Statistical Investigation of Muscle Fatigue using Multi-Sensors

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***Abstract*— The aim of this work is to find the relationship between EMG, MMG and AMG during muscle fatigue. To achieve the goal of this work, 3 different myograms (EMG, MMG and AMG) were recorded from the biceps femoris during the isometric contraction using bipolar surface EMG electrodes, accelerometers and cardio microphone. Nine statistical features were extracted from time and frequency domain. The extracted features were tests using Pearson Correlation and Linear Regression, to find the relationship between the features and behavior of the feature due to muscle fatigue. Based on the Pearson correlation result, there are relationships between these 3 myograms. In this paper, we also have discussed the behavior of myograms due to muscle fatigue.**

***Index Term*— EMG, MMG, AMG, Muscle Fatigue.**

I. Introduction

Hamstring muscle strains are the most prevalent muscle injuries reported in the sport. Epidemiology studies have revealed that hamstring injuries alone account for between 6 and 29% of all injuries reported [1]. The common reasons for hamstring strain or injuries are:-

- Previous hamstring injury
- Increasing age of player
- Sudden change in direction
- Poor flexibility and strength
- **Muscle fatigue.**
- Muscle strength imbalance between the quadriceps and hamstring
- Inappropriate, inadequate or no warm up.

Although, there are few risk factors that cause injury but this present work focus on muscle fatigue. Based on the clinical observation, muscle strain injuries were occurred during the late portions of practices and competitions. According to Mair et al., fatigued muscle significantly diminished the ability of muscle to absorb energy. It will reduce the muscle contractile strength and cause muscle failure or muscle injury [2, 3]. Muscle fatigue also increases the knee flexion angle. This provides the knee to flex beyond the optimum degree and its cause the muscle to injury by strain the muscle [2, 4]. Therefore, investigating muscle fatigue may avoid muscle strain injuries.

Muscle fatigue is defined as a failure to maintain or provided desired muscle strength [4]. Fatigue causes decline in force during sustained isometric and isotonic contraction [5]. Muscle fatigue is a common symptom in our daily activities. It is also a secondary outcome in many disease and health condition.

Various methods have been used to detect muscle fatigue. Surface electromyography (sEMG) has often been recorded to assess muscle activity. EMG shows the electrical activity of the muscle, which control by the nervous system. During muscle fatigue the low frequency components and amplitude of the EMG signal increases due to recruitment of motor unit [6].

Mechanomyogram (MMG) is another method that has been used to assess muscle fatigue. MMG or vibration signals recorded with accelerometer. The MMG signals represent the mechanical activity (known as muscle contraction) of the muscle. The amplitude of the MMG is correlated with force production, even a small change in force which reflected in the MMG amplitude [7, 8]. Therefore, MMG is useful to assess muscle fatigue.

Acoustic myogram (AMG) is audible sound produced when the muscle is contracted [9, 10]. AMG and MMG have shared the same concept where the amplitude of the signals reflects the force production.

Different type statistical tests have been performed to find the difference, correlation and reliability of the features among the myograms. There is no a clear understanding between the myograms. The aim of this work is to find the relationship between EMG, MMG and AMG during muscle fatigue. Previously, combination two sensors have been used to assess the muscle fatigue condition, which encourage us to assess muscle fatigue condition using 3 different myograms (EMG, MMG and AMG). Time domain and frequency domain features were extracted to assess muscle fatigue.

This paper was organized into 4 different sections. Section I is introduced, which consist of brief explains about the work, previous work and aim of the work. Section II describes about hardware integration, data acquisition protocol, and signal processing, which include pre-processing, feature extraction technique and statistical analysis. The next section explains about correlation result, discuss about the result. Last section, concludes the work and describe about future work.

II. METHODOLOGY

The different stages for classification of signal includes; recording of EMG, MMG and AMG of hamstring muscles, feature extraction from time, frequency and time-frequency domain and classification of the muscle fatigue condition using k-nearest neighbor.

