A Study on Variation in EMG Trends under Different Muscular Energy Condition for Repeated Isokinetic Dumbbell Curl Exercise

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Abstract: Quantification and detection of accumulated muscle fatigue to assess muscle condition is of pivotal importance in sports and injury prevention. Existing research on assessment of exercise-induced muscle fatigue provides information regarding change in EMG waveform of the muscle during a single set of exercise performed. However, currently there is no study which discusses the variation in EMG activity of same subject under different muscle conditions when the exercise is repeated at constant force level. This paper investigates the changes in muscular energy under different conditions using endurance time, mean power frequency (MPF) and integrated EMG (IEMG) as metrics. This paper presents an initial study on EMG data acquired from subjects subjected to repeated isokinetic contractions. The aim of the study is to focus on inter-subject and intra-subject variations in EMG data. Such studies are very limited. Most of the studies focus on isometric contraction and make use of average data of the subjects from which data is collected once per protocol. Such reports do not bring forward the inter-subject and intra-subject variability. Because of huge variability, this study does not validate use of Global Fatigue Index for determination of muscle force and fatigue. Study of this variability is important if any autonomous system is developed for individuals using the EMG data that can accurately make detection and prediction on individual basis. Moreover this study suggests, peak MPF value and average slope of MPF curve during transition to fatigue stage as useful features to predict remaining time to fatigue till failure point.

1 INTRODUCTION

Fatigue accumulation in muscles and subsequent recovery has special significance in sports activities and rehabilitation. As fatigue sets in, the muscle capacity to perform a physical action decreases. Accumulation of muscle fatigue causes muscle stiffness, tension and myalgia. Generated fatigue depends on multiple factors including intensity, duration, physical fitness and type of task being performed which may be static or dynamic in nature (Yates et al., 1987; Cornwall et al., 1994; Singh et al., 2004).

Recovery following fatigue accumulation is broadly characterized into two categories. Strength recovery deals with the ability of muscle to restore its strength after physical exertion to its original capacity. Muscular endurance is the ability of a muscle to persist a task for an extended period of time, referred to as endurance time. Reported rate of strength recovery is nearly five minutes, whereas the recovery to persist an isometric task is reported to take longer time (Yates et al., 1987).

Surface EMG is an effective non–invasive technique for fatigue detection and quantifies the underlying electrical activity of motor neurons responsible for generating the requisite force in muscle to sustain a particular activity. Analysis of changes in the time and frequency domain features of this myoelectric signal indicate the fatigue generated in muscle. The time domain analysis of EMG provides information regarding muscle activation while in frequency domain fatigue is observed as frequency shift towards lower frequency in EMG data (Hwaang et al., 2016). These parameters of s-EMG give a measure of muscle fatigue in a localised area.

While several studies exist which discuss the variation in s-EMG amplitude and frequency during continuous isometric exercises, relatively fewer studies are present on isokinetic exercises. Moreover, there is currently no study which provides an adequate method for prediction of time to fatigue and discusses changes in EMG activity of a muscle at same force level under different muscle conditions. Muscle condition while performing exercise at different time intervals with varying periods of rest in

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between exercises represent different muscle conditions. This paper presents an initial study based on changes in both time and frequency domain features of EMG signal for subjects under different muscular energy conditions for an isokinetic exercise of repeated dumbbell curls. Such a study can yield insight regarding modelling of different trends of time domain and frequency domain features of EMG signals for the purpose of reliable evaluation of fatigue levels incurred and prediction of upcoming failure point. Studies conducted earlier most of the time suffice on presenting generalized group results or average trends at individual level. However, diversity in trends depicted under varying muscle energy conditions needs to be studied and robustness of proposed evaluation and prediction methods against this diversity needs to be tested. Our study on subjects with very low level training indicate wide variation in performance trends of EMG features. This study is designed to bring forward the inter-subject and intra-subject variability that exists from individuals to individuals. Moreover, this also brings to challenges some of the claims or propositions found in the literature. Some initial findings and conclusions are being shared in this paper which can be used to devise new methods of evaluation of fatigue level and prediction of time to fatigue.

Traditionally two muscle states have been studied Non-fatigue and Fatigue. Recently in literature a three stage division has been proposed which include the Non-fatigue (or Pre-fatigue) stage, Transition-to-Fatigue stage and the Fatigue stage. The onset of fatigue in the fatigue stage leads to inability of the muscle to maintain a desired force or power which leads to the total fatigue state (failure point) where it is impossible for the subject to continue performing the task. This last phase is generally very short. Transition to fatigue stage signifies a phase where a fresh muscle starts to fatigue and where the remaining time to fatigue can be estimated with good accuracy.

