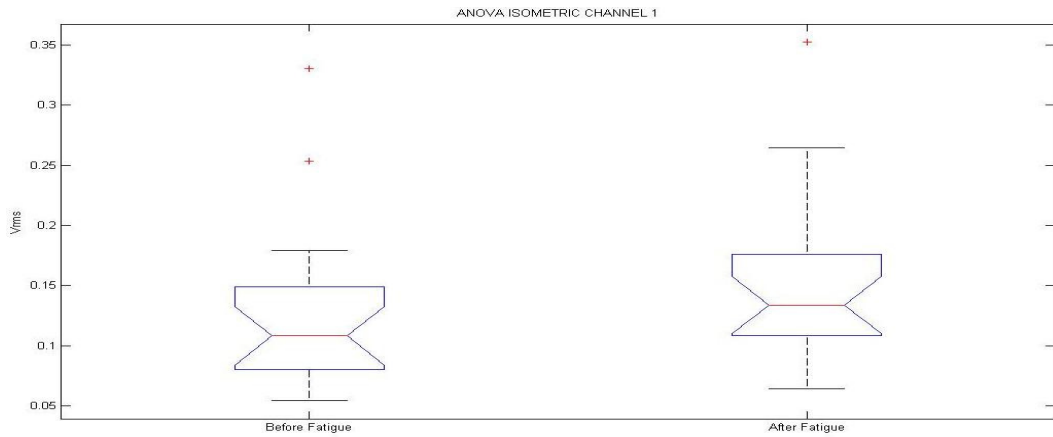


Figure: ANOVA plot for channel 1 V_{rms} (mV) during isometric contraction.

Table: ANOVA table of result for channel 1 V_{rms} (mV) during isometric contraction.

ANOVA Table					
Source	SS	df	MS	F	Prob>F
Columns	0.00376	1	0.00376	0.8	0.3776
Error	0.17913	38	0.00471		
Total	0.18289	39			

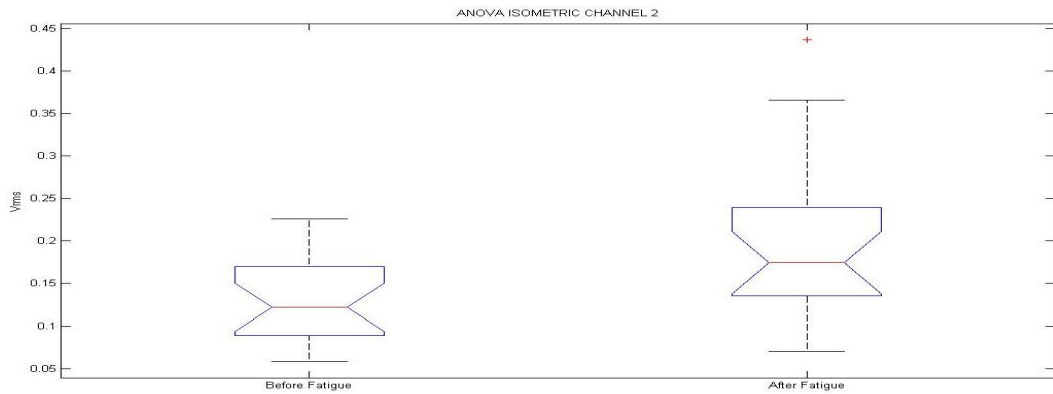


Figure: ANOVA plot for channel 2 V_{rms} (mV) during isometric contraction.

Table: ANOVA table of result for channel 2 V_{rms} (mV) during isometric contraction.

ANOVA Table					
Source	SS	df	MS	F	Prob>F
Columns	0.05222	1	0.05222	9.07	0.0046
Error	0.21881	38	0.00576		
Total	0.27103	39			

ANOVA Results for Vrms-Cyclic Contraction

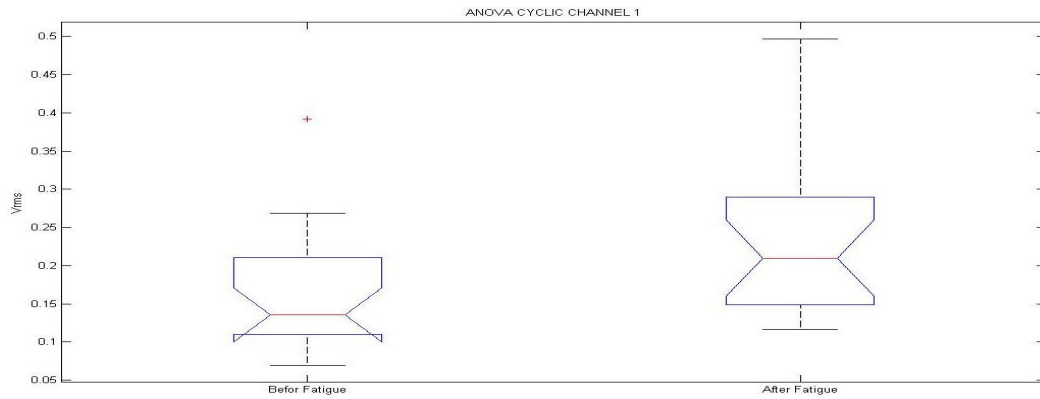


Figure: ANOVA plot for channel 1 V_{rms} (mV) during cyclic contraction.

Table: ANOVA table of result for channel 1 V_{rms} (mV) during cyclic contraction.

ANOVA Table					
Source	SS	df	MS	F	Prob>F
Columns	0.03692	1	0.03692	4.74	0.0357
Error	0.29596	38	0.00779		
Total	0.33288	39			

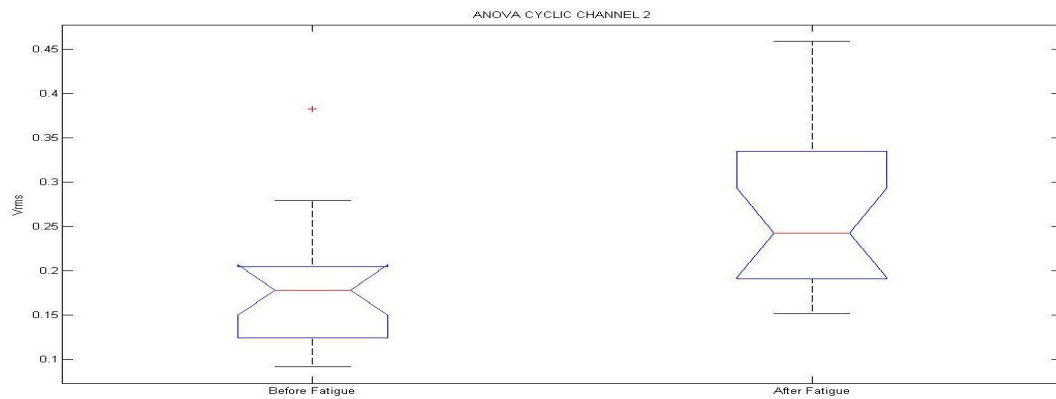


Figure: ANOVA plot for channel 2 V_{rms} (mV) during cyclic contraction.

Table: ANOVA table of result for channel 2 V_{rms} (mV) during cyclic contraction.

ANOVA Table					
Source	SS	df	MS	F	Prob>F
Columns	0.0785	1	0.0785	10.7	0.0023
Error	0.27882	38	0.00734		
Total	0.35732	39			

Appendix E Publication

Naik, G.R., Kumar, D.K., Yadav, V., Wheeler, K., Arjunan, S., "Testing of motor unit synchronization model for localized muscle fatigue," *Engineering in Medicine and Biology Society*, 2009, 360-363.