UNIVERSITI PUTRA MALAYSIA

CLASSIFICATION OF SURFACE EMG SIGNALS FOR EARLY SIGNS OF PROLONGED FATIGUE

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By

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October 2017

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Sports training are very important to athlete in maintaining and improving their performance. During training, adequate rest is essential to allow recuperation and build body strength. Inadequate rest may expose the body to prolonged fatigue (PF). This condition needs to be managed accordingly to avoid chronic fatigue syndrome. Currently, the non-invasive assessment in identifying PF are training log record, questionnaire and Borg scale. Recent findings indicate that there are strong characteristics on surface electromyography (EMG) under PF conditions such as glycogen breakdown, existence of lactate and soreness. This study extends the investigation of PF signs, especially on the inceptions of PF. An experiment has been conducted on twenty participants to investigate the behavior of surface EMG during five days of intensive training that was based on Bruce Protocol treadmill test. The intention was to induce PF on biceps femoris (BF), rectus femoris (RF), vastus lateralis (VL) and vastus medialis (VM). Besides surface EMG signals, physiological measurements were also collected from the participant.

Physiological results demonstrate that the earliest PF signs developed were soreness, lethargy and performance decrement. For the surface EMG, they went through three main processes: de-noising, feature extraction and classification. De-noising technique through stationary wavelet transform (SWT) was employed in enhancing quality of surface EMG signals. During de-noising process, new method in estimating threshold (*Th*) was proposed. The method demonstrated to have higher performance in term on noise removal and accuracy in PF classification, compared to conventional *Th* methods.

Nine features extracted from the de-noised surface EMG signals. There were changes in median frequency (ΔFmed), mean frequency (ΔFmean), mean absolute value (ΔMAV), root mean square (ΔRMS), and five features from wavelet indices (ΔWI). Daily fatigue

mappings indicate that the emergence of PF can be traced based on extracted features. The mappings indicate that ΔFmed and ΔFmean tend to increase under PF condition for all four muscles BF, RF, VL and VM. Additionally, under PF condition, the mapping indicates an increase in ΔRMS and ΔMAV but decrease in ΔWI for RF muscle.

In the classification stage, Naïve Bayes (NB) and Support Vector Machine (SVM) demonstrate accuracy with 98% and 97% respectively, in distinguish PF on RF, 94% and 96% respectively on BF, both 95% on VL, and 98% and 96% respectively on VM. Thus, this study successfully demonstrates that surface EMG can be used in identifying the inception of PF. The findings presented are significant in sports field to prevent higher degree of PF.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENGKELASAN ISYARAT EMG PERMUKAAN UNTUK TANDA AWAL KELETIHAN BERPANJANGAN

Oleh

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Latihan sukan adalah sangat penting kepada atlit untuk mengekalkan dan meningkatkan prestasi.Semasa latihan, rehat yang cukup adalah perlu untuk pemulihan and meningkatkan kekuatan sistem badan. Rehat yang tidak mencukupi boleh mendedahkan seseorang kepada keletihan yang berpanjangan (PF). Keadaan ini perlu diurus dengan baik untuk mengelakkan sindrom keletohan yang kronik. Ketika ini, kaedah non-invasif yang digunakan untuk mengenalpasti PF adalah log latihan, soal selidik dan juga skala Borg. Penemuan terbaru menunjukan terdapat karakter elektromyografi permukaan (EMG) di bawah keadaan penurunan glycogen, kewujudan laktat dan kesakitan otot. Kajian ini menyiasat beberapa tanda-tanda PF, terutamanya sewaktu bermulanya PF. Eksperimen dijalankan ke atas dua puluh orang peserta berdasarkan ujian treadmill Protokol Bruce untuk mendorong PF ke atas biceps fermoris (BF), rectus femoris (RF), vastus lateralis (VL) and vastus medialis (VM). Selain dari EMG permukaan, pengukuran fisiologi juga diambil daripada peserta.

