DETECTION OF ONSET MUSCLE FATIGUE BASED ON JOINT ANALYSIS OF SURFACE ELECTROMYOGRAPHY SPECTRUM AND AMPLITUDE

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Alhamdullilah,

Dedicate my appreciation to my beloved husband, family, supervisor and friends.

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ABSTRACT

Many studies have been conducted to track muscle fatigue and to understand the mechanisms that contribute to the deterioration of muscle performance. Electromyography fatigue threshold (EMG_{FT}) and Integrated Electromyography (IEMG) are two techniques that have been applied to determine the Onset of Muscle Fatigue (OMF) by depending on the percentage force output and amplitude respectively. Nevertheless, force and amplitude are correlated with one another during fatigue. Joint Analysis of EMG Spectrum and Amplitude (JASA) is commonly used to discriminate force-related from fatigue induced EMG changes. However, the length of signal affects the performance of JASA in discriminating fatigue signal. Apart from that, JASA has not been used to detect OMF. Thus, the purpose of this study is to determine the OMF region by applying JASA on the segmented EMG signal. Surface EMG signals were recorded from 30 college students while they were performing isometric contractions of Biceps Brachii muscles for 2 minutes. Each recorded signal was segmented into 15-second time interval. Root Mean Square (RMS) and Mean Frequency (MNF) were used as the muscle fatigue indicators. The indicators were extracted from 3-second epoch length within each segment. A polynomial regression model was applied to describe the trends of the indicators in a segment. The first segment that simultaneously showed a decrease in the frequency and an increase in the amplitude of a sEMG signal with correlation coefficient $r \geq 0.7$ was classified as the region where the OMF occurred. Out of 30 subjects, 20 subjects (67%) either admitted to experience muscle discomfort and at the same time the OMF region was also detected or vice-versa. For the other 10 subjects, the OMF region was able to be detected in 90% of them but due to better endurance levels, they required longer time to experience muscle discomfort. The temporal-spectral fatigue indicator (Instantaneous Mean Frequency (iMNF)) was used to determine the reliability of the developed technique. The decrement of iMNF on the detected OMF region showed high correlation coefficient ($r > 0.6$). The subjects were also asked to perform dynamic contractions for 2 minutes. The proposed technique was applied to the recorded signals and the OMF was detected in 24 subjects. Eighteen of them (72%) acknowledged that they had experienced muscle discomfort. Fourteen out of 18 subjects felt muscle discomfort after OMF was detected. The results indicate that muscle discomfort develops gradually after the onset of muscle fatigue. For handwriting activity, 4 subjects were asked to write for 5 minutes while the sEMG signals were captured from Flexor Carpi Radialis muscle (small muscle). Out of 4 subjects, all of them showed an increment in pen pressure, and 75% of them showed an increment in the writing speed after detecting OMF region. This study concludes that the proposed technique is feasible to detect the OMF; not only during isometric contraction but also during dynamic contraction. The technique also has the potential to be applied to small muscle contraction.

