# Evaluation of Lower Limb Muscles Fatigue and Force during Running 400-Meters Using Learning Machine

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# Evaluation of Lower Limb Muscles Fatigue and Force During Running 400-Meters Using Learning Machine

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**Keywords:** sEMG, 400-meters running strategies, muscles fatigue, muscles force, RMS and MDF.

**Abstract.** The main goal of this research work is to study and evaluate the muscles force and fatigue of Gastrocnemius Medialis (GMS), Gluteus Maximus (GM), and Gastrocnemius Lateralis (GL) during running for 400-meters based on surface Electromyography (sEMG) signals. The sEMG signals of the selected muscles from the right leg have been collected by using bipolar electrodes from 15 subjects during the run on the tartan athletic track with two pacing strategies. The first strategy: 1st 200-meters running 87% - 94% of full speed and last 200-meters sprinting (full speed). The second strategy: 1st 300-meters running 87% - 94% of sprinting and last 100-meters sprinting. The rate of fatigue has been calculated by using Root Mean Square (RMS) and Median Frequency (MDF) features. Then, the slopes of linear regression were calculated from both RMS and MDF at each 100-meters. The linear slope values represented the rate of fatigue and force. From the results of 1st and 2nd running strategies, the force of GM and GL muscles increased during the 4th 100-meters of the 1st strategy and decreased with GM and GMS muscles during the 4th 100-meters of the 2nd strategy. The less index fatigues were during the 1st strategy for most selected muscles. Finally, it can be concluded the running with the 1st strategy get less fatigues and the force of most selected muscles increased compared with the 2nd strategy based on the results of time and frequency domain features (RMS and MDF).

## Introduction

Muscle fatigue is known as a feeling of weakness or muscle pain or a reduction in muscle performance [1]. It describes the gradual decrease in muscle's ability to generate force, performs voluntary movements, or perform repetitive actions [2]. The reduction in muscle force can be monitored by analyzing changes in electromyography (EMG) activities. Where, the EMG has been used to measure the electrical activities of the muscles. However, the fatigue is known to be reflected in the EMG signals as an increase of its amplitude and a decrease of its spectral characteristics [3]. Fatigue occurs in our daily life activities and when the fatigue occurs in the muscle fibre cells, the nerves will produce a high-frequency signal to gain the maximum contraction. However, it cannot sustain the high-frequency signal for a long time, and that leads to a decline in muscle force. Normally, the fatigue in the muscle fibres occurs due to low nutrition and accumulation of metabolites. Prolong muscle activities will lead to acute fatigue which affects our ability to move any part of the body. There are many factors affect fatigue like muscle fibre composition, regulation of ionic, component in blood supply, energy supply, and many other factors [4]. However, many researchers have detected muscles fatigue from different muscles during running, where most of them recording the EMG signals during running over a treadmill and over ground for one phase of sprinting only [5]. The sprinting requires repetitive action carried out by the lower limb. Thus, one of the consequences of the repetitive action is fatigue which associated with decreased physical functioning and decreased running performance. This effect must be highly avoided in sprinting sports. The muscles fatigue can be also defined as decreased in the force producing capability of a muscle. This kind of change in mechanical performance capability results in EMG alterations. Generally, the exhaustion typically happens after mental or physical effort, insufficient rest or other short-term occurrences. Sometimes it is called as healthy or acute because the fatigue is commonly relieved with rest [6].

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 four 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, and fourth when amplitude decrease and spectrum increased that's mean recovery [7]. Root Mean Square (RMS) and Average Rectified Values (ARV) are the commonly used amplitude-based fatigue indices in studying EMG signal inconsistency [8]. To describe the changes in frequency, Mean Frequency (MNF) and Median Frequency (MDF) are normally used. The reduction of muscle fiber velocity explains the decrement of MNF and MDF that are normally observed during fatigue condition [9]. Indeed, the regression model is one of the learning machine technique that used to indicate the muscles fatigue and force based on the pattern of the surface electromyography (sEMG) signals [10]. However, the evaluation of force and muscles fatigue is very important in sports science like running competition to lower the possibility of injuries and to enhance the sprinting event in a comfortable manner. The exhaustion of the muscles during running may lead to difficulty or inability in continuity to run. For this reason, it is necessary to develop the strategy of running to overcome the muscles fatigue in early time during running. However, the EMG will be used as a tool to evaluate muscle fatigue and force and to look at muscle recruitment in several circumstances, by quantifying electrical signals that will be sent to muscle fibers through electrodes.

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. Indeed, many ongoing researchers have studied the detection of muscle fatigue and evaluate its force based on the time domain and frequency domain features. For instance, Raymond et al. (2002) examined the surface sEMG of rectus femoris and biceps brachii collected from 18 athletes when they performed a maximal extension of the knee and flexion of the elbow exercises. The calculated mean power frequency (MPF) by fast Fourier transform (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 [11]. In addition, Weyand et al. [12] found that applying force to the ground would explain why top sprinters are able to produce longer stride lengths and faster stride frequencies and thus faster times. Where this is significant because sprinters who desire to increase their speed will need to train to produce more force into the ground to decrease their sprint times. Thus, the ratio between body mass and the ability to produce force into the ground may be the equalizing factor for performing fast sprint times. The main goal of this research work was to evaluate the muscles force and fatigue during running with two pacing strategies based on sEMG signals that are collected from the GM, GL, and GMS muscles, were collected by using bipolar electrodes from the right lower extremity's muscles of fifteen subjects during running 400-meters on tartan athletic track, then the MDF and RMS features were extracted in the frequency domain and time domain respectively. Finally, the linear regression applied to these features separately to detect the muscles fatigue and force at each 100-meters.

## Materials and Methods

The bio-signals have been recorded from the GM, GL, and GMS muscles of the right leg during running for 400-meters with two types of pacing strategies. Then the sEMG signals are processed, and the features of MDF and RMS have been extracted to detect and evaluate the muscles fatigue. Afterwards, the fatigue based on the slope values of the linear regression, has been identified.

**Subjects**

This study involved 15 normal and healthy subjects to participate in this study for running 400-meters. Subject's mean and standard deviation of age, height, and body mass index were 26.2 (0.72) years, 172.5 (3.41) cm, and 23.12 (2.51) kg, respectively. Each subject read and signed the written knowledgeable agreement form. The details about the study and processes were presented to them clearly before the experiments were conducted. Furthermore, the subjects were mentally prepared and physically healthy throughout the experiment.

**Data Collection Procedures**

The experiments were conducted at UniMAP stadium. Next, the electrodes placing of the Gluteus Maximus (GM), Gastrocnemius Lateralis (GL) and Gastrocnemius Medialis (GMS) muscles have been started by locating the muscle using SENIAM recommendations [13], then shaving the hair and dead skin with a disposable blade. Next, the shaved area was cleaned with cotton dipped in alcohol until the area turned red. This is to enhance the contact between the electrodes and the skin. In addition, this is an important procedure to reduce skin impedance [14]. After letting the alcohol evaporate, the electrodes were placed in a bipolar configuration, each electrode is a 10 mm sized circle with an inter-electrode distance of 20 mm, the placement was done by tapping the electrodes on all sides to ensure that they would not detach during testing, or due to excessive sweating during running. The fixation of the electrodes cable minimized the movement of the cables during fast running and prevented the cables from coming off. Each subject wore a tubular stretch bandage to maintain all the electrodes in position. However, the electrodes wires were tightened using tape and bandages to avoid disturbing the subject and be tighten so it will not be disconnected when the subject runs. The GM, GL, and GMS muscles have been shown in Fig1.

