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FFM: A Muscle Fatigue Index Extraction by Utilizing Fuzzy Network and Mean Power Frequency

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***Abstract*:** Muscular fatigue refers to changes in the domain of amplitude and frequency for the muscle contractions. Muscle fatigue is important to the researchers for being familiar with muscle mechanism, rehabilitation, ergonomics, electrical functional stimulation and prosthesis control. Moreover, its significance to clinical research to identify weak muscle and demonstrate the strength training exercise efficiency.

In the present article, we propose Fuzzy Fatigue Model (FFM) which impost muscle fatigue index by mean of the raw EMG signal. FFM consist of two parts or fuzzy-network: First network, mean power frequency (MPF) estimation. Second network, imposts fatigue index as demonstration of muscle power drop. The mean power frequency (MPF) was employed as an index to represent the background activity. The novelty of our FFM, it uses raw EMG signal as input without any necessity to normalize with signal processing. Moreover, mapping muscle fatigue index as output without any mathematical operation requirement. Our FFM succeed to overpass 0*:*999 in the regression and 10^{-5} on root mean square error (MSE), which proves the qualification of the models. In addition, an investigation of the relationship between muscle fatigue and age was done in this study. According to our volunteer's ages the percent of power drop is between 20% and 42% of biceps brachii muscle, as well as, increasing around 1% in muscle power decline for the triceps than biceps brachii muscles.

Keywords: electromyography (EMG), mean power frequency (MPF), muscle fatigue index, fuzzy logic.

I. Introduction

Declivity in the muscle's ability to generate force can be defined as muscle fatigue. Moreover, it defined as the action of maintaining a muscle decrease as long as possible in the human body [1]. It occurs, when the shrunken proteins that enable muscle to generate power become impaired. Muscle starts to endure fatigue as soon as its power capacity begins to decline. When the tasks continue in maximal contraction, the drop in muscle performance increase parallels with fatigue [2]. The main causes of it can be illustrated in two expressions: First, nerve disable to generate a sustained signal. Second, behavior of muscle cell due to the mechanism of calcium and hydrogen ions increased [3].

Fatigue curves change between individuals depending upon the conditions that exist. Two different sites at least may cause impairment due to repeated contractions in muscular fatigue: transmission mechanism and contractile mechanism. As the mechanical response of the muscle fibers decline with fatigue, this can be affected by the number of active motor units and/or increasing the innervation frequency. Peripheral muscle fatigue reasons are mutated in the muscle conditions. These reasons are biochemical or the accumulation of metabolites. Biochemical can be illustrated as depletion of substrates (glycogen), compounds of high energy phosphate in the muscle fibers and terminal motor nerve branches acetylcholine. Metabolite, represent as electrolytes liberated from muscle activity [4][2].

A relationship between electromyography EMG signals and muscular activity in certain tasks presents a challenge define it in relevant quantitative terms. EMG signal is used to dictate individual or group muscle action. The EMG system consists of instrument to process the muscle electrical activity and amplify it to an appropriate level for analysis. Moreover, the system contains electrodes for EMG signal detection and high gain amplifier which provide the signal suitable for further processing [5]. As well as, fatigue causes change in the form of EMG signal and its relationship to muscle tension. Numerous observation to denote that motor unit behavior decrease in frequency because of fatigue [5][6].

During the last two decades, researcher's interest in study muscle fatigue using a wide variety of exercise models, assessment methods and protocols. Based on the definition of fatigue as reducing in the muscle's ability to generate force or power, different methods to measure fatigue by utilizing EMG signals, comparisons and simulations were introduced in this field [7], [8], [9],[10], [11], [12], [13], [14], [15].

Many methods to extract fatigue from EMG signal have been introduced, however, root mean square (RMS), median frequency (MF) and mean power frequency (MPF) are introduced as the popular estimation methods of muscle fatigue for the potentials of motor unit action[16][17]. Moreover, evaluations of MF and MPF of EMG power spectrum density, as well as, other distinguishing frequencies are usually utilized to monitor myoelectric [1].