ABSTRAK

Banyak kajian telah dijalankan bagi mengesan keletihan otot dan seterusnya bagi memahami mekanisme yang menyebabkan kemerosotan prestasi otot. Tahap Permulaan Keletihan Elektromiografi (EMG$_{FT}$) dan Elektromiografi Bersepadu (IEMG) merupakan dua teknik yang digunakan bagi menentu Permulaan Keletihan Otot (OMF) berdasarkan perubahan tenaga dan amplitud. Walau bagaimanapun, semasa keletihan, perubahan dua faktor saling berkait di antara satu sama lain. Bagi membezakan tenaga yang dikaitkan dengan keletihan yang mendorong kepada perubahan EMG, Analisis Elektromiografi (EMG) Spektrum dan Amplitud (JASA) digunakan. Tetapi, prestasi JASA dalam mengesan isyarat keletihan terjejas dengan pemilihan panjang isyarat yang digunakan. Selain itu, JASA juga jarang digunakan bagi mengesan OMF. Maka, tujuan kajian ini adalah untuk menentukan kawasan OMF dengan mempraktiskan JASA pada isyarat EMG bersegmen. Isyarat permukaan EMG merekodkan 2 minit aktiviti pengecutan isometrik (otot Biceps Brachii) yang dijalankan ke atas 30 subjek. Setiap isyarat telah dibahagikan kepada selang masa 15 saat. Punca Min Persegi (RMS) dan Kekerapan Min (MNF) digunakan sebagai penunjuk bagi keletihan otot. Penunjuk keletihan ini ditentukan bagi setiap 3 saat dalam segmen. Regresi polynomial telah digunakan bagi menggambarkan kadar perubahan. Segmen pertama yang menunjukkan penurunan kekerapan dan peningkatan amplitud dengan pekali korelasi $r \geq 0.7$ telah diklasifikasikan sebagai rantau OMF. Daripada 30 subjek, 20 (67%) subjek mengakui telah merasa ketidakselesaan otot dan pada masa yang sama kawasan OMF telah dikesan atau sebaliknya. Baki 10 subjek, kawasan OMF telah berjaya dikesan pada 90% daripada mereka tetapi atas faktor ketahanan otot yang baik, tempoh masa yang lama diperlukan sebelum mereka merasa ketidakselesaan otot. Masa-spektrum penunjuk keletihan (Frekuensi Min Serta-merta (iMNF)) digunakan untuk menentukan kebolehpercayaan teknik. Penyusutan iMNF di rantau OMF menunjukkan pekali korelasi yang tinggi ($r > 0.6$). Subjek juga diminta untuk melaksanakan kontraksi dinamik selama 2 minit. Dengan mengaplikasikan teknik yang dicadangkan, OMF telah dikesan di kalangan 24 subjek. Lapan belas daripada mereka (72%) mengakui mereka memgalami ketidakselesaan otot. Empat belas daripada 18 subjek merasakan ketidakselesaan otot selepas OMF dikesan. Keputusan ini menunjukkan ketidakselesaan otot akan berkembang secara pelahan selepas bermulanya keletihan otot. Untuk aktiviti tulisan tangan, 4 subjek telah diminta untuk menulis selama 5 minit manakala isyarat sEMG dirakam pada otot Flexor Carpi Radialis (otot kecil). Daripada 4 subjek, selepas OMF dikesan, kesemua mereka telah menunjukkan kenaikan tekanan pen, dan 75% menunjukkan kenaikan dalam kelajuan menulis. Kajian ini menyimpulkan bahawa teknik yang dicadangkan boleh dilaksanakan untuk mengesan OMF; bukan sahaja semasa penguncupan isometrik tetapi juga semasa penguncupan dinamik. Teknik ini juga berpotensi digunakan untuk penguncupan otot kecil.

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LIST OF ABBREVIATIONS

Ag-AgCI	-	Disposable Pre-gelled Surface Electromyography Electrodes
ANN	-	Artificial Neural Network
BMI	-	Body Mass Index
BPF	-	Band-pass Filter
BSF	-	Band-stop Filter
CMRR	-	Common Mode Rejection Ratio
CNS	-	Central Nervous System
CV	-	Conduction Velocity
CWD	-	Choi-William Distribution
ECG	-	Electrocardiogram
EEG	-	Electroencephalogram
EF	-	Experiencing Fatigue
EMC	-	Expected Maximum Contraction
EMG	-	Electromyography
EMG_{FT}	-	Electromyography Fatigue Threshold
FCR	-	Flexor Carpi Radialis
FI_{nsmk}	-	Fatigue Indices
HPF	-	High-pass Filter
IEMG	-	Integrated Electromyography
iMNF	-	Instantaneous Mean Frequency
iRMS	-	Instantaneous Root Mean Square
JASA	-	Joint Analysis of Surface Electromyography Spectrum and Amplitude
LPF	-	Low-pass Filter
MAV	-	Mean Absolute Value
MDF	-	Median Frequency

