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Assessment of Muscles Fatigue Based on Surface EMG Signals Using Machine Learning and Statistical Approaches: A Review

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Abstract. Muscle fatigue is described by the decline in muscle maximum force during contraction. The fatigue occurs in the nervous or muscle fibre cells. The nerves produce a high-frequency signal to gain the maximum contraction, but it cannot sustain the high frequency signal for a long time, and that leads to a decline in muscle force. The surface Electromyography (EMG) is the dominant method to detect muscle fatigue because the EMG signals give more information about the muscle's activities. This review discussed the EMG signal processing and the methods of detection muscles fatigue with three domains (time domain, frequency domain, and time-frequency domain) based on EMG signals that are collected from the muscles during dynamic and static movements.

Keywords: muscles fatigue, EMG, dynamic and static movement

1. Introduction

Muscle fatigue is described by the decline in muscle maximum force during contraction [1]. Acute fatigue affects our ability to lift or move. Many types of research have carried out a further study to detect and study muscle fatigue. Currently, there are many detection methods that are applied to muscle signals in order to detect fatigue [2]. However, the surface electromyography (sEMG) is the main method to record and study the muscles functions, by recording the electrical signal of the muscles. There are also many factors that can contribute to fatigue [3], like muscle fiber composition, regulation of Ionic in the bloodstream, energy supply, neural factors, and many other factors. The studies have indicated that muscle fatigue is related to the incidence of musculoskeletal injuries occurring in sports training and competition [4]. Nyland [5] made the comment that fatigue during running might be related to lower extremity injury. Recently, evidence has shown that muscle activation patterns and kinematics are altered due to fatigue. Hence, it may raise the possibility of the occurrence of an injury to both the muscles as well as the bones injury [6]. Pinniger [7] found that after a specific hamstring fatigue exercise, the kinematic data of sprinting were changed. The kinematics could display alteration owing to the functional changes which occur in order to prevent or minimize the level of unpleasantness and the occurrence of fatigue [8]. Rodacki [9] echoed that the regulation of movement of the individual portions is controlled and ultimately decided by the force of muscle, which when sufficient fatigue has occurred may display certain changes. They also concluded that this phenomenon gave a clue as to the available of a supporting methodology to negate the losses occurred during the process of the force-development characteristics which occurs



within the muscles owing to fatigue. In this paper, we will discuss the muscles fatigue during dynamic and static movements, EMG signal processing, methods of detection muscles fatigue.

2. Muscles Fatigue Measurements

The disparity in the opinion of the mechanism of muscle fatigue can be partially elaborated with the use of various models of exercise, procedures, and processes done applied to quantify fatiguing of muscles. With an objective, a quantifiable and continuous method to assess muscle fatigue, this will amplify the knowledge of ergonomics, work, and injury resulting from work physiology [4]. The single most relevant determination of fatigue is done through the measurement of force or power measurement, which is produced during the course of a voluntary effort of maximum intensity, maximal voluntary contractions (MVCs) test. In general, when the subject performs the task of interest or the fatigue task continuously, at the pre-, post- and/or the interim time point, brief MVC tests will be conducted to register the drop of maximal force output from particular muscle. This will quantify the muscle fatigue pattern in relation to the task performed. The force output decline rate measured in these MVCs tests will indicate the muscle fatigue pattern. The foundation of similar tests which assists in the direct evaluation includes force measurement equipment. Although the drop of maximal voluntary contractions output directly indicates the presence of muscle fatigue. *However*, the surface electrodes have the ability to record up the superficial muscle layer's electrical transmissions, after which it magnified and ultimately the determination of the signal power spectrum is done when the response produced in sEMG.