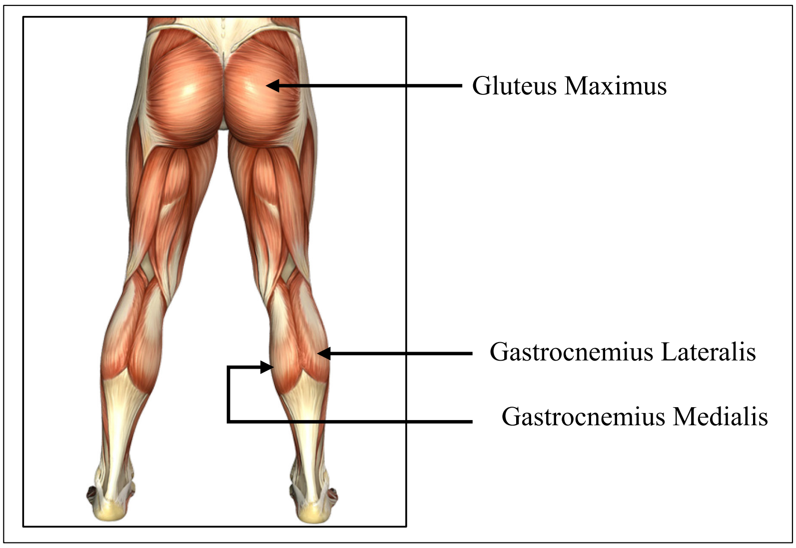


Fig. 1. The Gastrocnemius and Gluteus Maximus muscles

EMG measurements were recorded during the run on the tartan athletic track for two type of running strategies on separate days by using the Eego amplifier (Eego™sports) and bipolar disposable electrodes. The time for each 100-meters has been recorded where cones were used to determine each 100-m of the tartan athletic track. After fixed the electrodes on the selected muscles and connected the electrodes cable with the Eego device, the subjects were asked to warm up for 5 minutes (jogging). After the warming up procedures, the subject must rest for 5 minutes. Then the subject was started running for 400-meters on an outdoor running track with two types of running strategies, as shown in Fig 2.

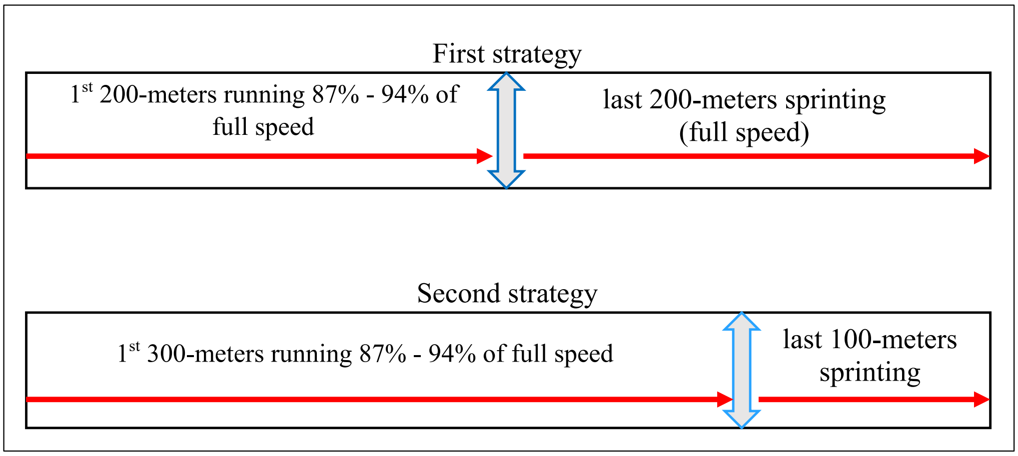


Fig. 2. The running strategies

To calculate the speed of running with normal speed, the mathematical equation (1) has been used:

$$speed = \frac{Distance\ (meters)}{Time\ (seconds)} \tag{1}$$

The speed was calculated for the first strategy only because it stated: the 1st 200-meter running with normal speed and the 2nd 200-meter sprinting (running with full speed), therefore the calculation was done for the 1st 200 meters and for the 2nd 200 meters separately. This calculation for only the first subject has been explained, as follow:

1st 200-meters running with normal speed.

$$Normal\ speed = \frac{200\ meters}{45\ sec} = 4.4\ meter/sec$$

2nd 200-meters running with full speed.

$$Full\ speed = \frac{200\ meters}{42\ sec} = 4.7\ meter/sec$$

Percentage of normal speed relative to full speed is $\frac{\text{Normal speed}}{\text{Full speed}} * 100\% = 93\%$ (2)

Normal speed is 93% of full speed for this subject.

The calculations for the other subjects were ranged (87% - 94%). Therefore, the normal speed during running for this research is 87% - 94% of full speed based on the subject's speed during running. However, the first strategy (1st 200-meters running 87% - 94% of full speed and last 200-meters sprinting (full speed)). The second test has been done after a break of at least two days. Then the subject was started running for 400-meters for the second strategy (1st 300-meters running 87% - 94% of sprinting and last 100-meters sprinting).

**EMG Data Processing**

The sEMG signal contained the original signal measured from the muscle and it was contaminated with unavoidable different types of noise, especially during dynamic movements. Therefore, the signal need to be filtered to remove the line noise and movement artifact noise [15]. The EMG signals were recorded with a sampling rate of 2000 Hz. After recorded the EMG signals, band stop filter 50 Hz for removing line noise, and second order Butterworth band pass filter (20-450Hz) have been used. Afterwards, the artifact noise which is lower than 20 Hz, and the unwanted signal that higher than 450 Hz have been removed using this filter. These filters are recommended for sEMG during dynamic movements [15].

EMG signal need to normalized first in time domain to compare EMG activity between the muscles. The normalization of the EMG signals based on the peak dynamic method [16] by recorded the maximum voluntary contraction (MVC) of each muscle.

The MVC was determined from three trials for each subject's muscle, then the maximum peak value is calculated. However, before the MVC and maximum peak are determined, the raw signals have been filtered. After the filtering process, the EMG signals are normalized based on the MVC method for feature extraction.

The filtered and normalized EMG signals were segmented into quarter second (window size = 500 samples) and the windows of the EMG signal were overlapped with 50% of the window size. Where each second of the recorded signals contain 2000 samples (sampling rate 2000 Hz).

**Features Extraction**

Feature extraction is an important method to collect useful information from the signals and remove the unnecessary data [17]. After filtering and normalizing the EMG signal, the feature of RMS was extracted in the time domain at each 100-meters. Next, the Fast Fourier Transform (FFT) was utilized to transfer the filtered data from the time domain to frequency domain at each 100-meters to get the power spectrum density then calculate the median frequency (MDF) at each 100-meters. However, the time domain and frequency domain are the two different standpoints which were used to view a signal that had one or more frequencies in it. In time domain, it is described how a signal changed over time, while the frequency domain, described how much of the signal lines in each given frequency band over a limit frequencies range [18].