Keputusan fisiologi menunjukkan bahawa tanda PF yang paling awal berlaku adalah kesakitan otot, keletihan dan juga penurunan prestasi. Untuk EMG permukaan, ianya melalui tiga proses utama: de-noising, pengekstrakan sifat dan pengkelassan. Kaedah de-noising melalui stationary wavelet transform (SWT) digunakan untuk meningkatkan kualiti isyarat EMG permukaan. Semasa proses de-noising, kaedah baru dalam menentukan nilah ambang (*Th*) diusulkan. Kaedah tersebut telah menunjukkan prestasi yang lebih baik di dalam membuang hingar and ketepatan dalam pengkelasan PF, berbanding kaedah konvensional.

Sembilan sifat diekstrak daripada isyarat EMG permukaan yang telah diproses. Ianya adalah frekuensi pertengahan (ΔFmed), purata frekuensi (ΔFmean), purata nilai absolut (ΔMAV), purata punca kuasa (ΔRMS), dan lima sifat daripada wavelet indice (ΔWI).

Plot keletihan harian menunjukkan bahawa permulaan PF boleh dikenalpasti melalui sifat yang telah diekstrak. Plot menunjukkan bahawa ΔFmed dan ΔFmean cenderung untuk meningkay di bawah keadaan PF untuk keempat-empat otot, BF, RF, VL dan VM. Tambahan lagi, plot juga menunjukkan bahawa ΔRMS dan ΔMAV meningkat semasa PF,dan ΔWI menurun untuk otot RF.

Ketika pengkelasan, Naïve Bayes (NB) dan Support Vector Machine (SVM) menunjukkan ketepatan masing-masing 98% dan 97%, dalam membezakan PF terhadap RF, 94% dan 96% masing-masing terhadap BF, kedua-duanya 95% terhadap VL, dan masing-masing 98% dan 96% terhadap VM. Maka, ini menunjukkan kajian ini berjaya menunjukkan bahawa EMG permukaan boleh digunakan untuk mengenalpasti permulaan PF. Penemuan ini sangat penting dalam industry sukan untuk mengelakkan tahap PF yang lebih tinggi.

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I certify that a Thesis Examination Committee has met on 6 October 2017 to conduct the final examination of Nurul Fauzani binti Jamaluddin on her thesis entitled "Classification of Surface EMG Signals for Early Signs of Prolonged Fatigue" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This is to confirm that:

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LIST OF EQUATIONS

LIST OF ABBREVIATIONS

ADC	Analog to Digital Conversion
Ag/Ag Cl	Silver silver Chloride
AIS	Anterior Aliac Apine
B	Details Baseline
BF	Biceps Femoris
B_M	Maximum Baseline
BMI	Body Mass Index
BP	Blood Pressure
C	Details Contract
cA	Approximation Details
cD	Coefficient Details
CV	Cross Validation
DWT	Discrete Wavelet Transform
EMG	Electromyography
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
Fmean	Mean Frequency
Fmed	Median Frequency
HPF	High Pass Filter
HR	Heart Rate
HRmax	Maximum Heart Rate
IA	Instrumentation Amplifier
IEMG	Integral EMG
MAV	Mean Absolute Value
M_T	Multiplier Threshold
NB	Naïve Bayes
NF	Normal Fatigue
PF	Prolonged Fatigue
PSD	Power Spectral Density
RF	Rectus Femoris
RMS	Root Mean Square
RPE	Rating of Perceived Exertion
SENIAM	Surface Electromyography for the Non-Invasive Assessment of Muscles
SNR	Signals to Noise Ratio
SURE	Stein's Unbiased Risk Estimate
SVM	Support Vector Machine
SWT	Stationary Wavelet Transform
Th	Threshold
VL	Vastus Lateralis
VM	Vastus Medialis
WI	Wavelet Indices