The effective observation to localized muscle fatigue is the recorded of surface EMG signals as a change in spectrum. This approach can be achieved as EMG signal consequence processing in the time and frequency domains [18]. Moreover, it shows a shift of the EMG power spectrum towards lower frequency. In addition, this shifts in the mean or median frequency for the spectrum employ in muscle fatigue indexes [19][20]. MPF and MF are extremely employed as the main tool to anatomize muscle fatigue in frequency domain; however, RMS is generally utilized in time domain [21]. As well as, only aggregated signal band analysis can be implemented by MPF and MF, which is no easily applied [22]. MPF can be denoted as frequency at which the average power epoch is reached [23]. MPF calculation is the influence method of several spectral evaluation methods, inclusive parametric and nonparametric techniques. It is accomplished that MPF appreciated method will donate the fatigue trend [21].

During muscle fatigue, the physiological indicators of muscle task can be characterizing by MPF shifted toward low-frequency and increase of RMS in the time signal [1]. RMS is a mathematical amount calculates by taking the square root of the average (mean power) of the squares of a set of random varying amounts observed at uniform periods during a cycle. In addition, it is recommended chosen for smoothing [23]. RMS during the fatigue, increases and lead to the assumption that the pattern of RMS during muscle fatigue is not a dependable indicator of fatigue [24][25].

The aim of this easement is to distinguish or predict muscle fatigue degree at each time during a given task. In this assessment, we have created a new and easy Fuzzy Fatigue Model (FFM) that extracts fatigue index from raw EMG signal during the voluntary contraction. The proposed method consists of two steps: First step, FFM procedure, which divided into two networks or parts: First network, mean power frequency (MPF) estimation to represent the preceding background activity. Second network, extracts fatigue index as demonstration of muscle power decline. The mean power frequency (MPF) was employed as an index to represent the background activity. Our model takes the EMG signal; convert it into muscle fatigue index without the complexity of converting from using mathematical equations. We used human arm in dynamic motion to predict the flow of EMG signals from the biceps and triceps brachii muscles. The second step in our assessment is the investigation of the relationship between fatigue and age.

The remainder of this paper is organized as follows. Section II closes by demonstrates the related work of other researchers. Section III, Fuzzy Fatigue Model (FFM), introduces the theories and algorithms that were used to create the research models. Section IV, describes the experiment and procedures that were used. Section V, concludes with the presentation of the results and observations. Finally, the paper ends with a summary and conclusion.

II. Related Work

In this section we will review the nature of other researchers work that related with our assignment, as well as, describing their methods of acquiring, processing, and analyzing. Moreover, difference between our methods and advantage will be present.

Using EMG signals to definition muscle fatigue is a well-known procedure, which has been used in many investigations. For example, Kiryu et al. **[19],** analysis the frequency to know the change in the EMG shapes during the fatigue. The researchers observed two different stages for the frequency in the time domain. The researcher's incompetence to locating where the fatigue will occur, unlike our work, we determined the points of muscle power decline (fatigue point).

Park and Meek **[26]** obtained the median frequency from EMG signal. The median frequency was converted to a fatigue coefficient by using conduction velocity. The researcher method was complex and need to adjust many parameters according to specific filter, muscle sites, and pattern. Moreover, need more equipment like strain gauge and load sensor. On the other hand, our method is easy and fast to demonstrated muscle fatigue index using the raw EMG signal only.

An approach to localized muscle fatigue using surface myoelectric signal (MES) done by MacIsaac et al. **[27],** a neural network was utilized to tune the input parameters of the function which maps a set of surface myoelectric parameters to a fatigue index. In this work, researcher used normalized MES signal as input to the neural model, unlike our fuzzy model, which uses raw EMG signal without any normalization. Researcher study used time-domain, our work involve in frequency-domain which is more appropriate to describe muscle fatigue.

A fatigue model proposed by Soo et al. **[28],** using EMG signal. Researcher's model used handgrip dynamometer to conduct a series of static contraction tasks. Researcher work was more complex since he used many mathematical equations. Moreover, it has been done on static contraction tasks. Our proposed method is easy and done on dynamic contraction exercises.

Kiso and Seki **[29],** proposed a model to evaluate the dynamic change in myoelectric potential due to muscle fatigue. Researcher's model depends on fuzzy inference method. Researcher work explains the change in the myoelectric potential due to muscle fatigue without determination of muscle fatigue where or when it happens. Root mean square (RMS) was used in researcher study, which made researcher's model less efficient. Our research extract fatigue points and mapping it as muscle fatigue index using MPF estimation method.