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 an increment in the parameter evaluated in the time domain [19]. In the time domain, RMS of the EMG signal is counted as a reliable estimator of muscle fatigue [20]. The amplitude of the surface EMG in RMS during the sustained muscle contraction increases due to the synchronization of the recruited motor unit (MU) and the activation of new ones. The MU is getting to be exhausted and new MU should be actuated to maintain set levels of output i.e. power, force, speed, and torque. The RMS is an alternative way used to capture the envelope of the EMG signals to calculate the root mean square value of the EMG signals, where it is one of the most popular features used in representation EMG signal [21]. Besides, the MDF currently has been addressed as the main standard for muscle fatigue evaluation which obtained from the analysis of surface EMG signal. This due to the fact that muscle fatigue results in a descending shift of the frequency spectrum of the EMG signal. Where the MDF is the frequency value that separates the power spectrum (PS) in two parts of equal energy. Where PS is the sEMG power spectrum that is calculated using Fourier transform, and f1 and f2 determine the bandwidth of the surface electromyography (f1 = lowest frequency and f2 = highest frequency of the bandwidth) [22].

Muscle fatigue is related to the both EMG signal characteristics each in deferent way, that lead to the Joint analysis of EMG spectrum and amplitude (JASA). This analysis has four situations to determine force and fatigue, as shown in Table 1.

Table 1. Regions of muscle activity based on JASA

| The trend of fatigue indices | | |
|---|---|---|
| **Region** | **RMS** | **MDF** |
| Fatigue | Increase | Decrease |
| Overcome Fatigue (non-fatigue) | Decrease | Increase |
| Force Increase | Increase | Increase |
| Force Decrease | Decrease | Decrease |

**Regression Line**

Statistical analysis is a method can be used to detect the muscles force and fatigue based on the extracted features [23]. However, in this research work, the learning machine (linear regression method) has been used to determine the muscles fatigue index and force, based on the extracted features in the time domain and frequency domain. Where the slope values of the regression line indicate the fatigue index and the muscles force status during the movements. Next, one-way ANOVA was performed for the individual muscles for all subjects with the running strategies, to find the significance for each muscle between the strategies at each 100m.

The muscles force can be detected based on the values of linear regression for RMS and MDF features as mentioned in Table 1. However. in order to quantify the distribution of time and frequency domain during the experiment of 400-meters, a linear regression analysis was applied to evaluate the trend of fatigue indices [24] . The linear function is defined in equation (3).

$$y = mx + b \quad (3)$$

Where y is the feature in time or frequency domain and x is the time interval, m is the regression slope value, and b is the intercept (the value of **y** when $x = 0$).

## Results and Discussion

The EMG signals of GM, GL, and GMS muscles have been collected from 15 healthy subjects during running 400-meters with two types of running strategies. Then, the EMG signals have been processed and segmented into the quarter second (window size = 500 samples) then overlapped with 50% of the window size. Next, extracted the features of RMS and MDF with the 1st and 2nd strategy. Finally, the linear regression line has been applied to the extracted features of the selected muscles for each 100-meters of the running strategies.

### Results of the First Strategy

The RMS feature has been extracted from the normalized signals and the MDF feature has been extracted from the filtered signals for each muscle at each 100-meters. Fig 3 shows the plot of RMS and MDF features and linear regression slope for GM muscle for only one subject during running with the 1st strategy for the 1st 100-meters.

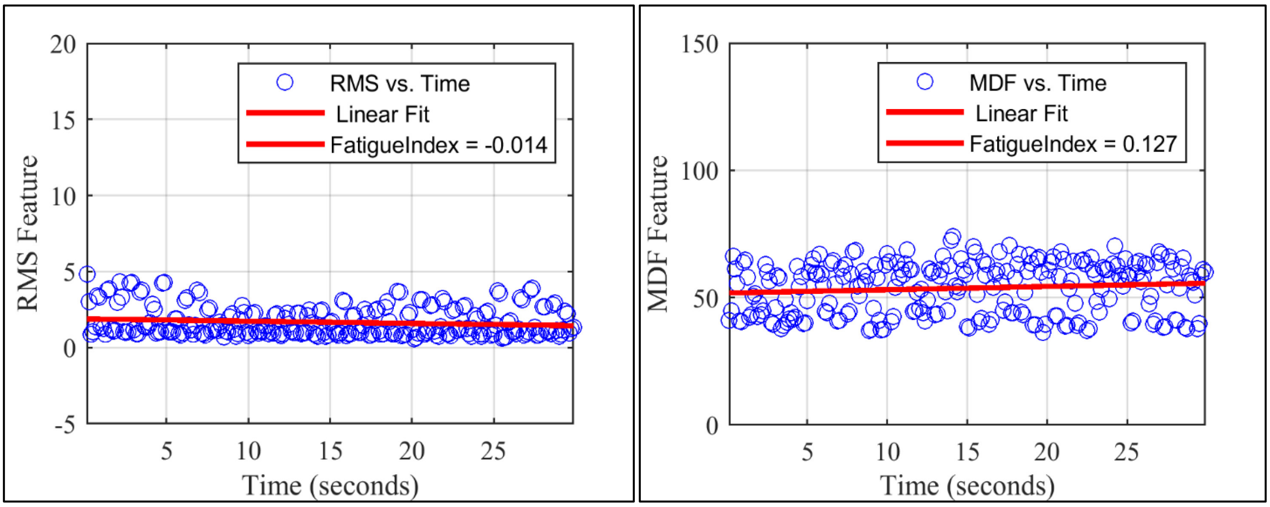


Fig. 3. RMS and MDF with linear regression slope for GM muscle for the 1st 100-meters during the 1st strategy

It is noticeable from Fig 3, the patterns of RMS decreased toward the negative slope, and the patterns of MDF increased toward the positive slope. Where the slope regression values of RMS and MDF muscle were -0.014 and 0.127 respectively. Based on the results of regression slope, it can be observed that there is a decrease in the time domain (negative slope value of RMS) and increase in the frequency domain (positive slope value of MDF) that means there is non-fatigue. Fig 4 shows the plot of RMS and MDF features and linear regression slope for GM muscle during running in the 2nd 100-meters.

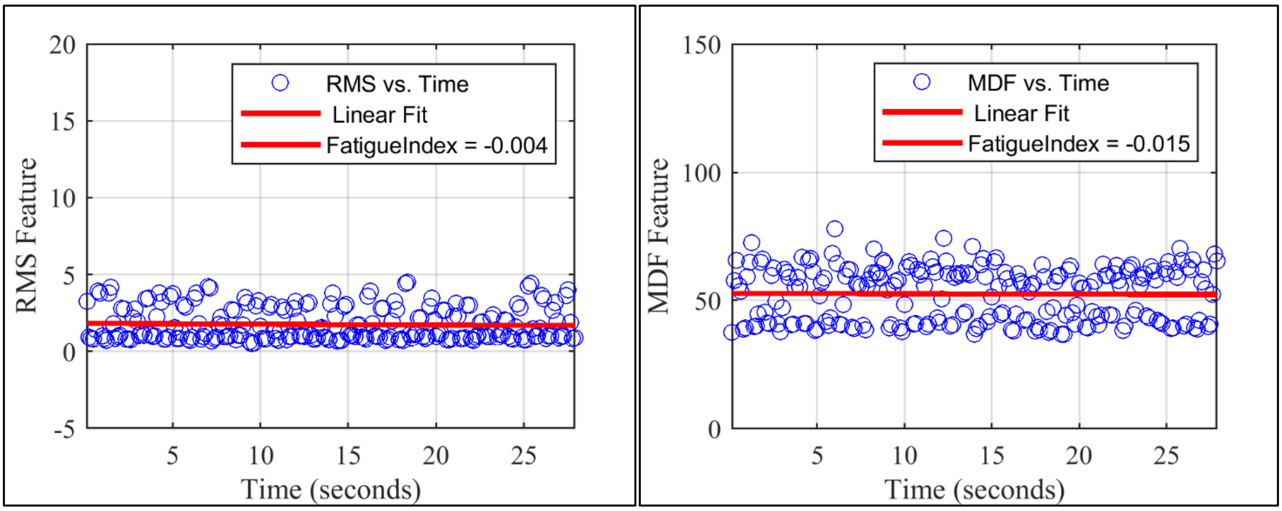


Fig. 4. RMS and MDF with linear regression slope for GM muscle for the 2nd 100-meters during the 1st strategy of running