The rest of the paper is organized as follows: Section II discusses experimental protocol. Section III presents processing scheme; Section IV presents the experimental results; Section V gives the conclusion.

2 EXPERIMENTAL METHODS

2.1 Subject

Four right–handed healthy 16 - 18 year old subjects with no prior reported neuromuscular injury participated in this project. Subject 1 and 2 had minimal prior training and exercise history while subject 3 and 4 were novice with no prior experience. Before the experiment the subjects were informed about the experimental protocol and asked to sign a written consent. The experiment consisted of two phases and was conducted on two consecutive days. First phase of the experiment was concerned with the determination of maximum voluntary contraction (MVC), while in the second phase subjects performed continuous isokinetic dumbbell curls.

2.2 Exercise Protocol

The endurance task was designed to fatigue the muscle and observe the effect of accumulated fatigue in muscle. After determination of MVC, each subject was asked to perform four sets of continuous exhaustive dumbbell curls at 35% of their MVC level. Generally, recommended rest interval for recovery during strength training is 2 to 5 minutes (Willardson, 2006). However, full recovery which depends on strength recovery as well as the ability to sustain any physical activity for same amount of time as the stage of pre-exhaustion, requires longer period of rest and is subject dependent. Set 1 and Set 2 were performed on Day 1 with an inter-set recovery period of 10 minutes whereas Set 3 and Set 4 were performed on Day 2 with an inter-set rest period of 2 minutes. Each subject was asked to perform continuous exhaustive dumbbell curls till failure in each set. Exhaustion was defined as the point where the subject could no longer perform curls. The subject stood erect with their upper arm fixed, and was directed to move their lower arm through a full range of motion at a speed of 20 repetitions per minute (3 sec/cycle). In order to regulate the time taken for one contraction the subject matched the speed for one complete repetition i.e. 3 sec with the visual cue played on screen. EMG signals were recorded from the bicep brachii using bipolar surface electrodes placed 2 cm apart. Prior to electrode placement, the skin was shaved, cleansed and abraded with skin cleaning gel. A conductive adhesive gel was applied at electrode skin contact point to increase conductivity of electrodes.

Existing literature suggests that lateral and medial positions on bicep muscle are adequate for data acquisition. Physical placement of channel markers on the surface of the skin is dependent on the identification of the localized sites with maximum motor unit activity. Electrodes were placed on proximal end from the muscle belly for medial bicep brachii and distal end from the centre of muscle for lateral head of bicep as they are preferred sensor sites (Zaheer et al., 2012).

3 PROCESSING SCHEME

The EMG data was collected through Shimmer EMG development kit, sampled at 1000 Hz and processed in Matlab. In this study, we concomitantly conducted a time domain and frequency domain analysis of EMG to assess fatigue accumulation in muscle over four sets performed by the subject on two consecutive days. The processing scheme used for EMG data analysis is discussed in detail in following steps.

3.1 Pre-processing

EMG signal is a non-stationary signal and is affected by noise (Singh et al., 2004).A non-causal moving average filter (MAF) was used for DC offset removal. The formula for moving average filter coefficient is given by (1).

$$mav(n) = \frac{\sum_{n-w}^{n+w} x(n)}{w} \quad (1)$$

$$y(n) = x(n) - mav(n) \quad (2)$$

In (1), *x (n)* represents the time domain signal, *w* represents the window size and *mav (n)* represents the averaged value which is subtracted from time signal. Equation (2) represents the resultant signal after application of moving average filter. The window size used in our experiment was 100 samples. After DC offset removal, the data was segmented in to multiple repetitions. The average time taken for completion of one repetition was approximately three seconds (3 sec) in-accordance with the protocol followed for data acquisition. However, as the time taken for completing a repetition exceeded the requisite time i.e. 3 seconds in later repetitions, data was segmented through visual inspection.

It is a well-established fact that useful EMG data lies in frequency range of 10 Hz to 500 Hz (Allison et al., 2002) and therefore a band pass filter of 5 Hz – 400 Hz was applied on data in frequency domain on each repetition separately. 1000 samples corresponding to the region of maximum activation for each repetition were selected. Region of maximum activation in EMG signal comprised of 1000 samples which had the largest cumulative EMG value.