A. Data Acquisition System

The data acquisition system consists of 3 sensors; there are surface electrode (to record EMG), accelerometer (to record MMG) and cardio microphone (to record AMG). Surface electrode and cardio microphone were connected to PowerLab 4/25T and accelerometer was connected to Data Translation (DT 9837A). PowerLab 4/25T and Data Translation were used as an A/D converter with sample rate of 1 kHz. The software interface was developed using LABVIEW software to collect MMG through Data Translation, whereas EMG and AMG were collected using LABCHART.

B. Data Acquisition Protocol (DAP)

The DAP started with oral explanation followed by answering the questionnaire (Consent Form), which cover the personal details and medical condition. After the briefing, the subject was guided to perform lower limb exercise as a warm up. Followed by sensor placement; bipolar surface EMG electrodes, accelerometers and cardio microphone were used to measure muscle activation from the hamstrings (biceps femoris) during the isometric contraction. Two surface EMG electrodes (Meditrace Pellet Ag/AgCl discs and 10 mm in diameter, Graphic Controls Ltd., Buffalo, NY) were placed 2-4 cm apart over the midpoint of the muscle belly between the gluteal fold and the popliteal fold [3] (as in Fig.1). Accelerometer and cardio-microphone were placed at the midpoint of the muscle belly between the gluteal fold and the popliteal fold [11] (as in Fig.1). All skin surfaces where the electrodes were placed were shaved, abraded, and cleansed with alcohol to improve electrical conductivity.

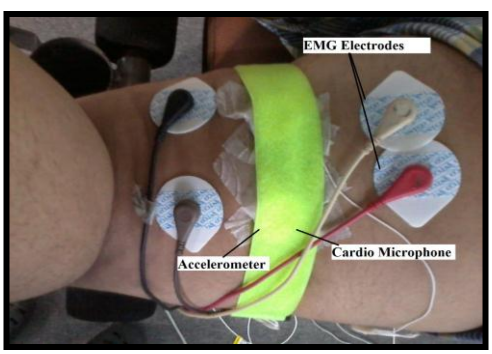


Fig. 1. Sensor Placement

The experiment was started after the sensor placement. The subject was laid on the lying leg curl machine to perform the isometric contraction. The subject was instructed to bend/curl the leg by lifting the given load (as in Fig. 2). They were requested to maintain the contraction / forces until exhaust. The task was repeated using a different load (5kg) and 30 minutes of rest time is given between the loads for recovery.

In this study, 20 healthy adults were recruited from University Malaysia Perlis. Subjects were diagnosed for diabetes; blood pressure and other neural system problem are not included in these studies because it will affect the data. Subjects with any previous leg or knee joint injury were excluded from our study too.

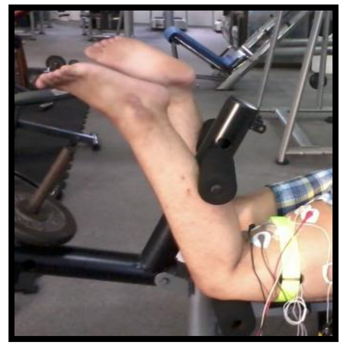


Fig. 2. Leg Curling with 5kg

C. Signal Processing

The first and last 5 seconds data were segmented from the myograms. The main idea of this segmentation is to obtain a stable myograms.

1) Pre-processing

The segmented myograms were filtered using a Butterworth filter with 4^{th} order to remove motion artifacts and noise. High-pass filter and stop-pass filter were used to denoise the EMG signals with cutoff frequency 20Hz and 50Hz respectively. The MMG and AMG signals were filtered by using a low-pass filter with cutoff frequency of 100Hz. The filtered myograms were segmented into non-overlapping 5 seconds frame.