It is noticeable from Fig 4 during the 2nd 100-meters, the patterns of RMS and MDF features decreased toward the negative slope, where the negative slope regression values of RMS and MDF features were -0.004 and -0.015 respectively. That is mean the subject has reduced his force as reported in Elena Bergamini [25]. Where some of sprinters try to save their energy at the beginning. Fig 5 shows the plot of RMS and MDF features and linear regression slope for GM muscle during running in the 3rd 100-meters.

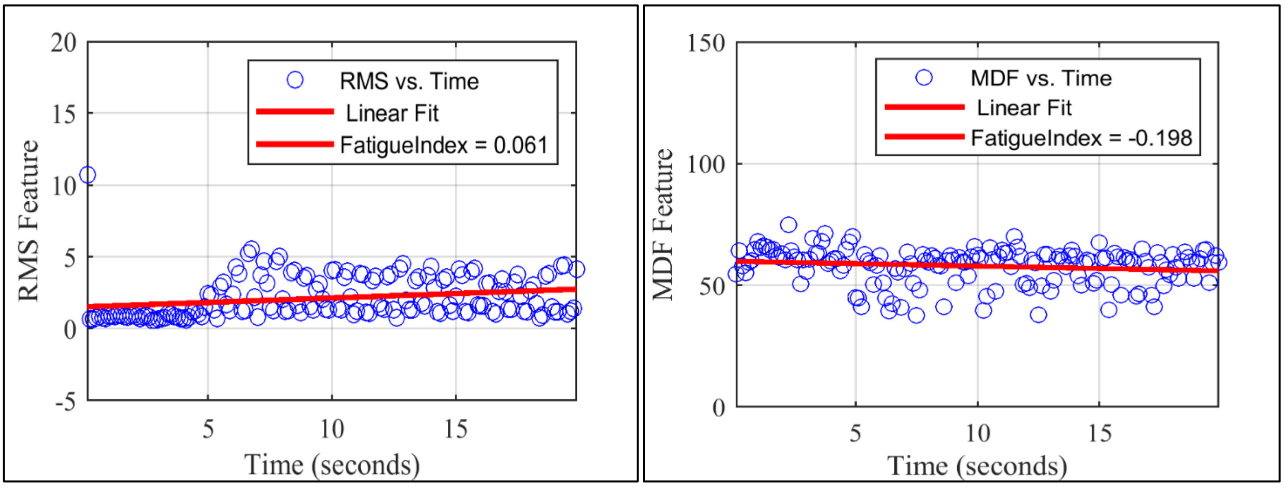


Fig. 5. RMS and MDF with linear regression slope for GM muscle for the 3rd 100-meters during the 1st strategy

It is noticeable from Fig 5 during the 3rd 100-meters, the patterns of RMS feature increased toward the positive slope, and the patterns of MDF feature decreased toward the negative slope. where the slope regression values of RMS and MDF features were 0.061 and - 0.198 respectively. However, based on the results of regression slope, it can be observed that there is an increase in the time domain and decrease in frequency domain features. That is mean the GM muscle got fatigued during the 3rd100-meters. Fig 6 shows the plot of RMS and MDF features and linear regression slope for GM muscle during running in the 4th 100-meters.

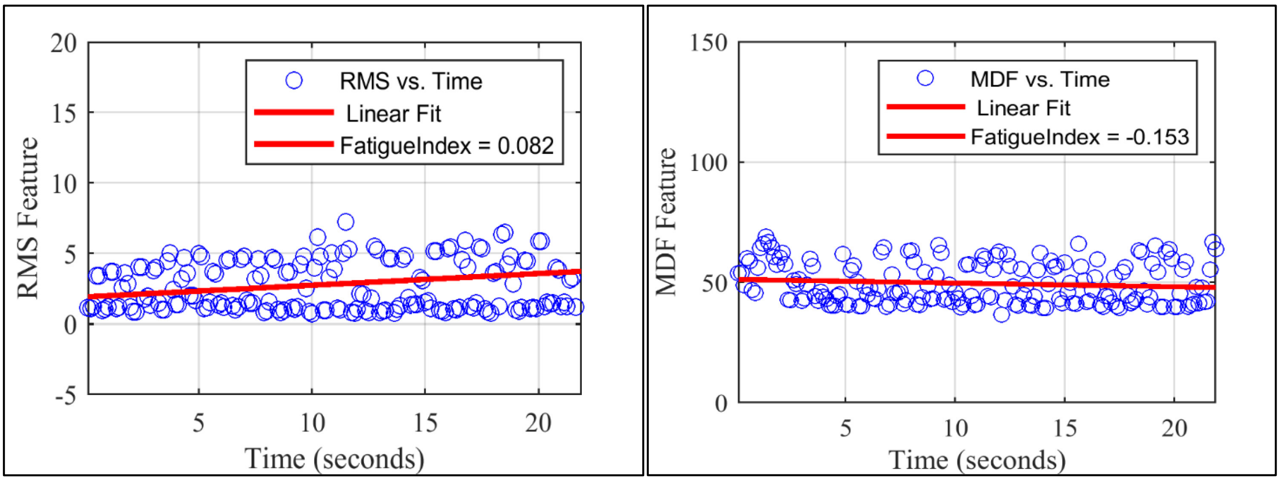


Fig. 6. RMS and MDF with linear regression slope for GM muscle for the 4th 100-meters during the 1st strategy

It is noticeable from Fig 6 during the 4th 100-meters, the patterns of RMS feature increased toward the positive slope, and the patterns of MDF feature decreased toward the negative slope.
Where the slope regression values of RMS and MDF features were 0.082 and - 0.153. respectively. However, based on the results of regression slope, it can be observed that there is an increase in the time domain and decrease in frequency domain features. That is mean the GM muscle got fatigued during the 4th 100-meters.

The slope values (mean values) of the selected muscles for all subjects with the first strategy of each 100-meters for RMS and MDF features, have been calculated to better understand the results as shown in Table 2.