MES	-	Transient Myoelectric Signal
MLPNN	-	Multi-layer Perception Neural Network
MNF	-	Mean Frequency
MUAP	-	Motor Unit Action Potential
MVC	-	Maximal Voluntary Contraction
nEMG	-	Needle Electromyography
OMF	-	Onset of Muscle Fatigue
PSD	-	Power Spectrum Density
r	-	Correlation Coefficient
RMS	-	Root Mean Square
sEMG	-	Surface Electromyography
SOM	-	Self-organizing maps
STFT	-	Short-time Fourier Transforms
TFD	-	Time-frequency Distribution
TFR	-	Time-Frequency Representation
UTM	-	Universiti Teknologi Malaysia
WAMP	-	Willison Amplitude
WL	-	Waveform Length
WVD	-	Wigner-Ville Distribution
ZC	-	Zero-Crossing
% MVC	-	Percentage of Maximal Voluntary Contraction
σ_{SEE}	-	Standard Error Estimate

LIST OF SYMBOLS

$AvePressure$ - Average pressure
$AveSpeed$ - Average speed
$EMG\ (t)$ - Amplitude of muscle signal
f - Frequency
f_c - Cut-off frequency
f_j - Frequency
FI_{nsmk} - Fatigue indices
$h\ (t)$ - Window function
$IEMG$ - Integrated electromyography
$iMNF$ - Instantaneous mean frequency
MAV - Mean absolute value
MDF - Median frequency
MNF - Mean frequency
N - Length of electromyography signal
n - Number of paired data
P_j - Power spectrum density
$P(t,w)$ - Spectrogram
$PSD(f)$ - Power spectrum density
RMS - Root mean square
$Speed_{15\text{-}second}$ - Speed in 15-second
$STFT(t,f)$ - Short-Time Fourier Transforms signal
t - Time
w - Window
WL - Waveform length
$WAMP$ - Willison Amplitude
x - x-coordinate
x_i - Electromyography signal

y - y-coordinate

Y - Actual data

Y' - Predicted data

ZC - Zero-Crossing

$\sum$ - Summation

% - Percentage

$|x|$ - Absolute value

σ_{est} - Standard error estimate value

$\int$ - Integral

$*$ - Complex conjugate

ψ - Wavelet Function

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Muscle fatigue is known as a feeling of weakness or muscle pain or a decline in muscle performance (Merletti, Rainoldi and Farina, 2004), commonly occurred when performing repetitive movements for a long period of time. When studying muscle fatigue, there is no-specific symptom, which means that it has many possible causes and accompanies many different conditions and illnesses. The mechanism is different in terms of the activities performed, gender, and the subject's physical level (patient, athlete, or ordinary person), which influenced by the muscle force applied and endurance level of the individual. Thus, to understand the mechanisms that have contributed to the decline of the muscle performance, it is crucial to know the Onset of Muscle Fatigue (OMF) (Enoka and Duchateau, 2008). Basically, the OMF is known as a starting point where the muscle starts to experience fatigue as soon as the muscle activity began.

Muscle fatigue is not only about the decline in muscle performance, but also the decrease in the ability of a muscle to exert force (Vøllestad, 1997; Moshou *et al.*, 2005); the reduction of force causes the decline in muscle performance (Marson, 2011). Yet, people have ability to manipulate their muscle force while performing certain activity (Maton, 1981). This has further complicated process of determining the OMF.

In general, the OMF is not only affected by the activity's intensity and duration but also the person's endurance level (Coorevits *et al.,* 2008a). Endurance level indicates the ability of the muscle to perform an activity until it becomes exhausted. Individual who has lower muscular endurance will experience fatigue earlier than the others. In some cases, due to exhaustion, individuals use fatigue as an excuse to discontinue their muscle activity, which results in subjective and questionable decision on fatigue (Hewlett *et al.,* 2005).