3. Signal Processing

Electromyogram signals are gradually becoming more essential in various fields of application, such as in prosthesis devices, human to machine interactions, clinical/biomedical, and rehabilitation devices [10]. But, distorted EMG signals possess a major challenge in further expanding the performance applications mentioned above [11]. The EMG signals that are collected from the muscles by the electrodes will have noise, where the noise has a role in the hampering of the recording signals. For this reason, the EMG signal must be filtered in a proper manner to remove any noise [12]. The frequency of noise contaminating the EMG signal may be low or high. Low-frequency noises usually come from an amplifier's direct current offsets. Normally this noise can be avoided with the use of a high pass filter, while the high-frequency noises arise from nerve conduction. The interference of high frequency comes from computers, radio broadcasts and can be removed by using a low pass filter. The high pass filter is used to eliminate the low ranged frequencies that result at the electrical signal collection. The frequencies that are passed with a filter transmission as a band are known as a passband. The frequencies that cannot be passed with a filter are known as stop band [12]. The concept of a low pass filter is opposite to that of high pass filters. This means the frequencies exceeding the cut off value are removed and those below it will be transmitted. The EMG transmission needs to remove the high frequencies and low frequencies, while a specific band of frequencies must be transmitted forward, this is done by using a specific filter called a bandpass filter. This bandpass filter permits for specific bands to be transmitted according to the range that is determined by the user, however, the bandpass filter is very suitable for EMG signals to take a specific range of frequencies that is perfect for the type of analyzing [13]. Figure 1 shows the general procedures of EMG signal processing.

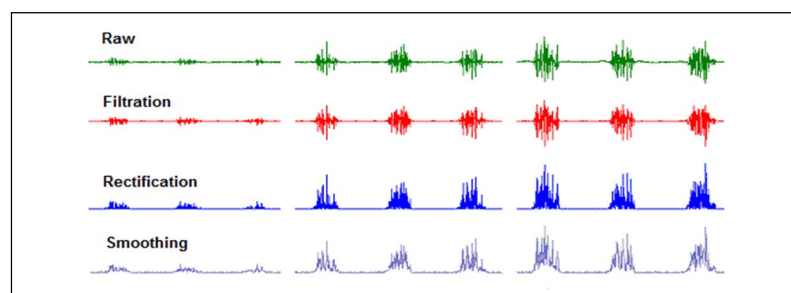


Figure1. EMG signal processing procedures included filtering, rectifying, and smoothing [14].

4. Feature Extraction

Feature extraction is a method to extract useful information from EMG signals during fatigue condition is simply explained as the diminishing of the capacity to generate force within the neuromuscular system. Generally, muscle fatigue is recognized by the EMG signal as long as there is a mutual decline in parameter examined in the frequency domain and time-frequency domain, and an increment in the parameter evaluated in the time domain [15], as shown in Figure 2. The type of EMG features can be divided into three domains: time domain, frequency domain, and time-frequency domain.

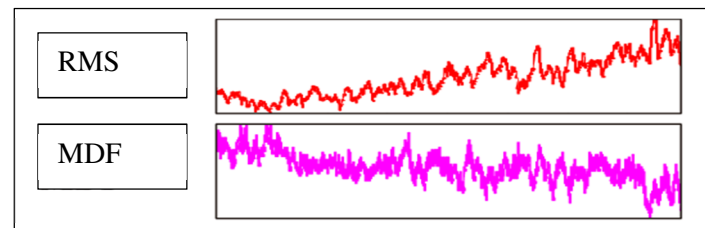


Figure 2. The increment in the pattern of RMS and decline in the pattern of MDF features for the EMG signal during muscle fatigue [24].

4.1. Time Domain Features

The signal recorded in the time domain is filtered to eliminate and minimize the noise, crosstalk, and line noise. The fatigue is related to the increment of the EMG amplitude [16]. The muscle fatigue detection in the time domain can be estimated by extracting features like root mean square (RMS) and mean absolute value (MAV). The detection of fatigue by observing the amplitude of the EMG signal is rarely used, and it will be more accurate if it is combined with other methods such as spectral analysis [17] to get better detection and more reliability. Later was discovered that the connection occurring between signal amplitude and force generated within the muscle are different among fatigue protocol [18]. However, there is a method that use multiple time windows (MTW) to get over this issue, by using different functions like Multiple hamming windows (MHW), multiple Slepian windows (MSW) and Multiple trapezoidal windows (MTRW) [19]. Thus, the signal processing to be combined with another feature extraction for better detection.