Table 2. Mean values for linear regression slope applied to RMS and MDF features for individual muscles with the 1st running strategy

| **1st 100 - meters** | | | | **2nd 100 - meters** | | | |
|---|---|---|---|---|---|---|---|
| **Regression slope values** | GM | GL | GMS | **Regression slope values** | GM | GL | GMS |
| RMS | - 0.016 | 0.032 | 0.931 | RMS | 0.092 | 0.039 | 0.021 |
| MDF | - 0.043 | - 0.028 | - 0.012 | MDF | - 0.011 | - 0.034 | - 0.010 |
| **Region** | Decrease force | Fatigue | Fatigue | **Region** | Fatigue | Fatigue | Fatigue |
| **3rd 100 - meters** | | | | **4th 100 - meters** | | | |
| **Regression slope values** | GM | GL | GMS | **Regression slope values** | GM | GL | GMS |
| RMS | 0.039 | - 0.021 | 0.016 | RMS | 0.004 | 0.001 | 0.082 |
| MDF | - 0.013 | - 0.035 | 0.018 | MDF | 0.054 | 0.032 | - 0.013 |
| **Region** | Fatigue | Decrease force | Increase force | **Region** | Increase force | Increase force | Fatigue |

From Table 2, during the 1st 100-meters have been found that the Root Mean square (RMS) has negative slope value (-0.016) and the Median frequency (MDF) of Gluteus Maximus (GM) muscle has a negative slope value either (- 0.043), with all the parameters are decreasing that is mean there is no sign for muscle fatigue, according to the time and frequency domain features slopes of GM muscle are decreasing [26] that is mean the subjects have reduced their force (decrease force) as reported in Elena Bergamini [25] some of the sprinters try to save their energy at the beginning. For Gastrocnemius Lateralis (GL) and Gastrocnemius Medialis (GMS) muscles the values of linear regression slope were positive with RMS and negative with MDF features, according to time domain feature the slope values of GL and GMS are increased while the slope values of frequency domain feature are decreased, it's hard to say that there is muscle fatigue because this is the first 100-meters and the rest of muscle shows different results and as reported in Elena Bergamini [25] some sprinters tend to reduce force to save energy to the end all these reasons make it difficult to say that there is muscle fatigue.

During the 2nd 100-meters have been found that the RMS has positive slope value and the MDF has negative value with GM, GL, and GMS muscles, that means these muscles got fatigued during the 2nd 100-meters. During the 3rd 100-meters, it can be observed that the regression slope values of GM muscle were positive with RMS and negative with MDF, that means the GM muscle got fatigued during the 3rd 100-meters. For GL muscle the values of regression slope were negative with time domain and frequency domain features, that means the force (activity) of GL muscle has been reduced during the 3rd 100-meters of 400-meters running event. For GMS muscle the values of regression slope were positive with the RMS and MDF, with all the parameters of GMS are increasing that is mean there is no sign for muscle fatigue , and when the time and frequency domain features slopes increase it means there is increasing in muscle activity (Increase Force) [26]. During the 4th 100-meters, it can be observed that the regression slopes of GM and GL muscles are increased toward the positive values, that means there is no fatigue, and there is increasing in muscles force (muscle activity). For GMS muscle the regression slope values were positive with RMS and negative with MDF, that means the GMS muscle got fatigued during the 4th 100-meters.

However, from all the results it can be observed that the GM muscle got less fatigue during the 3rd 100-meters. Where the slope values of RMS and MDF were 0.039 and - 0.013. For the GL muscle, the lowest fatigue was during the 2nd 100-meters, where the slope regression values of RMS and MDF were 0.039 and - 0.034 respectively. For the GMS muscle had less fatigue during the 2nd 100-meters, where the slope values of RMS and MDF were 0.021 and - 0.010 respectively. While the force of most the selected muscles increased during the 4th 100-meters

**Results of the Seconds Strategy**

The plot of RMS and MDF features and linear regression slope for GM muscle for only one subject during running with the 2nd strategy for the 1st 100-meters is shown in Fig 7.

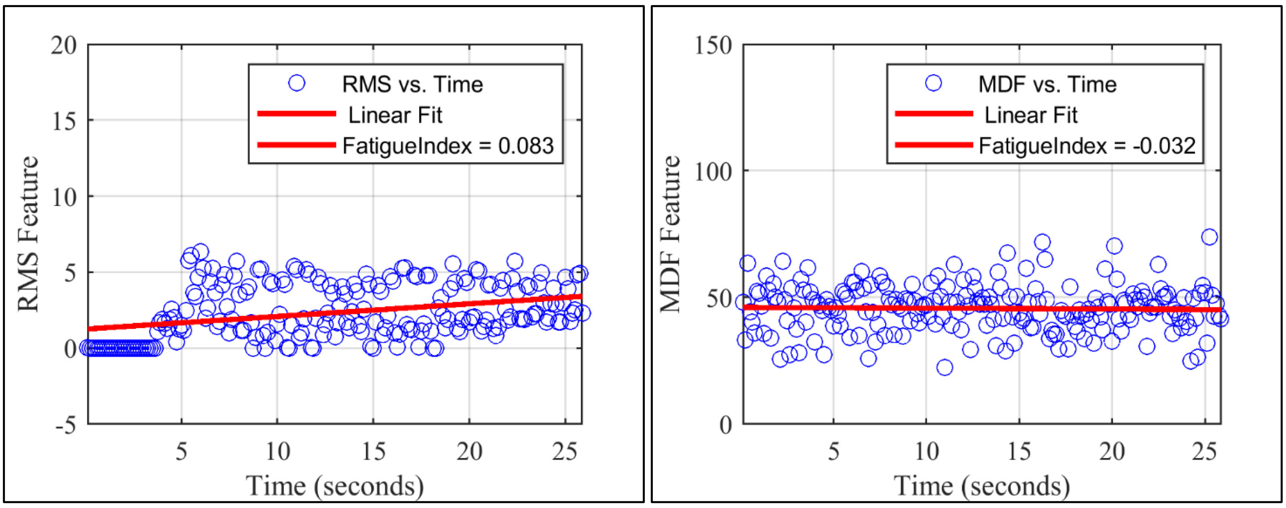


Fig. 7. RMS and MDF with linear regression slope for GM muscle for the 1st 100-meters during the 2nd strategy

It is noticeable from Fig 7 during the 1st 100-meters, the patterns of RMS feature increased toward the positive slope, and the patterns of MDF feature was decreased toward the negative slope. Where the slope regression values of RMS and MDF features were 0.083 and -0.032 respectively. Based on the results of regression slope, it can be observed that there is an increase in the time domain and a decrease in the frequency domain that means there is fatigue. But indeed, it is difficult to say this is fatigue because this is the 1st 100-meters, and sometimes the muscles get spasm during the 1st 100-meters running. Fig 8 shows the plot of RMS and MDF features and linear regression slope for GM muscle in the 2nd 100-meters.