LIST OF SYMBOLS

I	Decomposition Level
N	Number of Samples
X	Signal
Fs	Frequency Sampling
L	Length of Signal
Δ	Changes
T	Time
Σ	Standard deviation

CHAPTER 1

INTRODUCTION

1.1 Introduction

Sports training are very important to athlete in maintaining and improving their performance. Nevertheless, sports training cause the athlete to become fatigue. Fatigue is a natural physiological sign showing the limitation of a human body. It is characterized by lower level of performance, reduction of organism forces, and failure to maintain the level of forces exerted (Al-Mulla & Sepulveda, 2010; Boyas & Guével, 2011; Davis, Walsh, & Edin, 2010; C J De Luca, 1984; R. H. Edwards, 1981; Sesboüé & Guincestre, 2006).

In normal fatigue (NF), fatigue usually disappears by itself after a while. Recovering from fatigue indicates that biochemical reactions during sports activity are able to return to a normal level (Pearce, 2002). Occasionally, the load and intensity of sports training are greater than the body can handle and this leads to imbalance. However, adequate recovery process due to imbalance enhances strength and improve performance (Howwit, 2004; Myrick & Aprn, 2015). Unfortunately, inadequate recovery period causes more biochemical reactions accumulation; thus fatigue continues (Kreher & Schwartz, 2012). Inadequate recuperation leads to prolonged fatigue (PF) and takes several days to weeks to recover (Myrick & Aprn, 2015).

There are several degrees of PF, and it is categorized according to the diagnosed signs. The mildest signs of PF are musculoskeletal disorder (soreness, pain or aches), unexplained lethargy, performance decrement, restlessness, hypertension and sleeping and psychological disturbance (Jeukendrup, 2010; Purvis, Gonsalves, & Deuster, 2010). Playing sports under this condition may lead to injury, continued underperformance, possible damage of body structure and development of more serious state of PF (Jeukendrup, 2010; Myrick & Aprn, 2015). If this situation occurs, the athlete is not able to participate in any competition; hence, risking the athlete's career (Pearce, 2002). The recovery process is time and cost consuming, and affects national sports industry as the athletes fail to participate in national and international competitions.

Prevention from the occurrences of PF condition is the best solution (Pearce, 2002). The identification of PF signs at the earliest of its inception helps in providing proper fatigue and training management. There are no specific tools used for PF identification. Currently, PF is diagnosed invasively through blood test and biopsies. Alternatively, PF can also be diagnosed non-invasively through heart rate, endurance time, the rating of perceived exertion and distress questionnaire (M. Haddad et al., 2013; Hernandez, Estrada, Garcia, Sierra, & Nazeran, 2010; Sakurai et al., 2010).

Nonetheless, there is a significant growth in investigating fatigue via surface electromyography (EMG). In fact, the progression of fatigue process can be determined via surface EMG (Massó et al., 2010).
Surface EMG is a reflection of the behavior, potentials, voltages and electrical field of human skeletal musculature (Joachim H.Nagel, Bronzino, 2000; Medved & Cifrek, 2011; Thakor, 1999). It is acquired by placing electrodes on the surface skin, near to human muscle. The amplitude and frequency of the signals signify the behavior and condition of muscle's motor unit, conduction velocity and ionic alteration of the muscle. Furthermore, there are many advantages of using surface EMG in investigating fatigue including it is a non-invasive process, easy to use, comfortable and inexpensive. Any investigation on fatigue based on muscle evaluation is denoted as muscle fatigue.

Fatigue can be determined by changes in its amplitude and frequency. Most of the opinions agree that the degree of fatigue begins with the increment of amplitude, followed by the unchanged and decreased trends, as well as accompanied by the decrement center of frequency (Dimitrova & Dimitrov, 2003). Recently, there is significant growth in investigating PF using surface EMG. It covers several PF signs such as biochemical reactions, performance decrement and soreness (Gavin, Myers, & Willems, 2015; Sterczala & Nicol, Jx; Fry, 2015; Tenan, Blackburn, & Robert, 2016). The results of these studies prove that useful information can be extracted from surface EMG signals to distinguish PF condition.