Subasi and Kigmik **[18],** used artificial neural network method to detect muscle fatigue. The proposed study use time frequency methods and independent component analysis (ICA) on 14 healthy persons, recording EMG signals during a phasic voluntary movement. Researcher work was complex, using many mathematical equations. The researcher's didn't demonstrate where the fatigue occurred, unlike our method; we impost the points of muscle fatigue using Fuzzy-Model.

III. Fuzzy Fatigue Model (FFM)

Fuzzy Fatigue Model (FFM) is a proposed approach to extracts the muscle fatigue index from pure EMG signal. FFM is constructed by utilizing the fuzzy theory. In this theory, any new created model should be trained, tested and validated to predict fatigue index of new tests. The architecture of FFM is constructed mainly of two parts of fuzzy networks. The first part or fuzzy network is MPF estimator. Besides, the second part is utilized to extract the fatigue index.

To train FFM and validate its results, mean power frequency (MPF) was used to extract the fatigue index from EMG signals. MPF can locate the power decline from EMG signal. These points are utilized as fatigue index. In the following sections we will illustrate fatigue index calculation. Subsequently, we will address FFM structure.

A. Fatigue Index Calculation

The fatigue index is a connotation used to investigate the growth of fatigue during muscle activities. Moreover, it's defined as the regression coefficient of the mean power frequency (MPF) slope across lower frequencies. Fatigue index presents as the intercept which is the crossing point of MPF slope and the y-axis **[23].**

The MPF estimation method begin with calculation of the instantaneous frequency elicited by analytic the surface EMG signal using Hilbert transform **[30][19],** which employed in the evaluation of signal spectrum.
The spectrogram of the signal can be written as follows **[31]:**

$$f_{sp}\ (\emptyset, \tau) = \int h^{\cdot} \left(u - \frac{t}{2} \right) h \left(u + \frac{t}{2} \right) e^{-j\theta_u}\ du \qquad (1)$$

Using Fourier transform for the spectrum frequency of EMG signal to obtained the MPF of each interval, which is calculated as the average frequency of the power spectrum. The estimation equation can be shown as follows **[21][30][32][33]:**

$$\bar{f}_{ave} = \frac{\int_0^{f\,o/2} f |H_x(f)|^2 df}{\int_0^{f\,o/2} |H_x(f)|^2 df} \qquad (2)$$

Where, $H_x(f)$ is the spectrum frequency of EMG signal. The $\bar{f}_{ave}$ provide the change of power spectrum over time information.

The extracting of muscle fatigue index procedure is divided into three steps. First elicitation MPF slopes. Second locating shifting point in MPF slopes. Finally impost these points as a downgrade in power produced from the muscle (fatigue index).

B. FFM Structure

FFM consists of two parts or fuzzy networks. The first part or fuzzy network educes MPF from EMG signal. The first fuzzy network impost the MPF curves, which can be used to locate shifting point in MPF slopes. The second fuzzy network imposts the muscle fatigue index as the drop in muscle power for three periods of lifting task, using shifting points in MPF curves. Our proposed model input is raw EMG signal for three periods, which represent the beginning, middle and final stages of lifting exercises of maximum voluntary contraction (MVC).

The FFM based on Takagi-Sageno method (TS method) **[34].** Fig.1 shows the second fuzzy network structure of the three inputs, two rules and one output. First fuzzy network is same of the second the only difference is two inputs. The architecture of our model consists of five layers, which can be classified as follows:

1. First layer: nodes adaptive layer, which generate membership grades of the inputs.
2. Second layer: verification which part of the rule is satisfied.
3. Third layer: normalization of the network normalized firing strengths layer.
4. Fourth layer: nodes adaptive layer, which modified parameters pertaining to the first-order polynomial.
5. Fifth layer: fixed node layer, summation of all incoming signals to computes the overall output.