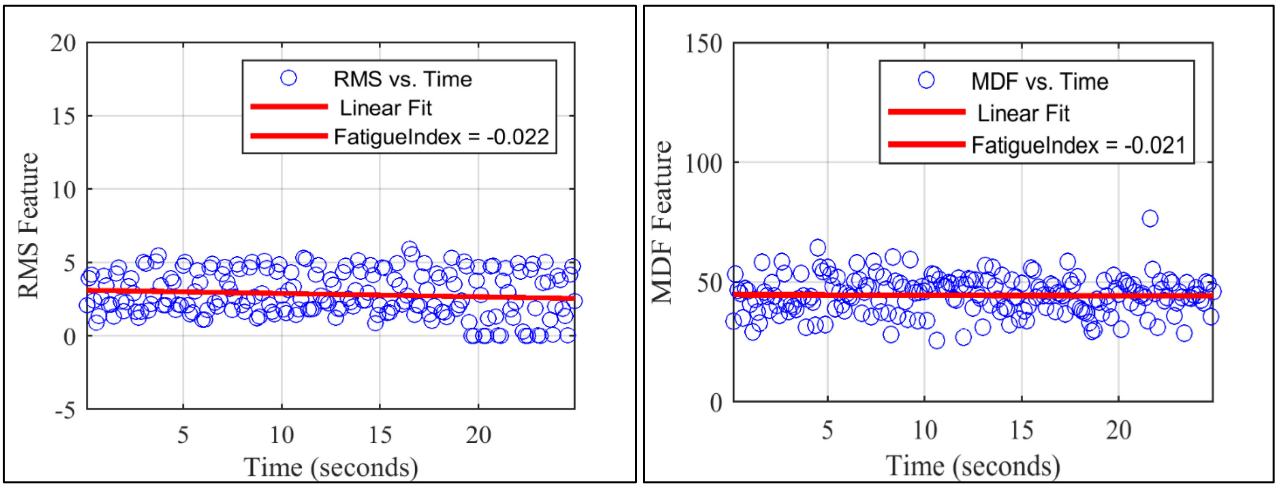


Fig. 8. RMS and MDF with linear regression slope for GM muscle for the 2nd 100-meters during the 2nd strategy

It is noticeable from Fig 8 during the 2nd 100-meters, the patterns of RMS and MDF features were decreased toward the negative slope. Where the slope regression value of RMS and MDF were -0.022 and - 0.021 respectively. Based on the results of regression slope, it can be observed that there is a decrease in the time domain and frequency domain that means there is this subject has reduced his force. Fig 9 shows the plot of RMS and MDF features and linear regression slope for GM muscle during running in the 3rd 100-meters.

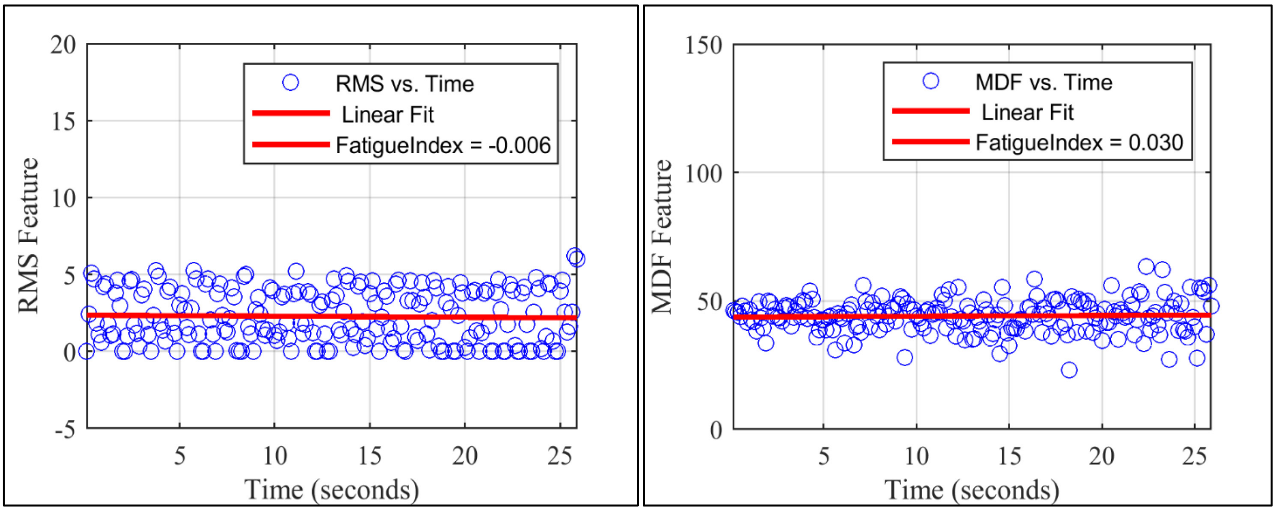


Fig. 9. RMS and MDF with linear regression slope for GM muscle for the 3rd 100-meters during the 2nd strategy

It is noticeable from Fig 9 during the 3rd 100-meters, the pattern of RMS feature was decreased toward the negative slope, and the pattern of MDF features was increased toward the positive slope, where the regression slope values of RMS and MDF were – 0.006 and 0.030 respectively. Based on the results of regression slope, it can be observed that there is a decrease in the time domain and an increase in the frequency domain that means there is non-fatigue and the GM muscle got recovery during the 3rd 100-meters. Fig 10 shows the plot of RMS and MDF features and linear regression slope for GM muscle in the 4th 100-meters.

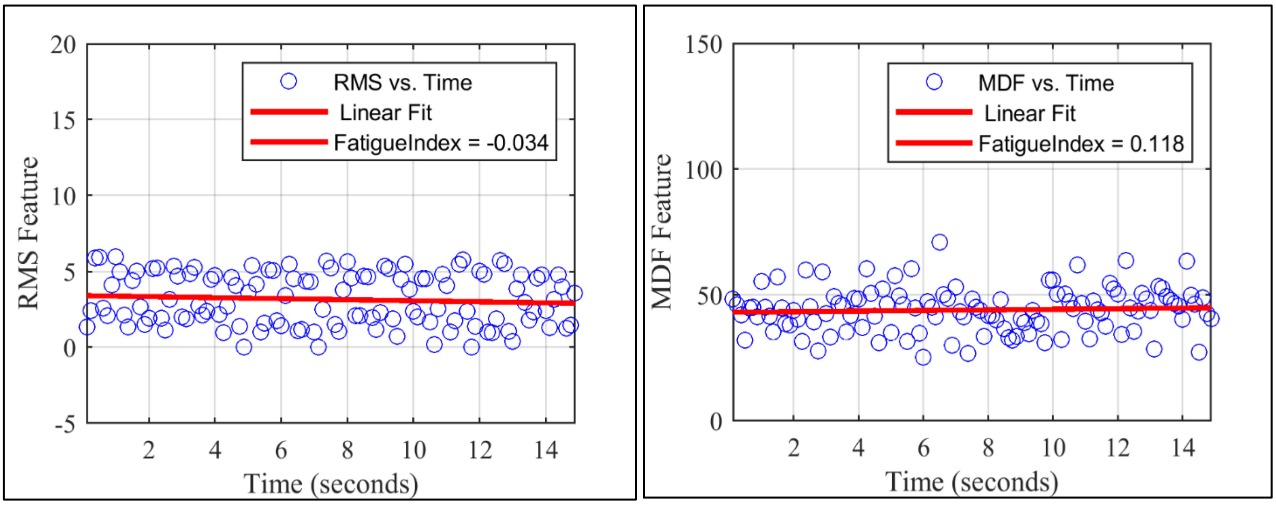


Fig. 10. RMS and MDF with linear regression slope for GM muscle for the 4th100-meters during the 2nd strategy

It is noticeable from Fig 10 during the 4th100-meters, the pattern of RMS feature was decreased toward the negative slope, and the pattern of the MDF feature was increased toward the positive slope. Where the regression slope values of RMS and MDF features were -0.034 and 0.118 respectively. That is mean there is non-fatigue and the GM muscle got recovery during the last100-meters of 400-meters running event.