Hence, this thesis focuses on investigating surface EMG behavior under the earliest signs of PF. In fact, the characteristics identified can be used as a prevention measure for the serious state of PF.

1.2 Motivation and Problem Statement

Reports show that 20% to 60% of athletes, 60% of elite runners, 33% of non-elite runners, and 35% swimmers experienced PF at least once in their career life (Kreher & Schwartz, 2012; Myrick & Aprn, 2015; Purvis et al., 2010). Meanwhile, Nederhof, Lemmink, Visscher, Meeusen, & Mulder, (2006) reported that 20% to 60% of athletes have experienced chronic fatigue due to untreated signs of PF.

To date, invasive methods such as muscle biopsies and blood test are considered as the most reliable indicator in diagnosing PF. However, the methods are time-consuming, cost ineffective and unable to be applied frequently. The existing non-invasive methods mostly require close supervision and time-consuming. This method is ineffective in monitoring a large number of athletes. Nevertheless, identifying early signs of prolonged fatigue is important to avoid injury and disorder. Most importantly, it is able to prevent the occurrence of higher PF state. Therefore, an alternative method such surface EMG, which is cost effective, easier and requires less processing time, procedure and supervision, is essential in diagnosing early sign of PF.

Surface EMG has been used to identify fatigue since 1912. Currently, the information is limited to non-fatigue, the transition to fatigue and fatigue under normal condition. There are recent and growth findings from high-intensity exercise and associated with PF condition. However, the findings are restricted to glycogen breakdown, existing of lactate and soreness only. Investigation on other PF signs, especially during the emergence of the condition is essential for early detection. That is why the investigation of surface EMG under PF condition benefits in determining fatigue classification. At the moment, the classification is successfully performed in distinguishing between non-fatigue to fatigue (Marri & Swaminathan, 2015; Sarillee et al., 2015; Venugopal, Navaneethakrishna, & Ramakrishnan, 2014; Zhang, Jian E.Lockhart, Thurmon Soangra, 2015), and transition from non-fatigue and fatigue (Sepulveda, Colley, & Kattan, 2009) under normal condition. Therefore, the classification to distinguish fatigue under normal condition (NF) and PF has many advantages, particularly in sports.

The success of the classification process highly depends on the quality of surface EMG. Surface EMG is commonly contaminated by corner frequency and baseline noises. Nevertheless, corner frequency noise is easily removed by applying high-pass filter, since it exists in a specific range of frequency. Unfortunately, there is no specific frequency range for baseline noises. Worse, baseline noises merely exist within the surface EMG frequency range. Fret not, wavelet de-noising method can be used in removing baseline noises. In the de-noising process, thresholds need to be estimated. During de-noising process, signals above threshold value are preserved, while signals under threshold value are removed. However, the available conventional threshold estimations are not suitable for surface EMG application. The methods tend to remove important information from surface EMG signals and keep unwanted signals (Bartolomeo, 2012; Phinyomark, Limsakul, & Phukpattaranont, 2009b). Therefore, new estimation of threshold value that is suitable for surface EMG application is required. Essentially, the new threshold estimation is capable to remove noises and preserves a great deal of information. In addition, the de-noised signals based on the proposed technique have better performance in fatigue identification and classification.

1.3 Aim and Objectives

This thesis aims to investigate the behavior of surface EMG signals under the earliest signs of mild PF condition. The classification of PF will help the practitioner to identify and manage fatigue accordingly. This classification certainly assists in preventing a higher state of PF, which eventually is capable of preventing more serious injury.

The specific objectives of the study are as follow:

1. To propose a new technique in estimating threshold value for surface EMG wavelet de-noising application.
2. To investigate the surface EMG features behavior under the earliest signs of PF developed during five days of intensive training.
3. To investigate the significant features and muscle activation types for classification process that can be used to imply the inception of PF.