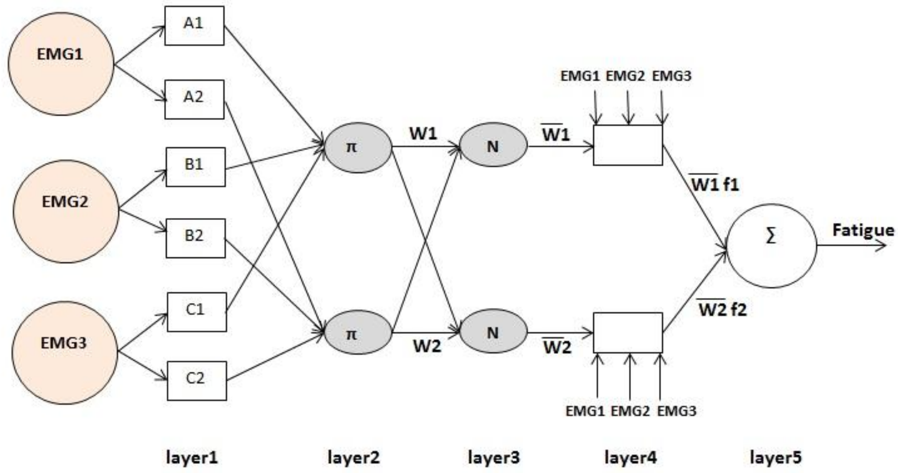

Fig.1 Fuzzy Fatigue Model (FFM), second network, Architecture

IV. Expremental

A. Subjects

Fifteen healthy non-athletic male volunteered to participate in this study. All the subjects didn't have any history of musculoskeletal complaints. Their age range (20-50) years, mean weight 84.75 ± 15 Kg and mean height 175 ± 8.5 cm. All the subjects were in good condition at the start of the experiments. Right hand, biceps brachii and triceps brachii muscles (Table 1) of each volunteer were included in this experiment.

Table 1. Muscles location and their actions

Muscle Name	Location	Action
Biceps brachii	on the upper arm between the shoulder and the elbow	flexes the elbow and forearm
Triceps brachii	on the back of the upper limb	extends forearm and long head extends shoulder

Differences in age of the subjects were chosen to investigate the effect of age on muscle fatigue, therefore according to the ages of our volunteers; we divided them into three groups as illuminate in Table 2.

Table 2. Age groups of volunteers

Group	Age Range (year)
A	20-29
B	30-39
C	40-50

All the exercise procedures carried out according to the Helsinki Declaration. The subjects consented to exercise after a fully explained about the purpose and procedures of the experiment. They gave written informed consent.

B. EMG Recording

1. The surface EMG signals were obtained from the right biceps brachii and triceps brachii muscles.
2. The skin was cleaned gently with alcohol and shaved carefully to improve the electrode-skin contact.
3. Six surface EMG electrodes (M-00-S), were placed on the muscles according to standard procedures **[35],** perpendicular to the fiber direction and away from the muscle innervation zone.
4. Two channels, two EMG preamplifier cables (ME6P) and EMG Bio-monitor (ME6000 8ch.) device were used to record the electrical activity of the muscles.
5. The signals were preamplifier, rectify and filtered using a band-pass Butterworth filter (1-500Hz) and 2000 Hz sampling rate.

C. Testing Procedure

Subjects were required to perform two isometric exercises, each one for a muscle (biceps brachii, triceps brachii). After putting the surface electrodes on the right dominant arm, the experiment began by measuring EMG signals of each volunteer for lifting weight exercise (2.7 Kg). Each exercise consists of three periods of which lasted 5 min, about 2 min of rest time was allowed between. The three periods represent the beginning, middle and final stages of lifting exercises of maximum voluntary contraction (MVC). The two exercises, shown in Fig. 2, can illustrate as follow:

Biceps-brachii muscle exercise: upper arm sits on a horizontal surface, as in Fig. 2A, the forearm flexed from the horizontal position to a 90^o angle vertical on elbow point, carrying 2.7 Kg in the hand.

Triceps-brachii muscle exercise: upper arm fixed to the top, horizontal to trunk and parallel to the head, as in Fig. 2B, the forearm flexed backward from the vertical position to a 90^o angle horizontal with the head, carrying 2.7 Kg in the hand.

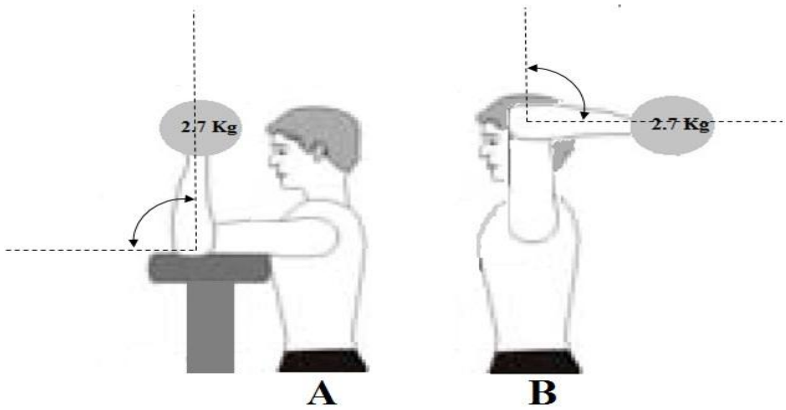

Fig. 2 Lifting weight experiment: A. biceps brachii exercise, B. triceps brachii exercise.