1.2 Background of Study

The decline in muscle performance due to fatigue is not immediately apparent if a sub-maximal activity is performed. In such activity, monitoring the progress of fatigue is easy when the researcher only depends on the subjective information given by the subjects. Unfortunately, this subjective information is unreliable (Juszka and Papir, 2015). The scientific procedure to determine the initial point of fatigue is required in order to authenticate the study.

Electromyography (EMG) is a commonly used diagnostic procedure to assess muscle performance. It measures electrical activity in response to a nerve's stimulation of the muscle resulting from a by-product of contractions. The recorded EMG signal and the analysis performed have opened an opportunity to objectively detect the OMF without depending on the subjective information given by the subjects.

Determining the OMF is one of the important elements in fatigue study. Soylu and Arpinar-Avsar (2010) reported that the OMF occurred when the force output reached their maximum value. Unfortunately, the scope of the research was only focused on muscle activity during isometric Maximum Voluntary Contraction (MVC). Basically, MVC is known as the highest amount of force that muscle can voluntarily exert. Alas, this information was contradicted to the idea proposed by Enoka and Duchateau (2008); the human muscle is still capable of performing the contraction activity even though it has started feeling fatigue. The idea was supported by Maton (1981); the muscle fatigue can be detected from the beginning of the sub-maximal contraction. Moreover, this statement was vindicated in Electromyography Fatigue Threshold (EMG_{FT}) technique; the threshold value has been detected before the force reached the MVC value.

Electromyography Fatigue Threshold (EMG_{FT}) is one of the techniques to determine the starting point of fatigue in respect to the force level (Hendrix *et al.*, 2009; Hendrix *et al.*, 2010). It is commonly used to distinguish fatigue signal from the non-fatigue signal (Hendrix *et al.*, 2009). In this technique, the progress of fatigue is estimated by interpolating a maximal contraction.

Determination of the EMG_{FT} is based on the force output (Bouillard, Guével, and Hug, 2011). The procedures require the subjects to perform isometric contraction at different percentages of load, such as 10 %, 20 %, 30 %, and 40 %, in relation to MVC (Bilodeau *et al.*, 2003). In each load, the behaviour of fatigue indicators such as Root Means Square (RMS) and Mean Frequency (MNF) are analysed and projected onto a graph (Figure 1.1(a)). Linear regression between each fatigue indicator and time for each per cent load is performed to obtain the slope. Another linear regression is then performed between the slope and its corresponding load. The y-intercept of the line is described as the EMG_{FT} as shown in Figure 1.1(b).

Unfortunately, some difficulties were observed when depending only on the MVC value to determine the fatigue threshold. As determination of MVC requires the subjects to exert their maximum voluntary force, this technique was limited only to limb muscle (Vøllestad, 1997). Furthermore, MVC is measured during static contraction. Therefore, the measured MVC value may not picture the maximum muscle force during dynamic contraction. The amplitude of the muscle signal during dynamic activity could be higher than the recorded MVC value.