2) Feature Extraction

Nine different features were extracted from each 5 seconds frame of the myograms. Out of 9 features, 5 features as time domain and the remaining features is frequency domain. The features were described in TABLE I

TABLE I
Mathematical Expression of Extracted Features

Feature	Description
Time Domain	
Mean (μ)	$\mu = \frac{\sum_{i=1}^{N} xi}{N}$
Variance (Var)	$Var = \frac{\sum_{i=1}^{N} (x_i - \bar{x})^2}{N-1}$
Root Mean Square (RMS)	$RMS = \sqrt{\frac{\sum_{1=i}^{N} x_i^2}{N}}$
Peak (PC)	Counting peak above the semi-amplitude
Spike (SC)	Counting spike above the semi-amplitude
Frequency Domain	
Mean Power Frequency (MNF)	$MNF = \frac{\int_{f_{min}}^{f_{max}} f.P(f)}{\int_{f_{min}}^{f_{max}} P(f)}$
Median Power Frequency (MDF)	$MDF = \frac{1}{2} \int_{f_{min}}^{f_{max}} P(f)$
Average Instantaneous Frequency (AIF)	$AIF = \frac{\int_{f_1}^{f_{max}} P(f)}{f_{max} - f_1}$
Spectral Indices (FIN)	$FIN = \frac{\int_{f_1}^{f_{max}} f^{-1} P(f) df}{\int_{f_1}^{f_{max}} f^{5} P(f) df}$

D. Statistical Analysis

1) Pearson Correlation

Pearson Correlation was used in this work. It is a test to measure the linearity strength between two variables with coefficient, *r* ranges from -1 to +1. The *r* value is +1 means that there is a perfect positive linear relationship between variables. The *r* value is -1 means that there is a perfect negative linear relationship between variables. When the *r* value is 0, it means there is no relationship between variables [12].

2) Linear Regression

A data model explicitly describes a relationship between predictor and response variables. Linear regression fits a data model that is linear in the model coefficients [13]. Therefore, linear regression was used to find the relationship between 2 variables.

III. Result and Discussion

The most 2 common features were chosen to view the change in time domain and frequency domain. Therefore, RMS and MNF were selected and find the regression line with time. The pattern of RMS and MNF with time for 3 different myogram was depicted in Fig.3, Fig.4, Fig.5, Fig.6, Fig.7, and Fig.8 together with a regression line.

The Fig.3, Fig.5 and Fig.8 have shown the response of RMS, which is increasing with time due to muscle fatigue. It is because recruitment of motor unit and increasing in firing rate of motor unit during isometric contraction. The Fig.4, Fig.6 and Fig.8 have shown the response of MNF with time. The MNF of EMG and MMG is declining with time, but for AMG is increasing with time.