D. Model and Data Acquisition

An EMG signal was recorded from the subjects during the three-consecutive activity of the muscles (biceps brachii, triceps brachii). The three exercises represent the signal activity of the muscle at the beginning, middle and final of the experiment to show the difference in signals at constant MVC levels. Mean power frequency (MPF) obtained by programming it by MATLAB using the equations mentioned above.

Our proposed Fuzzy Fatigue Model (FFM) consists of two parts (fuzzy network); the first part estimates the MPF from the EMG signals. This part or fuzzy network shows the change in muscle activity due to muscle fatigue according to changes in the frequency domain.

The second part estimates the muscle fatigue index from the original signals (raw EMG) without any processing applied to it. The schematic architecture of our whole processing is depicted in Fig. 3.

Different number of nodes and layers, and different types of function were examined for the two networks of FFM. The configuration of the research model, the number of inputs, nodes, epochs, membership and type functions that were used in each part is shown in table 3.

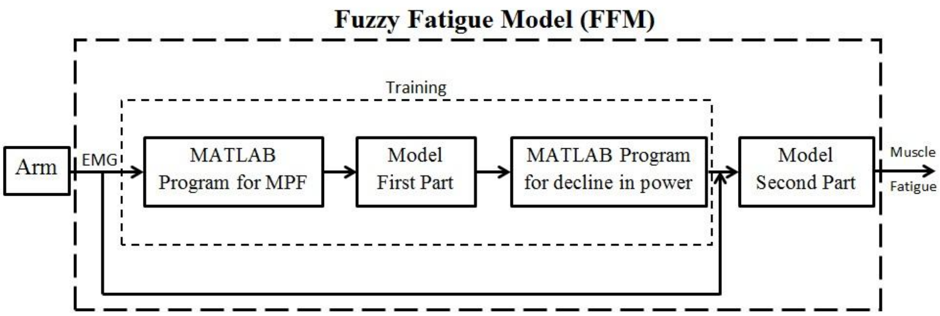

Fig. 3 Our method schema

Table 3 The configuration parameters of the FFM.

Configurations	Part 1	Part 2
Number of inputs	2	3
Epochs	4000	5000
Membership	2	3
Nodes	3 in each member	3 in each member
Function	Gaussian, Generalized bell	Gaussian, Generalized bell, Gaussian

V. Results and Discussion

In this section we will present our results and discussion according to the sequence of our work procedures. This section divided into four parts, calculation of MPF, estimation of fatigue index, change in fatigue according to age, and qualification of our models.

A. MPF Estimation

In fact of the raw EMG signal is stochastic in nature; it can used with the equations mention above to calculate mean power frequency (MPF). The output from this operation was used in the first part of FFM training. As illustrated in Fig. 4, a comparison between first part of FFM and theoretical calculations to extract the MPF curve of biceps brachii muscle. This curve showed the relationship between MPF and muscle fatigue. The area under the curve represents EMG power (muscle power) of the voluntary at maximum voluntary contraction (MVC). As clearly demonstrated in Fig. 4 the muscle power decreased with increasing of subject exercise periods. In middle period curve, the area under the curve (muscle power) decreased with shifted to the low frequency range. Also in final period curve, muscle power decreased more than previous stage of lifting exercise when subject start feeling of fatigue.