1.4 Scope of Works

The intensive training experiment is conducted based on five consecutive days of Bruce Protocol treadmill test. It is employed in the experiment as it provides high-intensity exercise and induces PF signs. As currently practiced, PF signs observed are limited to mild signs such as soreness, performance reduction, restlessness, hypertension, unexplained lethargy, sleeping disturbance and psychological stress. In this study, EMG signals are analyzed to investigate the shown behavior under the earliest signs of PF. PF signs are diagnosed non-invasively by Sports Officer Akademi Sukan Universiti Putra Malaysia (UPM) through 24-hours training distress questionnaire, training log and interview session. The occurrence of PF signs within five days of Bruce Protocol treadmill test (intensive training) indicates the earliest signs developed. This certainly means that not all PF signs are involved. Again, the signs developed are subjected to ethical reasons and potential risk endured by the participants. In addition, five days of intensive training on recruited subject is presumed to be adequate as approved by Jawatankuasa Etika UPM.

During the investigation, firstly, four lower extremities muscles were chosen since these are the activated muscles during running, and suffer the highest muscle injuries during sports particularly during running activities. Secondly, only healthy subjects, who possessed the inclusion and exclusion criteria between the age of 20 to 30 and with the body mass index (BMI) $18<x<25$, were selected to participate in these experiments. Finally, in total twenty (20) participants, five (5) males and fifteen (15) females, were recruited.

In the study, the pre-processing tool utilized for detecting surface EMG signals was Stationary Wavelet Transform (SWT). The conventional threshold methods applied in de-noising process were RigRSURE, HeurSURE, minimax and fixed from threshold. The proposed new estimation threshold value adopted SWT, with six level decomposition and 'db45' employed as mother wavelet. Apart from comparing the de-noised signals to standard quality of surface EMG signals, removing corner frequency and mitigating baseline noise to acceptable value, the performance of threshold estimation (for conventional and proposed methods) were verified by its ability to classify PF.

In fact, PF was classified in accordance to supervised classification methods namely Naïve Bayes (NB) and support vector machine (SVM). These classifications were made on the individual muscle. Then, the performance of the classifications was evaluated based on its accuracy, specification, precision and cross-validation (CV) error.

1.5 Contribution

General contribution of the study lies in the ability to identify the earliest PF signs based on EMG signal analysis and classification. It indicates that there are other non-invasive tools which are quantifiable, have less procedure and need less supervision in diagnosing PF. Apart from that, the study contributes to the society as the identification can be used as one of on-site monitoring tools in sports training. The outcomes of the study assist particularly in training management to prevent injury and serious state of PF. Other than that, it helps in selecting athletes during competitive matches to ascertain their ability in delivering optimal performance.

1.6 Thesis Structure

This thesis consists of five chapters which describe the research activities involved. Chapter 1 presents a general introduction, problem statements, and motivation to do this research. This chapter clarifies the objectives, scopes of research works, contributions of this study, and the structure of thesis.

Chapter 2 discusses the literature review related to the research work. The chapter further elaborates the mechanism of PF, its signs and diagnostics tool commonly used. In addition, this chapter reviews the ability of surface EMG in PF identification. The review includes the characteristics of surface EMF signals itself, methods of acquisition and analysis.

Chapter 3 describes the research methodology employed in this study. It includes the development of surface EMG data acquisition system and data collection procedure. The design and consideration in proposing the new threshold value estimation method are also presented in this chapter. Apart from that, this chapter defines the feature extraction parameters involved, and the classification techniques used in the study.

Meanwhile, the main findings and discussions are presented in chapter 4. The performance of de-noising technique is presented first, then, followed by the results of the experimental design which includes physiological responses during the intensive training. The findings are presented in the form of fatigue mapping for the extracted features. Not only that, this chapter also presents classification performance in PF identification.

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