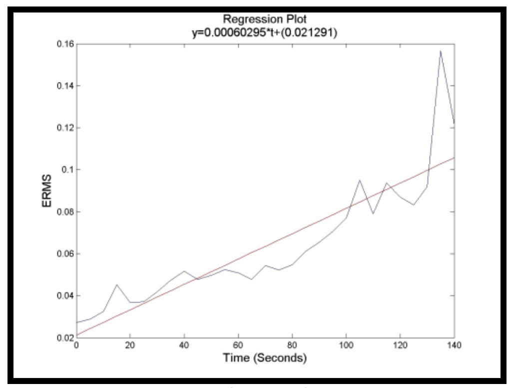


Fig. 3. Response of RMS of EMG with time

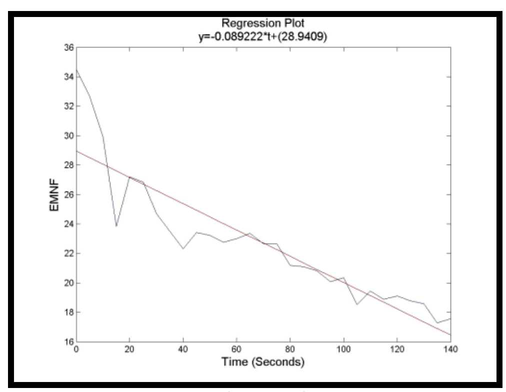


Fig. 4. Response of MNF of EMG with time

TABLE II
Pearson correlation coefficients for 27 features

		AMG									EMG									MMG								
		PC	SC	μ	Var	RMS	MNF	MDF	AIF	FIN	PC	SC	μ	Var	RMS	MNF	MDF	AIF	FIN	PC	SC	μ	Var	RMS	MNF	MDF	AIF	FIN
AMG	PC	1.00																										
	SC	-0.17	1.00																									
	μ	-0.01	-0.13	1.00																								
	Var	-0.17	0.19	0.07	1.00																							
	RMS	-0.18	0.17	0.06	0.99	1.00																						
	MNF	0.26	0.34	-0.01	0.11	0.08	1.00																					
	MDF	-0.17	0.19	0.07	1.00	0.99	0.11	1.00																				
	AIF	0.07	0.39	0.08	0.78	0.75	0.54	0.78	1.00																			
	FIN	-0.13	0.02	0.06	0.31	0.35	0.14	0.31	0.31	1.00																		
EMG	PC	0.07	-0.02	0.01	-0.44	-0.46	-0.09	-0.44	-0.35	-0.26	1.00																	
	SC	0.10	0.01	-0.07	-0.51	-0.53	-0.02	-0.51	-0.36	-0.25	0.79	1.00																
	μ	-0.05	0.02	0.00	-0.06	-0.06	0.07	-0.06	-0.06	0.06	-0.02	-0.03	1.00															
	Var	-0.21	0.19	0.06	0.67	0.66	0.11	0.67	0.54	0.19	-0.57	-0.64	-0.05	1.00														
	RMS	-0.22	0.19	0.06	0.72	0.72	0.11	0.72	0.57	0.24	-0.59	-0.68	-0.05	0.98	1.00													
	MNF	0.24	-0.14	-0.01	-0.66	-0.69	-0.05	-0.66	-0.52	-0.36	0.53	0.65	0.04	-0.73	-0.83	1.00												
	MDF	-0.21	0.19	0.06	0.67	0.66	0.11	0.67	0.54	0.19	-0.57	-0.64	-0.05	1.00	0.98	-0.73	1.00											
	AIF	-0.21	0.19	0.06	0.67	0.66	0.11	0.67	0.54	0.19	-0.57	-0.64	-0.05	1.00	0.98	-0.73	1.00	1.00										
	FIN	-0.22	-0.05	-0.03	0.37	0.41	-0.13	0.37	0.21	0.37	-0.28	-0.35	0.00	0.32	0.40	-0.61	0.32	0.32	1.00									
MMG	PC	0.07	-0.12	0.02	-0.02	-0.01	-0.06	-0.02	-0.04	0.09	-0.12	-0.13	0.03	-0.07	-0.04	-0.04	-0.07	-0.07	-0.02	1.00								
	SC	0.04	0.02	0.01	-0.22	-0.23	0.04	-0.22	-0.17	-0.13	0.03	0.20	-0.09	-0.10	-0.12	0.11	-0.10	-0.10	-0.16	-0.14	1.00							
	μ	-0.14	-0.04	-0.01	0.07	0.08	-0.07	0.07	0.04	0.07	0.09	0.02	-0.02	0.06	0.07	-0.06	0.06	0.06	0.15	-0.29	-0.02	1.00						
	Var	0.16	0.19	-0.10	0.29	0.30	0.31	0.29	0.42	0.18	-0.02	-0.11	0.00	0.08	0.12	-0.14	0.08	0.08	0.17	0.02	-0.33	0.12	1.00					
	RMS	0.15	0.19	-0.10	0.31	0.32	0.32	0.31	0.43	0.21	-0.04	-0.13	-0.01	0.10	0.14	-0.16	0.10	0.10	0.18	-0.01	-0.35	0.10	0.99	1.00				
	MNF	0.17	0.01	0.08	-0.33	-0.33	0.03	-0.33	-0.16	-0.21	0.23	0.27	0.06	-0.29	-0.33	0.32	-0.29	-0.29	-0.28	0.01	0.44	-0.09	-0.56	-0.60	1.00			
	MDF	0.16	0.19	-0.10	0.29	0.30	0.31	0.29	0.42	0.18	-0.02	-0.11	0.00	0.08	0.12	-0.14	0.08	0.08	0.17	0.02	-0.33	0.12	1.00	0.99	-0.56	1.00		
	AIF	0.20	0.33	0.07	0.42	0.43	0.47	0.42	0.66	0.19	-0.11	-0.20	-0.02	0.27	0.30	-0.28	0.27	0.27	0.12	-0.08	-0.15	0.03	0.59	0.62	-0.09	0.59	1.00	
	FIN	-0.02	-0.02	-0.05	0.20	0.22	0.18	0.20	0.25	0.34	-0.05	-0.19	-0.05	0.15	0.19	-0.29	0.15	0.15	0.29	-0.18	-0.17	0.10	0.37	0.41	-0.26	0.36	0.39	1.00