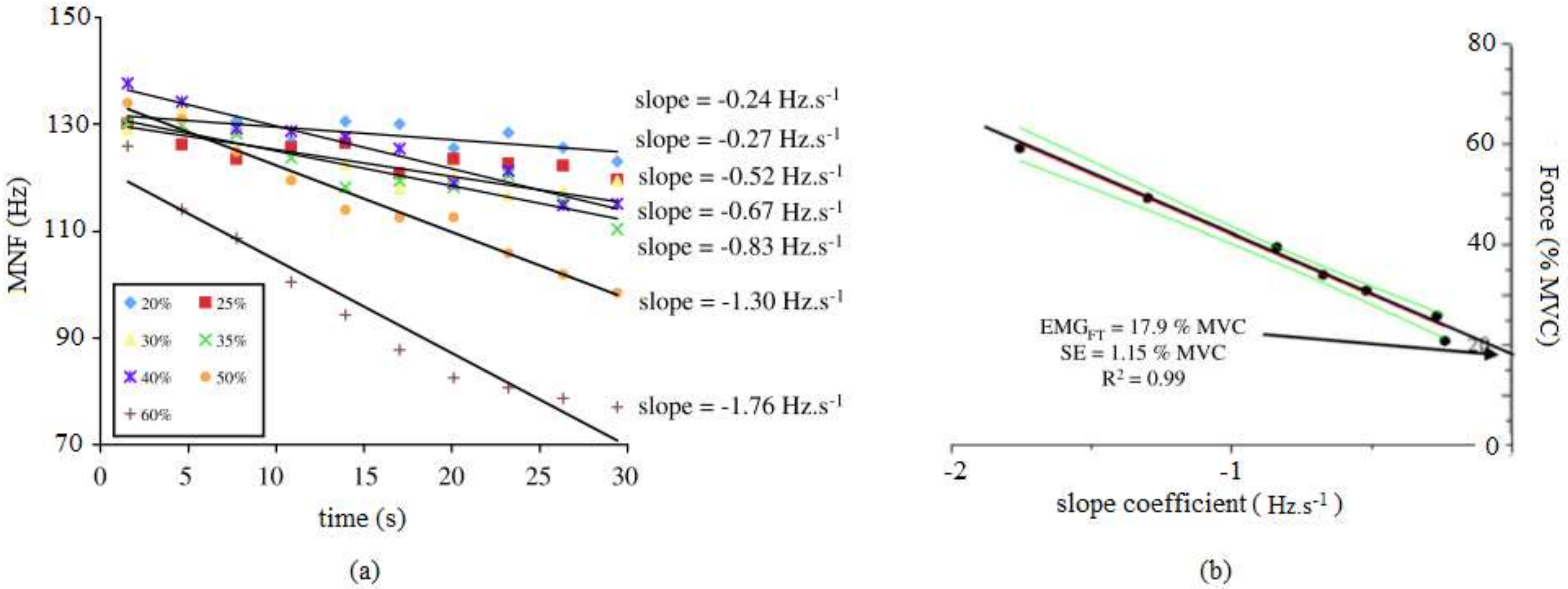

Figure 1.1: EMG Fatigue Threshold: (a) Regression analysis of MNF and (b) Force-slope coefficient graph (Bouillard, Guével, and Hug, 2011)

The activities that involve small muscle movement such as handwriting will also limit the application of the EMG_{FT} technique (Bouillard, Guével, and Hug, 2011). Estimating MVC for small muscles (muscles for small movements) has been reported to produce varying ranges of accuracy at different levels of MVC (Young *et al.*, 2005). This may be due to the fact that the muscles used for small movement are smaller and thinner than the muscles used for large movement.

Above all, muscle used for small movement and dynamic contraction are also experiencing fatigue and the OMF for such conditions cannot rely on the method that requires MVC value.

Ordinarily, the trends of amplitude and spectrum parameters have been used to study fatigue behaviours. Joint Analysis of Surface Electromyography Spectrum and Amplitude (JASA) is a method that is used to discriminate force-related from fatigue induced EMG changes (Luttmann, Jäger, and Laurig, 2000). However, contradicting results were reported. Since there was no significant trend shown in spectrum parameters, Moshou *et al.* (2005) concluded that JASA was not appropriate for fatigue analysis. On the contrary, Oh, Kim, and Hong (2014) reported that the observed trends in both spectrum and amplitude parameters can be used to describe fatigue. These two opposing results lead to further research on the use of JASA.

1.3 Problem Statement

Whenever muscle performances become the subject matter, muscle fatigue is one of the related topics usually discussed. However, there are few arising issues when studying this topic such as the detection of the fatigue starting point and the selection of the muscle to be studied. These critical issues are significant in order to ensure the validity of the study.