However, the slope values (mean values) of the selected muscles for all subjects with the second strategy of each 100-meters for RMS and MDF features, have been calculated to better understand the results as shown in Table 3.

Table 3. Mean values for linear regression slope applied to RMS and MDF features for individual muscles with the 2nd running strategy

| **1st 100 - meters** | | | | **2nd 100 - meters** | | | |
|---|---|---|---|---|---|---|---|
| **Regression slope values** | GM | GL | GMS | **Regression slope values** | GM | GL | GMS |
| RMS | 0.011 | - 0.002 | - 0.047 | RMS | 0.023 | 0.031 | 0.008 |
| MDF | - 0.053 | - 0.320 | - 0.040 | MDF | - 0.001 | - 0.012 | 0.102 |
| **Region** | Fatigue | Decrease force | Decrease force | **Region** | fatigue | fatigue | Increase force |
| **3rd 100 - meters** | | | | **4th 100 - meters** | | | |
| **Regression slope values** | GM | GL | GMS | **Regression slope values** | GM | GL | GMS |
| RMS | 0.201 | 0.101 | 0.043 | RMS | - 0.005 | 0.062 | 0.033 |
| MDF | 0.210 | - 0.005 | - 0.302 | MDF | 2.420 | - 0.382 | 2.411 |
| **Region** | Increase force | Fatigue | Fatigue | **Region** | Overcome fatigue | Fatigue | Increase force |

From Table 3, during the 1st 100-meters have been found that the slope values of GM muscle were positive with RMS and negative with MDF features, according to time domain feature the slope values GM is increased while the slope value of the frequency domain feature is decreased, it is hard to say that there is muscle fatigue because this is the first 100-meters and the rest of muscle shows different results and as reported in Elena Bergamini [25] some sprinters tend to reduce force to save energy to the end all these reasons make it difficult to say that there is muscle fatigue. For GL and

GMS muscles the slope values were negative with RMS and MDF features, that is mean there is no sign for muscle fatigue, and the subjects have reduced their force (Decrease Force) trying to save their energy at the beginning.

During the 2nd 100-meters have been found that the RMS has positive slope value and the MDF has negative value with GM and GL muscles, that means these muscles got fatigued during the 2nd 100-meters. While, for GMS muscle the values of regression slope were positive with the RMS and MDF, with all the parameters of GMS are increasing that is mean there is no sign for muscle fatigue, and there is increasing in muscle force.

During the 3rd 100-meters, it can be observed that the regression slope values of GM muscle were positive with RMS and MDF, that means there is increasing in muscles force (activity). For GL and GMS muscles, it can be observed that the regression slope values were positive with RMS and negative with MDF, that means these muscles got fatigued during the 3rd 100-meters.

During the 4th 100-meters, it can be observed that the regression slope values of GM muscle were negative with RMS and positive with MDF, that means there is no fatigue and the GM muscle got recovery during the 4th 100-meters. For GL and GMS muscle the regression slope values were positive with RMS and negative with MDF, that means the GMS muscle got fatigued during the 4th 100-meters.

However, from the results, it can be observed that the GM muscle had less fatigue during the 2nd 100-meters and the slope values of RMS and MDF were 0.023 and - 0.001respectively. GL and GMS muscles had less fatigue during the 3rd 100-meters, where the slope values for regression line of RMS and MDF were 0.101 and - 0.005 respectively for GL and for GMS muscle were 0.043 and - 0.302 respectively. While the force of most the selected muscles decreased during the 4th 100-meters.

**Analysis of Variance (ANOVA)**

ANOVA is a statistical model used to analyze the variation among and between different groups. In this research work, one-way ANOVA has been used to find the significance of the linear regression slope for RMS and MDF features at each strategy. One-way ANOVA was applied for each muscle separately of all subjects to find the significance for each muscle between the 1st and 2nd running strategies at each 100-meters. Table 4. shows the *p*-value results for linear regression slope for both strategies for RMS.

Table 4. The p-value of ANOVA results for the 1st and 2nd strategies with RMS

| **1st 100-meters** | | | **2nd 100-meters** | | |
|---|---|---|---|---|---|
| **Muscles** | **p-value** | **ANOVA test** | **Muscles** | **p-value** | **ANOVA test** |
| GM | 0.061 | P > 0.05 | GM | 0.021 | **P < 0.05** |
| GL | 0.019 | **P < 0.05** | GL | 0.498 | P > 0.05 |
| GMS | 0.250 | P > 0.05 | GMS | 0.021 | **P < 0.05** |
| **3rd 100- meters** | | | **4th 100-meters** | | |
| **Muscles** | **p-value** | **ANOVA test** | **Muscles** | **p-value** | **ANOVA test** |
| GM | 0.049 | **P < 0.05** | GM | 0.312 | P > 0.05 |
| GL | 0.120 | P > 0.05 | GL | 0.431 | P > 0.05 |
| GMS | 0.020 | **P < 0.05** | GMS | 0.308 | P > 0.05 |

It is noticeable from Table 4, during the 1st 100-meters only GL muscle has significant results between the 1st and 2nd strategies. During the 2nd and 3rd 100-meters of running the GM and GMS muscles have a significant result between the two strategies. While there is no significant result for the strategies at the 4th 100-meters of the running. Table 5. shows the *p*-value results for linear regression slope for both strategies for MDF.

Table 5. The p-value of ANOVA results for the 1st and 2nd strategies with MDF

| 1st 100-meters | | | 2nd 100-meters | | |
|---|---|---|---|---|---|
| **Muscles** | **p-value** | **ANOVA test** | **Muscles** | **p-value** | **ANOVA test** |
| GM | 0.079 | P > 0.05 | GM | 0.089 | P > 0.05 |
| GL | 0.203 | P > 0.05 | GL | 0.505 | P > 0.05 |
| GMS | 0.041 | **P < 0.05** | GMS | 0.084 | P > 0.05 |
| **3rd 100-meters** | | | **4th 100-meters** | | |
| **Muscles** | **p-value** | **ANOVA test** | **Muscles** | **p-value** | **ANOVA test** |
| GM | 0.332 | P > 0.05 | GM | 0.029 | **P < 0.05** |
| GL | 0.019 | **P < 0.05** | GL | 0.910 | P > 0.05 |
| GMS | 0.121 | P > 0.05 | GMS | 0.231 | P > 0.05 |

It is noticeable from Table 5, during the 1st 100-meters only GMS muscle has significant results between the 1st and 2nd strategies. During the 2nd 100-meters, there are no significant results for all strategies. During the 3rd 100-meters of running the GL muscle has a significant result between the two strategies. While only GM muscle has significant results between the 1st and 2nd strategies at the 4th 100-meters of the running.

From Table 4 and Table 5, it can be concluded that the p-value of ANOVA test was $P < 0.05$ for GL muscle during the 1st 100-m, GM and GMS during the 2nd and 3rd 100-m with RMS feature during the 1st and 2nd strategy, that mean there is a significance between the slope regression of the muscles after evaluating the muscle performance. While with MDF feature the p-value was $P<0.05$ for GMS muscle only during the 1st 100-m, for GL muscle during the 3rd 100-m, and for GM muscle during the 4th 100-m, that mean there is slightly significant between the slope regression values of the selected muscles after evaluating the muscle performance.