3.2 Data Analysis

Time domain metrics including root mean square (RMS) and integrated EMG (IEMG) are generally used for EMG fatigue analysis. According to existing literature, both RMS and IEMG exhibit an increase in value as fatigue onsets in muscle. To predict muscle fatigue in time domain we observed changes in mean and normalized IEMG for each bicep curl. IEMG gives a measure of area under the curve and account for the number of the recruited motor units providing the requisite muscle force while performing an activity. Usually, the increase in IEMG value is linear in nature. The formula for Integrated EMG is given by (3)

$$IEMG = \int_{t=0}^{t=T} | \, EMG(t) \, | \, dt \quad (3)$$

The T represents the time taken to complete one complete cycle. The formula shows that the value of IEMG varies as a function of time (Hwaang et al., 2016). IEMG value determined for each repetition was time normalized over the time taken in seconds for its completion to compute IEMG per second (IEMG/s).

The notion that the mean power frequency (MPF) and median frequency (MDF) decrease in effect to fatigue generation in muscle is well accepted in scientific society (Hotta and Ito, 2013). As fatigue develops EMG spectrum shifts towards lower frequency. It is well established in literature that the mean frequency of the power spectrum is proportional to propagation velocity. MPF is by given by (4).

$$MPF = \frac{\sum_{j=fL}^{j=fH} f_j P_j}{\sum_{j=fL}^{j=fH} P_j} \quad (4)$$

Here f represents frequency vector, and P represents power spectrum. Power spectrum is determined by taking square of spectrum of a time domain signal. f_L denotes lower frequency bin whereas f_H denotes higher frequency bin. Frequency range varies from 5 to Fs/2, where Fs is the sampling frequency. In our scheme MPF is determined on best window EMG data for each repetition.

4 RESULTS AND DISCUSSIONS

In this section we discuss fatiguing trends during different muscular conditions. This study is designed to bring forward the intra-subject and inter-subject variability that exists from individual to individual. Also changes observed in IEMG curves and MPF under different states of muscle capacity and fatigue conditions are reported.

The trends obtained for medial and lateral position of bicep muscle were similar. However, EMG activity was found to be more prominent on lateral position of bicep muscle and its results are discussed in this paper. It is to be noted that the fatiguing trends for other muscles will be somewhat different and dependent on subject's training or exercise regime. The observation yields that there exists quite some variability in the nature of the IEMG and MPF curves of the subjects with different training levels. The subjects used in our study are male unexperienced teen agers with only limited exposure to prior dumbbell training. These could be divided in two categories: one with some prior training (Subject 1 and 2) and other initial beginners (Subject 3 and 4).

Fig. 1 shows the superimposed plot of IEMG values for each subject while Fig. 2 represents the IEMG best fit curves on four sets of subject 1. Fig. 3 shows the superimposed MPF plot of all the sets performed by subjects 1, 2, 3 and 4 respectively. Fig. 4 shows the graph to predict time to fatigue using slope of the MPF curve of Set 1 for subject 1. Fig. 5 shows the simultaneous time and frequency information of EMG signal as MPF vs. IEMG graph for all four subjects, analogous to the global fatigue index proposed in (Hwaang et al., 2016). In Fig.5 the IEMG values for each set are percentage normalized with respect to the initial value while MPF values are percentage normalised with respect to the maximum value of each individual set respectively. Table 1 shows the values for threshold factor and average slope across all four sets for each subject, explained later in the paper.

Endurance time (ET) is the time taken by the subject to reach failure while performing an activity. ET provides information regarding the energy condition of the muscle. If muscular strength is greater, the subject is likely to sustain a fatiguing activity for greater amount of time, which is labelled as endurance time.

A general trend observed in the endurance time for each subject showed that 75% – 100% strength recovery occurred during the first two consecutive sets having a rest period of 10 minutes in-between the sets whereas 50%-60% recovery occurred between consecutive sets performed on Day2, having an inter-set rest period of 2 minutes. After 100% strength recovery the repetitions performed by the subject were either equal to or exceeded the number of repetitions performed in the preceding set. Consistent with the results in earlier literature (Yates et al., 1987) for isotonic exercise, percentage recovery in isokinetic exercise is also found to be proportional to the rest period between consecutive sets.

4.1 Integrated EMG (IEMG) Trends

IEMG curves show considerable inter-subject variation in EMG data collected in different trails from individuals, however intra-set analysis for each subject represented a dominant trend.