Learning the OMF is important especially when mechanism changes afterwards is concerned. There are several techniques that have been used by researchers to determine the OMF such as EMG_{FT}, force output and integrated EMG (IEMG) (Maton, 1981; Moshou *et al.*, 2005; Hendrix *et al.*, 2009; Soylu and Arpinar-Avsar, 2010). For EMG_{FT}, the value of MVC plays an important role in determining the threshold value. In spite of that, several disadvantages were reported especially in the studied muscle (limited to limb muscle) (Vøllestad, 1997) and experimental method (dynamic contraction activity) (Luttmann, Jäger, and Laurig, 2000). Furthermore, Bouillard, Guével, and Hug (2011) had stated that this technique is inapt to access the muscle function.

According to Soylu and Arpinar-Avsar (2010) and Maton (1981), OMF could be identified based on the increment of force output and amplitude parameter (IEMG) respectively. OMF was identified when the force output has reached the maximum value (Soylu and Arpinar-Avsar, 2010). Nonetheless, this experiment was performed in maximum contraction activity. On the contrary, Maton (1981) determined the OMF based on the increment in IEMG. The author reported that the OMF was detected at the beginning of the sub-maximal contraction. Anyhow, Luttmann, Jäger, and Laurig (2000) claimed that the increment of amplitude signal (IEMG) was not the only criteria to determine fatigue, but also the increment of force. In order to discriminate between force and fatigue, the combination on both temporal and spectrum parameters are suggested.

JASA introduces four muscle conditions: fatigue, overcome fatigue, force increase, and force decrease. Although Moshou *et al.* (2005) stated that JASA was inappropriate to be applied when studying muscle fatigue, it should be noted that Oh, Kim, and Hong (2014) and Jonkers *et al.* (2004) were able to detect fatigue using JASA. Originally, JASA was used to declare the existence of fatigue signal. Jonkers *et al.* (2004) had used JASA to quantify muscle fatigue during the activity of powering the wheelchair. In this study, the 0.5-seconds of initial and end points of the muscle signal were used to extract the average of the rectified signal and median frequency. Based on these two fatigue indicators, the signal was declared as fatigue signal if the average of the rectified signal gives a positive value and median frequency gives a negative value. However, the procedure was different from Moshou *et al*. (2005) and Oh, Kim, and Hong (2014); the regression analysis was performed on the extracted fatigue indicators, and the trend of the fatigue indicator were used as the parameters to determine the region in JASA. Although both studies used similar procedure, the results had shown to be affected by the length of data. By using a shorter signal (1200-seconds) (Oh, Kim, and Hong, 2014), the regression analysis can interpret the fatigue-induced EMG trends (spectrum and amplitude) better; Moshou *et al.* (2005) on the other hand used a longer signal (3600-seconds). This comparison shows that the length of data does affect the regression performance in JASA. In addition, Smith (1997) had highlighted that the segmentation with similar characteristics is needed especially for a long recording signal. Thus, it is the intention of this study to apply JASA with specific regression analysis on the segmented EMG signal to determine the OMF.

1.4 Research Objectives

The objectives of this research are:

i. To detect the onset of muscle fatigue region based on JASA for the recorded EMG signal from isometric contraction.

ii. To determine the appropriate data to be presented in regression analysis throughout the segmented signal.

iii. To assess the performance of the proposed technique in detecting the OMF region for different types of contractions: isokinetic contraction and small muscle contraction.

1.5 Research Scopes

The scopes of this research are divided into three different sections: participants, experimental setup, and data analysis.

i. Participants: 30 subjects consisted of 15 males and 15 females from Universiti Teknologi Malaysia (UTM) were selected for this study. The subjects are right handed and in the age range of 19 to 30 years old.
ii. Experimental setup: three different experiments were conducted- static activity (isometric contraction), dynamic activity (isokinetic contraction) and handwriting activity (small muscle contraction). For static and dynamic activities, a two-kg dumbbell was used as an instrument. NeuroPrax System was used to record the myoelectric signal produced by the muscle during the activity. Meanwhile, Wacom Tablet was used to record the dynamic data produced during handwriting activity.
iii. Data analysis: Matlab software was used to process and analyze the recorded data. Excel software was used for statistical analysis.