## Conclusion

As stated previously, the patterns of RMS and MDF features indicating the force and fatigue of the muscles. Where the relationship between the slope value of RMS and the level of fatigue are directly proportional to each other at most times. Where, if the slope value of RMS is increasing toward the positive values, that means the level of fatigue will increase and vice versa. While the relationship between MDF and the level of fatigue are reversely proportional to each other at most times. Where, if the slope value of MDF is decreasing toward the negative values, that means the level of fatigue will increase and vice versa. For the force, the relationship between the slope values of RMS and MDF and the force are directly proportional to each other at most times. Where, if the slope values of RMS and MDF are increasing toward the positive values, that means the force will increase and vice versa. However, the signal analyses were done to measure muscles condition and calculate the rate of fatigue during running with two running strategies based on Joint Analysis of EMG Spectrum and Amplitude (JASA) method. where the first strategy stated: 1st 200-meters running 87% - 94% of full speed and last 200-meters sprinting (full speed). The second strategy stated: 1st 300-meters running 87% - 94% of sprinting and last 100-meters sprinting. The rate of fatigue has been calculated by using RMS and MDF features. Slopes of linear regression were calculated from both RMS and MDF, then the linear slope represented the rate of fatigue and muscle force status.

From all the results it can be noticed that the lowest positive and negative values of the regression slope for RMS and MDF were as following: for GM muscle 0.023 and - 0.001 during the 2nd 100-meters of the 2nd running strategy. For GL muscle 0.039 and - 0.034 during the 2nd 100-meters of the 1st running strategy. For GMS muscle 0.021 and - 0.010 during the 2nd 100-meters of the 1st running strategy. While the force of most the selected muscles (GM and GL) increased during the 4th 100-meters of the 1st strategy. For the 2nd strategy, the force of GM and GMS muscles decreased during the 4th 100-meters either. Finally, from the results of the first and second running strategies with the selected muscles, the lowest fatigue was during the 1st strategy for most selected muscles.

## References


[1] A. Mesin, L. Cescon, C. Gazzoni, M. Merletti, R. and Rainoldi, A bi-dimensional index for the selective assessment of myoelectric manifestations of peripheral and central muscle fatigue. J. Electromyogr. Kinesiol, 19 (2009), pp. 851-863.

[2] R. M. Enoka, and J. Duchateau, Muscle fatigue: what, why and how it influences muscle function. The Journal of physiology, 586 (2008), pp.11-23.

[3] A. Hakonen, M. Piitulainen, H. and Visala, Current state of digital signal processing in myoelectric interfaces and related applications. Biomed. Signal Process. Control. 18 (2015), pp. 334-359.

[4] G.C. Bogdanis, Effects of physical activity and inactivity on muscle fatigue. Frontiers in physiology, 3 (2012), p.142.

[5] A.T. Nummela, K.A. Heath, L.M. Paavolainen, M.I. Lambert, A.S.C. Gibson, H.K. Rusko, and T.D. Noakes, T.D, Fatigue during a 5-km running time trial. International journal of sports medicine, 29 (2008), pp.738-745.

[6] C. Fritschi and L. Quinn. Fatigue in patients with diabetes: A review. J. Psychosom. 1(2010), pp. 33–41.

[7] W. Luttmann, A. Jäger and Laurig. Electromyographical indication of muscular fatigue in occupational field studies. Int. J. Ind. Ergon. 6 (2000), pp. 645-660.

[8] W. Luttmann, A. Jager, M. Sokeland and Lauring. Electromyographical study on surgeons in urology. II. Determination of muscular fatigue. Ergonomics. 2 (1996), pp. 298–313.

[9] K. Doix, A. C. M. Gulliksen, A. Brændvik, S. M. and Roeleveld. Fatigue and muscle activation during submaximal elbow flexion in children with cerebral palsy. J. Electromyogr. Kinesiol. 3 (2013), pp. 721-726.

[10] K. G. Marras, W. S. and Davis. A non-MVC EMG normalization technique for the trunk musculature: Part 1. Method development. J. Electromyogr. Kinesiol. 1 (2001), pp. 1-9., 2001.

[11] O. So, R. Chan, K. M. and Siu. EMG power frequency spectrum shifts during repeated isokinetic knee and arm movements. Res. Q. Exerc. Sport. 1 (2002), pp. 98-106.

[12] S. Weyand, P. Sternlight, D. Bellizzi, M. J. and Wright. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. J. Appl. Physiol. 89 (2001), pp. 1991–1999.

[13] D. F. Stegeman. Standards for surface electromyography: The European project Surface EMG for Standards for surface electromyography: the European project. Surface EMG for non-invasive assessment of muscles (SENIAM). January 2007.

[14] P. Konrad. The ABC of EMG. A practical introduction to kinesiological electromyography.1 (2006), P. 30-35.

[15] C.J. De Luca, L.D. Gilmore, M. Kuznetsov, and S.H. Roy, Filtering the surface EMG signal: Movement artifact and baseline noise contamination. Journal of biomechanics, 43 (2010), pp.1573-1579.

[16] R. M. Howard. Epidemiological surveillance of AIDS in Spain: situation on June 30. [Spanish]. Bol. Epidemiol. Sem.12 (2002), pp. 121–124.

[17] A. Phinyomark, "Feature reduction and selection for EMG signal classification. Expert Syst. Appl. 8 (2012), pp. 7420–743.

[18] W. Huang and D. MacFarlane. Fast fourier transform and matlab implementation. The University of Texas at Dallas. Dr. Duncan L. MacFarlane. Web, 24, 2016.

[19] D. Roman-liu, T. Tokarski and K. Wo. Quantitative assessment of upper limb muscle fatigue depending on the conditions of repetitive task load. (6) 2004, pp. 671–682.

[20] M. Al Zaman, A. Sharmin, T. Khan and Ferdjallah. Muscle fatigue analysis in young adults at different MVC levels using EMG metrics.," in Proceedings 2007 IEEE SoutheastCon, pp. 390–394.

[21] T. Y. Fukuda. Root mean square value of the electromyographic signal in the isometric torque of the quadriceps, hamstrings and brachial biceps muscles in female subjects. J. Appl. Res,1(2010), pp. 32–39.

[22] F. M. Spektra and M. Ultrajahooim. Evaluation of the mean power frequency of the emg signal power spectrum at endurance levels during fatiguing isometric muscle contractions. 2008.

[23] M. Sarillee, M. Hariharan, M.N. Anas, M.I. Omar, M.N. Aishah, and Q.W. Oung, November. Assessment muscle fatigue using statistical study and classification: A review. In 2015 IEEE International Conference on Control System, Computing and Engineering (ICCSCE) (pp. 206-211). IEEE.

[24] Xie. H and Z. Wang. Mean frequency derived via Hilbert-Huang transform with application to fatigue EMG signal analysis. Computer methods and programs in biomedicine, 82 (2006), p.114-120.

[25] E. Bergamini. Biomechanics of sprint running: a methodological contribution. (Doctoral dissertation). 2011.

[26] M. A. Nussbaum. Static and dynamic myoelectric measures of shoulder muscle fatigue during intermittent dynamic exertions of low to moderate intensity. European journal of applied physiology, 85(2001). pp. 299–309.