p value < 0.01
p value < 0.05

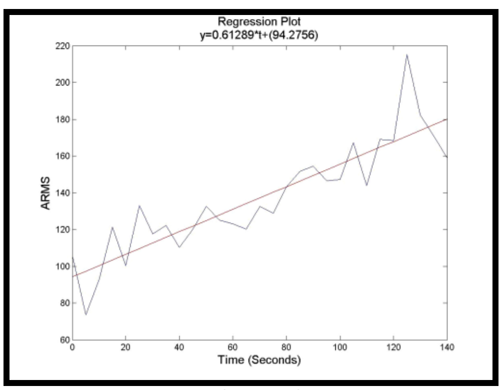


Fig. 5. Response of RMS of AMG with time

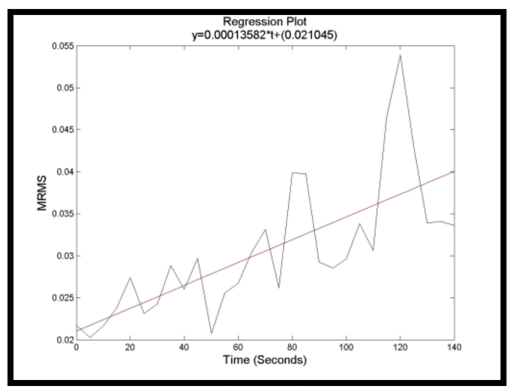


Fig. 7. Response of RMS of MMG with time

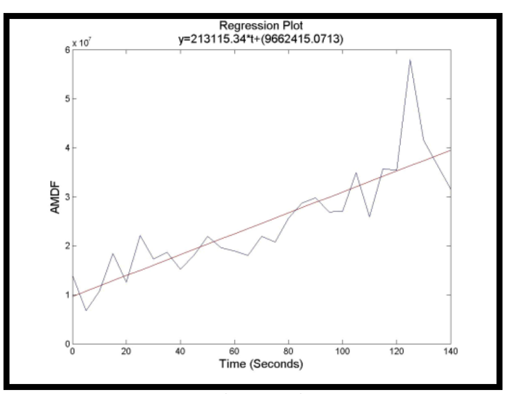


Fig. 6. Response of MNF of AMG with time

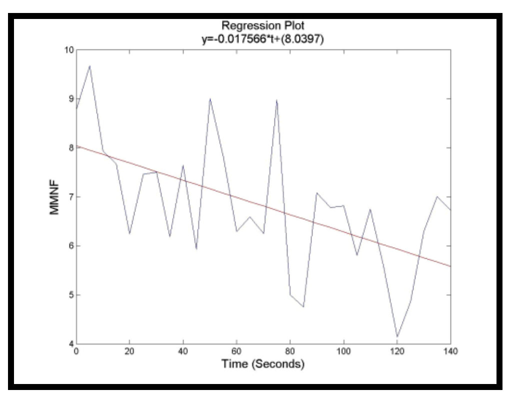
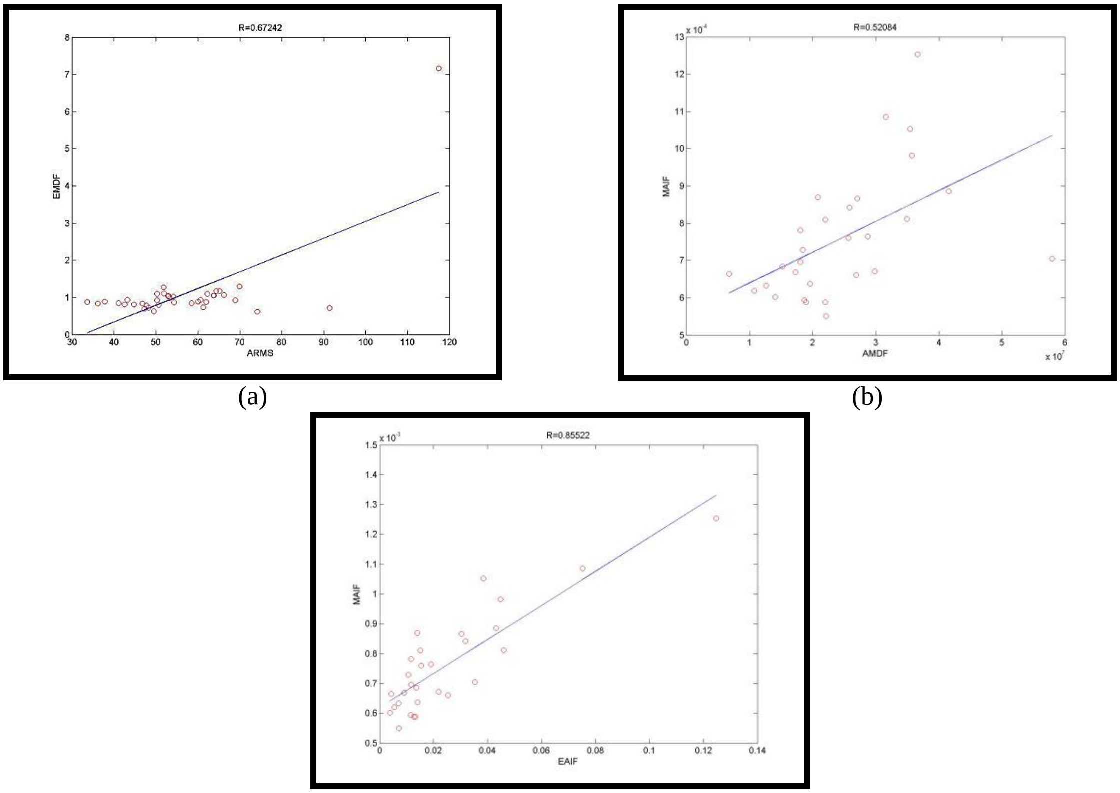


Fig. 8. Response of MNF of MMG with time

Pearson correlation test was applied to 27 features for 20 subjects and the average of correlation coefficients (*r*) were



(a) (b)

(c)

Fig. 9. Scatterplot and line of best fit, via regression analysis of: (a) MDF of EMG versus RMS of AMG; (b) AIF of MMG versus MDF of AMG; (c) AIF of MMG versus AIF of EMG.

reported in TABLE II. The main motive of this test is to find a relationship between the myograms. The table also presents the significant of the correlation coefficients.

According to the TABLE II the results suggest that 64 out of 351 correlations were statistically significant. However, only 33 out of 64 correlation have shown a direct relationship; with r values greater or equal than +0.4 (p<0.05) and 23 out of 64 correlation have shown an inverse relationship with r values less or equal than -0.4 (p<0.05). There are 2 significant r values to indicate the relationship between MMG and AMG and 4 values to indicate the relationship between MMG and EMG. In general, the results suggest that a strong relationship between AMG and EMG and it also shows a weak relationship between MMG and AMG or MMG and EMG.

Fig.9(a) illustrates the significant (r=0.67, p<0.01) linear relationship between MDF of EMG and RMS of AMG. Whereas the Fig9(b) present the linear relationship between AIF of MMG and MDF of AMG with r=0.52 and p<0.05. The linear relationship AIF of MMG and AIF of EMG was depicted in Fig.9(c).

IV. Conclusions

This work presents the relationship between 3 different myograms. To assess the relationship between the myograms; 3 different myograms were recorded from the biceps femoris muscle during isometric contraction. 9 features were extracted from the each myograms. Two types statistical analyses were carried out to the extracted features. Based on the result have been obtained, this work can be concluded that, there is a strong relationship between the EMG and AMG. Whereas, EMG and MMG; AMG and MMG has weak relationship. In general, all the 3 myograms are related into each other. Therefore, the combination of 3 myograms is helpful in investigating muscle conditions.

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