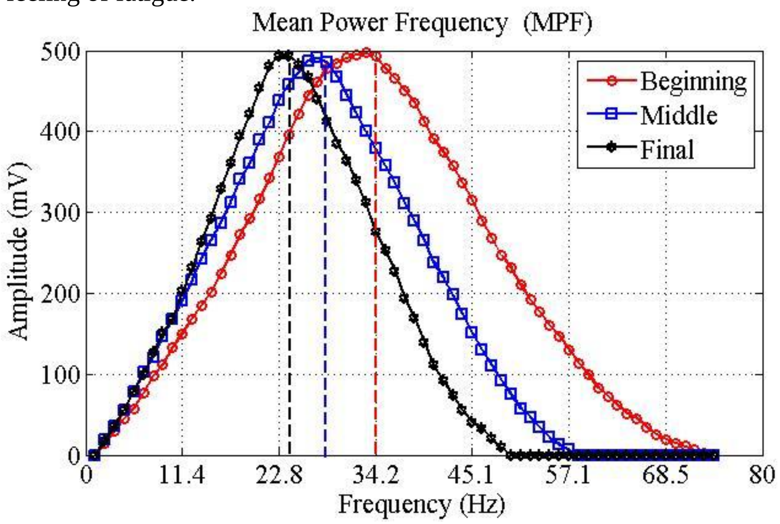

Fig. 4 MPF outputs: comparison between FFM (first part) and theoretical calculation for biceps brachii muscle for the three periods of lifting exercise.

Fig. 4 illuminate a gradual shift of the muscle power from high to low frequency range as muscle activity continued. Moreover, the success of our FFM (first part) to extract the MPF of the muscle from raw EMG signals, without the necessity of using the long mathematical operations.

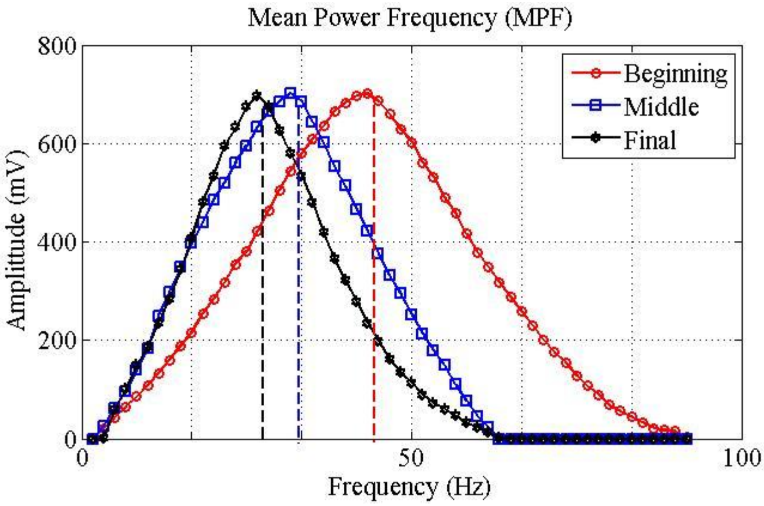

Fig. 5 MPF outputs: comparison between FFM (first part) and theoretical calculation for triceps brachii muscle for the three periods of lifting exercise.

Fig. 5 shows the same results in Fig. 4, the only difference is MPF estimation was done on the triceps brachii muscle. On the other hand, it showed the decline in muscle power was more than the power drop of biceps brachii muscle.

B. Muscle Fatigue Index

The main purpose of this work is to impost muscle fatigue index. After MPF estimation from FFM (first part), the point of the start of frequency decline can be easily nominated in MPF curve, as shown in the dash line in Fig. 4 and Fig. 5. This data used in FFM (second part) training.

FFM (second part) elicit three points assimilate the decline in MPF for the three periods of lifting exercise (beginning, middle and final). These three points represent the drop in muscle power, which mean the shift points in frequency, which known as muscle fatigue index.

Fig. 6 and Fig. 7, shows the muscle fatigue index for biceps and triceps brachii muscles respectively. Moreover, it shows the drop in muscle power in triceps muscle more than the drop in biceps muscle.