4.2. Frequency Domain Features

The shift towards lower frequencies of the EMG frequency spectrum calculated by fast Fourier transform (FFT) method [20]. Where the most common procedure is to monitor the relative changes in the mean (MNF) and median power frequencies (MDF) and to relate these measures to the initial value or non-fatigue state mean and median power frequencies. Kaljumae [21] used the phenomena of the shift of sEMG MNF and MDF towards lower frequencies under the isometric condition to document the change of fatigability of vastus lateralis (VL) and vastus medialis (VM) after 10 weeks of bicycle-ergometer training program in male subjects. Gerdle and Fugl-Meyer [22] had 10 healthy women perform repetitive maximal isokinetic plantar flexion. The sEMG MNF measured on the soleus, gastrocnemius medialis (GM) muscle along with the gastrocnemius lateralis (GL) were decreased in parallel with the work output within the first 50 contractions which was later superseded by constant levels in the resultant 50 contractions. So [23] examined the surface sEMG of rectus femoris (RF) and biceps brachii (BB) collected from 18 athletes when they performed maximal extension of the knee and flexion of the elbow exercises. The calculated MPF by FFT was found to reduce along with the reduction of work output and they suggested that an approximate reduction of 37.2% in relative MPF might be handy in performing the role of a parameter for assessing the level of muscle fatigue.

However, the MDF and MNF are very important to detect the muscles fatigue based on the power spectrum, but it will be more reliability and clarity if it combined with the time domain features to get more information about the function of the muscles.

4.3. Time Frequency Domain Features

Muscle fatigue is related to both EMG signal characteristics each in a deferent way, that leads to the Joint analysis of EMG spectrum and amplitude (JASA). This analysis has 4 situations to determine force and fatigue, first when both amplitude and spectrum increases that's mean force increase, second when both amplitude and spectrum decreases that's mean force decrease, third when amplitude increase and spectrum decrease that's mean fatigue, fourth when amplitude decrease and spectrum increased that's mean recovery [4]. Time-frequency methodologies are utilized to extensively study signals in which there is considerable variation of the frequency content with the change in time, which is similar to the situation seen in muscle fatigue. Short-Time Fourier Spectrum (STFT) is considered as a relatively common time-frequency distribution. However, the time-frequency functions can be utilized in the analysis of sEMG signals arising during a localized fatiguing of a muscle. Research conducted by Davies and Reismann clearly states that the STFT has the ability to most accurately depict spectrum compression which occurs during the time of muscle fatigue. In a study conducted on the relationship which exists between STFT and continuous wavelet transforms (CWT) to analyze EMG signals from the back and hip muscles during fatiguing isometric contractions, it was discovered that both methods ultimately give out the same output on EMG spectral variables [2]. The discrete wavelet transform (DWT) has been used to indicate the low-level muscles fatigue of brachioradialis (BRD), biceps brachii long head (BBL), and biceps brachii short head (BBS) when the subjects performing force exertion [25]. The muscle fatigue is seen in children suffering from cerebral palsy [26]. The muscle fatigue that occurs to PC gamers after continuous playing [27], and in helicopter pilots who are suffering from lower back pain [28]. Multiple classical, as well as newly designed modern methods of signal processing modalities, are used [17] these include RMS, zero-crossing rate (ZCR), averaged instantaneous frequency, wavelet analysis, fractal analysis, and both MNF and MDF. The instantaneous mean and median frequency (IMNF and IMDF) are added so as to complete the need [29] through the utilization of time-frequency or time-scale approaches, such as STFT [17], Wigner distribution (WD), Choi-Williams distribution (CWD) [30], time-varying autoregressive approach (TVAR) [31], and CWT [32].