1.6 Research Contributions

Several techniques have been used by previous researchers in determining OMF: EMG_{FT}, force output, and amplitude changes. EMG_{FT} uses threshold value to determine the starting point of fatigue (Hendrix *et al*., 2009). Meanwhile, Soylu and Arpinar-Avsar (2010) determined the OMF based on the decrement in maximum force value. However, these techniques depend on MVC value, which limits the scope of this study. In terms of amplitude trend, Maton (1981) has used the increment in IEMG parameter to proclaim the OMF. Despite that, the increment on the amplitude parameters not only demonstrates fatigue but also force changes. Therefore, to differentiate between force and fatigue, a new approach was introduced. Adapting JASA's definition for muscle fatigue condition, this technique used the trends of time-domain and frequency domain fatigue indicators to detect the OMF.

JASA is a method that uses the trend of amplitude and spectral parameters to identify four regions of muscle activity. The trend of the parameters is used to decide whether the muscle experiencing fatigue or just adjusting the muscle force (Luttmann, Jäger, and Laurig, 2000). Moshou *et al*. (2005) stated that the JASA was unable to detect fatigue signal (amplitude increase and spectral decrease) during dynamic contraction. It is important to note that the authors performed regression analysis on 3600-second signal. It was contradicted to the findings reported in Oh, Kim, and Hong (2014). By applying regression analysis on 1200-second signals, the existence of fatigue signal was detected. These two contradicting findings highlight the effect of signal length during the regression analysis. Thus, by performing the segmentation on the sEMG signal, this study was able to observe the trends of the fatigue indicators and consequently validate the JASA’s capability in detecting the OMF region.

The application of JASA in detecting the OMF has been extended to sEMG signal captured during dynamic as well as small muscle contractions. Currently, it is a convention to detect the OMF in sEMG signal during static, but not during dynamic contraction and small muscle contraction. The difficulty to obtain the MVC value has made the process to determine the OMF for small muscle is impossible. Without requiring MVC value, this proposed technique had provided an opportunity to objectively assess muscle fatigue due to small muscle contraction from handwriting activity.

1.7 Thesis Organisation

This thesis is divided into five chapters: introduction, literature review, methodology, results, analysis and discussions, and conclusion and future works recommendation.

Chapter 1 starts with brief description about muscle fatigue, the importance of knowing OMF, and limitations of the current methods in determining the OMF. The objectives and the scopes of this research are then highlighted. This chapter ends with the research contributions.

Chapter 2 discusses ideas, facts, and the information related to this study. This chapter consists of 4 subsections: human muscular system, the principle of EMG and sEMG, sEMG machines and muscle fatigue detection. In each subsection, the facts and findings from previous researches are discussed.

Chapter 3 explains in detail the methodology applied in this study. This chapter is divided into 5 subsections: participants, data acquisition, signal processing, detection of the OMF, and verification. In the first subsection, the characteristics of the recruited participants are highlighted. Experimental setup and fatigue exercise protocols are described in the second subsection. The procedures used to analyse the signals are elaborated in the third subsection. This subsection also specifies the filtering and parameter extraction (time domain and frequency domain) processes. The procedures to determine the OMF is clarified in the fourth subsection. The last subsection explains the procedures to justify the proposed method.

Chapter 4 presents and discusses the results. The appropriate epoch length and regression model are reported at the beginning of this chapter. The chapter continues with the analysis on the performance of the JASA technique in detecting the OMF. This chapter ends with the discussion on the applicability of the proposed technique to the different types of muscle contraction.

Chapter 5 concludes the findings of the research. The chapter ends with some suggestions and strategies for future research works in improving the quality of the proposed technique.

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