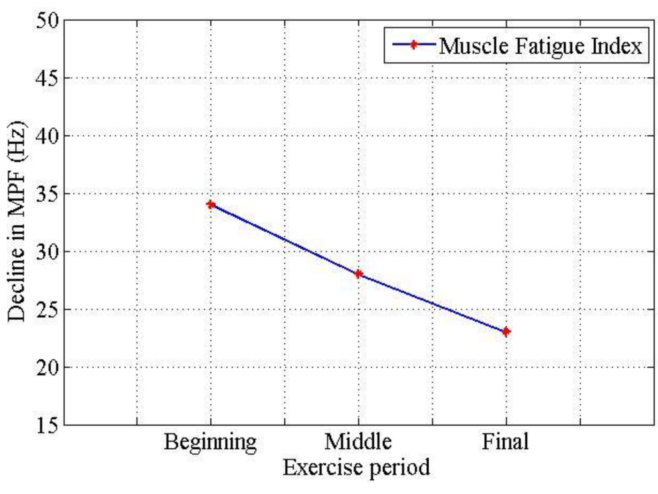

Fig. 6 Muscle fatigue index for biceps brachii muscle

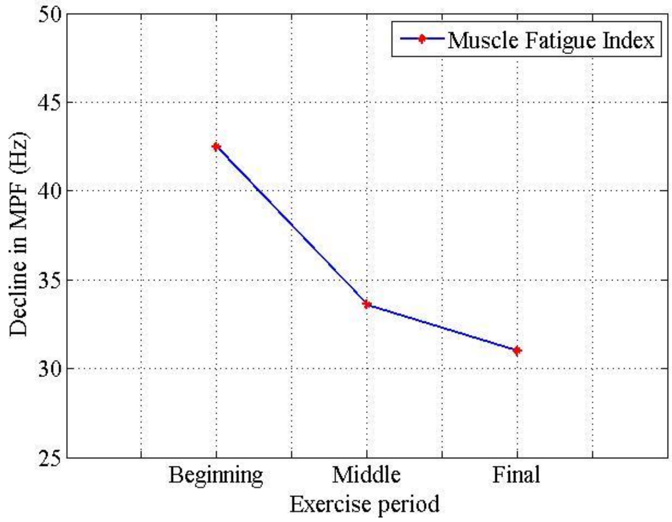

Fig. 7 muscle fatigue index for triceps brachii muscle

One of the important things to mention, our FFM mapping muscle fatigue index as output using raw EMG signal as only input, without any need of signal processing or utilization of mathematical equations complexity.

C. Fatigue Variation According to Muscle Type and Age

In this research, we investigate the relationship between age and fatigue. Using biceps and triceps brachii muscles as reference and our groups of volunteers age (Table 2), as shown in Fig. 8 that describes muscle fatigue of varying age of volunteers (three groups) as the difference between MPF at the beginning and final stages of lifting exercise for two muscles, biceps and triceps brachii. Our results present that: group B has augment fatigue than group A. Moreover, group C has biggest fatigue amount than other groups. According to the results, as illustrated in Fig. 8 fatigue in triceps brachii muscle greater than biceps brachii muscle. Fatigue was immense in triceps brachii muscle because of it underused in daily life for our non-athletic volunteers, which substantiate the efficiency of the strength training exercises of the muscles. In addition, the percent of power decline of muscles according to our groups of volunteer's age can be illustrative in table 4, which describe the power drop in the two muscles biceps and triceps brachii according to fifteen minutes of lifting exercise for each muscle.

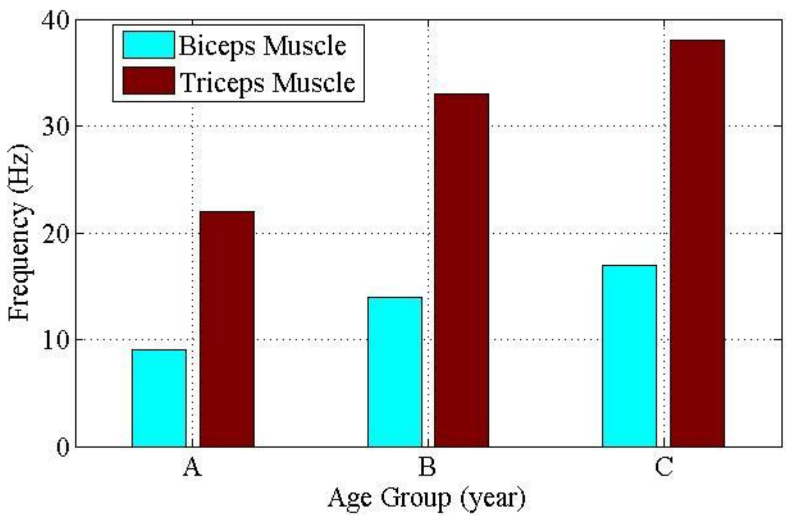

Fig. 8 Relationship between decline in MPF (muscle fatigue) and volunteer's age.

Table 4 Muscle power drop percent for fifteen minutes of lifting exercise.