5. Methods of Detection Muscles Fatigue

There are many non-invasive methods to detect muscle fatigue, the main methods are surface Electromyography (sEMG) and Mechanomyography (MMG). The EMG records the electrical activity signal from the muscle, while the MMG record the mechanical activity of the muscle [33]. There are many other methods but less use in clinical or research in fatigue like sonomyography (SMG) that use ultrasounds to detect fatigue and controlling prosthesis [34], near-infrared spectroscopy (NIRS) that use near-IR light to measure the hemoglobin absorption properties, and Acoustic myograph (AMG) that record the sound of muscles it's particular application of MMG. Each method tries to record and analyze one or multi symptoms, signals, and characteristics of muscle. However, the better method for detection muscles fatigue is surface EMG. There are many researchers collected the EMG signals from subject's muscle like BF, Medial Hamstrings (MH), GM, RF, Tibialis Anterior (TA), GL, Medial Gastrocnemius (GMS), semimembranosus (SEMB), VM, GA, BB, Triceps Brachii (TB), and VL) to use it as indicator for muscles fatigue index based on using the machine learning (regression) or statistical approach (ANOVA test), and some of them based on the pattern of the features to indicate the muscles fatigue as shown in Table 1.

Table 1. Literature review of the methods for detection muscles fatigue during contraction based on EMG signals.

References	Muscles	Contraction Protocol	Analysis Methods
Marco [36]	RF, BF, GM	Cycling 30 minutes constant	IMNF
Christin [37]	GM, BF, VL, RF, TA, GA	Incremental running test on a treadmill	iEMG
Kumar [38]	RF, GL, GM, VL, VM	Cycling for prolonged constant	RMS, MF
Bing Yu [39]	SEMBS, BF	Running over ground with maximal speed.	EMG Peak, ANOVA
Takayuki [40]	BB, TB	Utilized the dumbbell as a burden	FFT, MPF
Kenichi [41]	Long Head BB	Exercise for 8 minutes during low-level isometric contraction.	recurrence quantification analysis
Andrzej [42]	RF, BF	Run 400m on tartan athletic track with a different intensity.	MPF, Linear Regression
Ahamed [43]	Middle BB	Eccentric and concentric contractions	RMS
Tatsushi [44]	RF, TA, BF, GM	Cycling with 70 RPM, 100 watts	RAW EMG and statistical
Rubana [45]	Right RF	During walking.	DWT
Kiran [46]	TB	Dumb-bell curl exercise.	FFT & Spectral Density
Crozara [47]	RF, VL, BF, GL	Incremental running on a treadmill	RMS, Linear Regression
Maner [48]	RF, VL, VM	5km running on variables surface	iARV, iMAV, iRMS, WL, IMNF, IMDF
Ridzuan [49]	GA	Running on a treadmill for 30min	MDF, Linear regression
Mastaler [50]	RF, BF, TA, GAS	Running, 200m/outdoor and 400m/ treadmill.	MPF, Linear Regression

6. Discussion

The sEMG is the most dominant method used for muscle function and fatigue detection, where there are many papers describing the fatigue and detecting it. However, the most used analyzing methods are RMS, MNF, MPF, WL, MDF, iMAV, iRMS, IMNF, and IMDF and then applied the statistical analysis or machine learning (ANOVA, Regression Line) based on the linear regression slope values where these values describe the muscles fatigue index as shown in Figure 3. In the time domain the fatigue is related to increment of the EMG amplitude [16], in the frequency domain the shift towards lower frequencies, and in time-frequency domain when the amplitude increase and spectrum decrease that's mean fatigue [4]. Indeed, the better methods that used for detection muscles fatigue are MDF and MNF were based on the power spectrum analysis of the EMG signals that result from the FFT, because the spectral analysis of the data be more reliable and give more information about the muscles functions compared with the other methods. But it will be more reliability and clarity if it combined with the time domain features to get more information about the function of the muscles and to avoid losing the information. However, the most researches detect fatigue in GM, RF, BF, GSM, GL, VL, and VM muscles because they are easy to implement the electrodes on it and they are superficial muscles, also can control it efficiently. The sEMG can detect fatigue during dynamic and static contraction.