Age Group	Power drop %	
	Biceps brachii	Triceps brachii
A	22.5	23.5
B	35	36
C	41	42.5

D. Qualification of Our FFM

Our input data for FFM divided into three part training, testing, and validation taken 60%, 20%, and 20% respectively. Qualification of Fuzzy-Model tested by root mean square error (MSE) and regression. Our FFM succeed to overpass 0.999 in the regression and 10^{-5} in RMS. FFM first part regression equal to 0.99998 and MSE = $1.064*10^{-8}$, as shown in Fig. 9. FFM second part regression equal to 0.99955 and MSE = $1.11*10^{-6}$, as shown in Fig. 10.

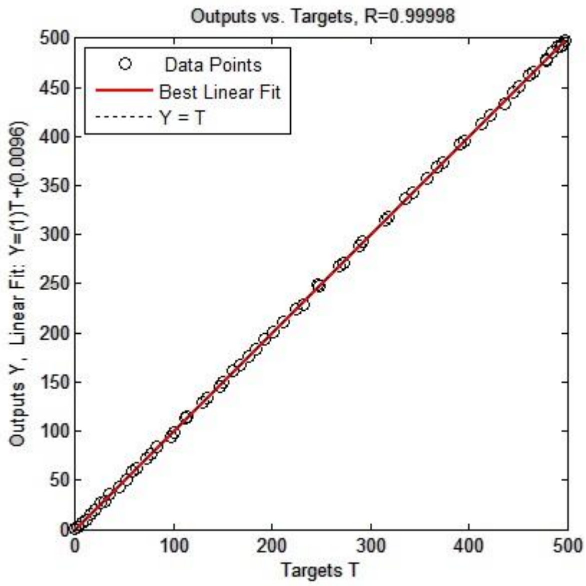

Fig. 9 first part FFM regression

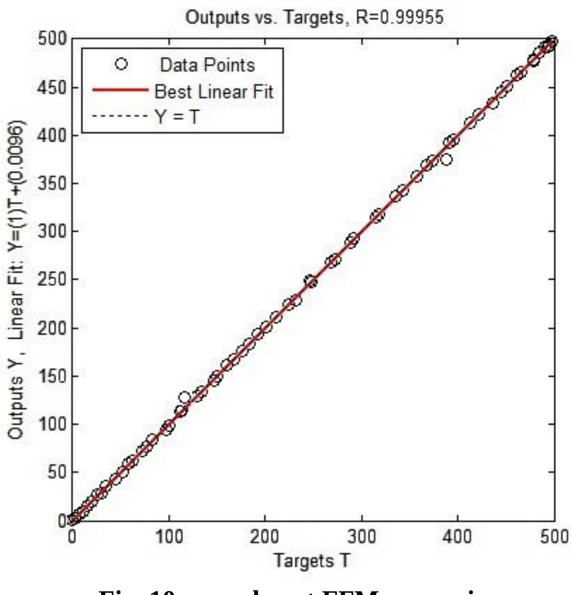

Fig. 10 second part FFM regression

VI. Conclusion

In the last decade, it was widespread to evaluate muscle fatigue by using electromyography (EMG) signal. A large number of studies were done in this field. In the present work we proposed Fuzzy Fatigue Model (FFM) which impost muscle fatigue index by mean of raw EMG signal. FFM consists of two fuzzy networks. The first fuzzy network educes MPF. The second fuzzy network imposts the muscle fatigue index. Our proposed model input is raw EMG signal for three periods, which represent the beginning, middle and final stages of lifting exercises of maximum voluntary contraction (MVC). Muscle fatigue index showed a decline in muscle power during the periods of lifting exercise. Also describe the relationship between preceding MPF and downgrade in muscle power (fatigue degree) at each time of exercise. The novelty of our model it uses raw EMG signal as input without any necessity to normalize by signal processing. Moreover, impost muscle fatigue index as output without any mathematical operation requirement. Our results show, the fatigue degree in triceps brachii muscle was highly than biceps brachii muscle, since the triceps muscle is less in use in daily life were more susceptible to fatigue. Also older ages were more exhibitions to the fatigue than younger ages according to our groups of volunteer's age and the percent of power decline of muscle is between 20% and 42% for biceps brachii muscle, as well as, increasing around 1% in muscle power decline for the triceps than biceps brachii muscles.

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