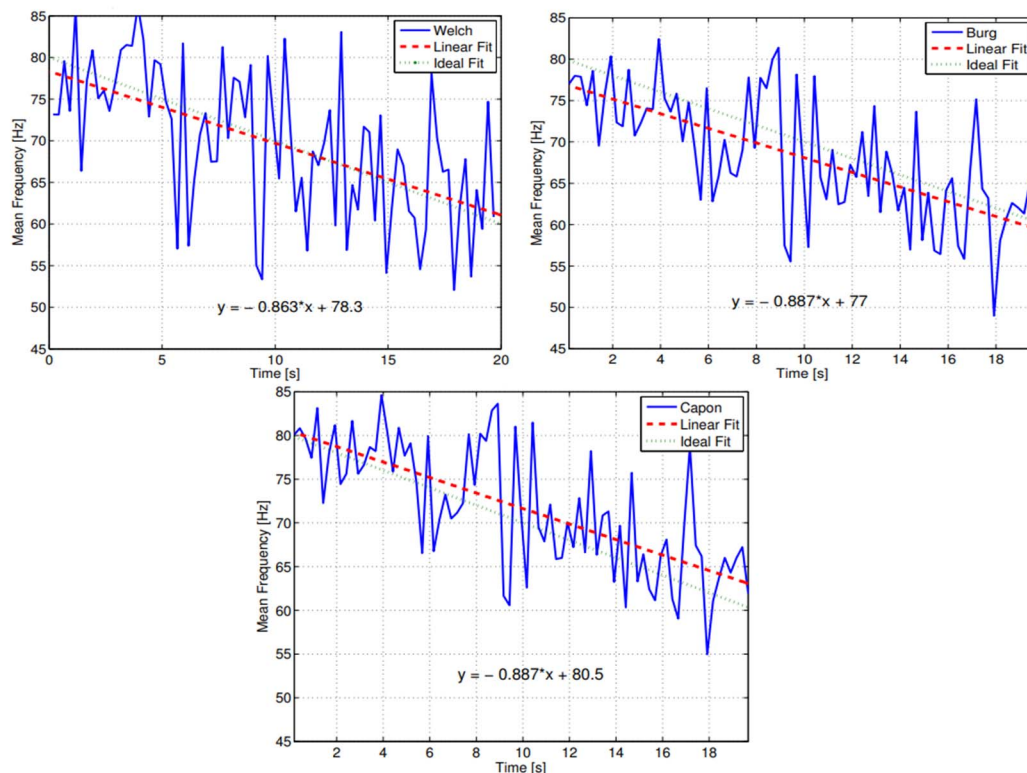


Figure 3. Muscle fatigue detection based on frequency decline with applying linear regression [35].

7. Conclusion

Muscle force production involves a sequence of events, extending from cortical excitation to motor unit activation to excitation–contraction coupling, and ultimately leading to muscle activation. Changes at any level in this pathway, including changes in the nervous, ion, vascular, and energy systems, impair force generation and contribute to the development of muscle fatigue. However, the current states for fatigue detection are still in the research area, therefore must be real application are found for fatigue. Even though the sEMG electrodes and MMG transducers are not meant to be for long time monitoring. Also, very little real time myography fatigue detection is done, there should be some trials in fatigue detection and classification using Neural Network for fast accurate fatigue detection. We believe that the combination of two methods (features) will provide more useful information, compared with the information obtained from uni-method. Therefore, the combination of multi features should be considered to develop and improve the performance of the methods that related with the muscles fatigue assessment.

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