Fig. 1 clearly shows an initial increase in amplitude of IEMG in each individual set for subject 1, 3 and 4. This increase in IEMG amplitude is attributed to activation of additional motor units to maintain strength during submaximal fatiguing contractions (Conwit et al., 2000). However, in case of subject 2, the IEMG trends do not show an increase in the value but maintain a constant linear level in the beginning and then exhibit slightly decreasing trends

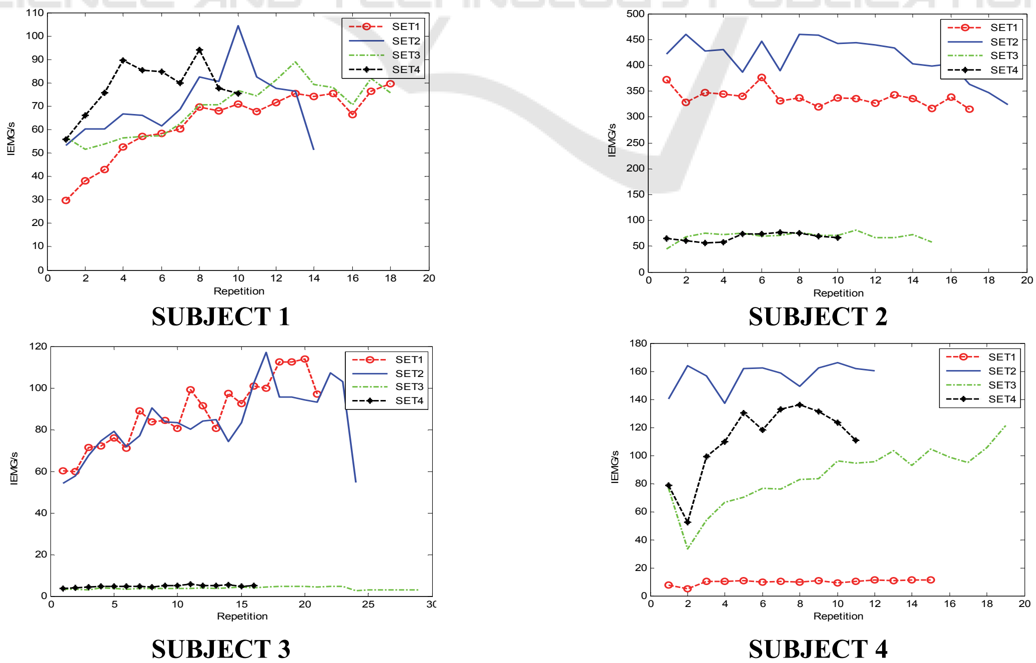

Figure 1: Superimposed IEMG (mV) graphs of four different sets under different muscle rest conditions for subject 1, 2, 3 and 4 respectively.

near exhaustion. Is has been reported in earlier studies that during continuous isometric exercise, the EMG amplitude increases for 70% of the total endurance time. After this point the amplitude tends to level off (Allison and Fujiwara, 2002). The trends obtained for isokinetic exercise in (Hwaang et al., 2016) shows an abrupt increase in the value of IEMG at onset to fatigue. However, in contrast to results reported earlier in (Hwaang et al., 2016) and (Allison and Fujiwara, 2002), we have observed that the IEMG amplitude may increase or decrease abruptly for different subjects, after 70% of the endurance time has passed. We can clearly observe these trends in best fit superimposed IEMG graph for subject 1. The maximum number of repetitions carried out by the subject were 18, 14, 18 and 10 in Set 1, 2, 3 and 4 respectively, with average completion time for each repetition approximately around 3 seconds. An instant decay can be seen in IEMG amplitude after repetition 12 in Set 1. Similar decay can be observed in IEMG graph for Set 2, 3 and 4 at repetition 10, 12 and 7 respectively which accounts for approximately 70% of the total number of repetitions in each set respectively. It shows that onset to fatigue takes place after about 70% of endurance time has passed, and the subject can sustain the activity for an additional time of 42.9% of the elapsed time before the subject reaches the failure point. This can be observed in Fig. 2.

However, in-contrast to the IEMG trends observed for subject 1, subject 4 exhibits a rise in the value of IEMG in Set 3 after onset of fatigue during fatigue stage as shown in Fig. 1. So we conclude that the IEMG graphs show considerable variation in shape from subject to subject. Intra-subject variation also exist which could be considerable. However, general shape of the intra-subject graphs shows similar trend. In most of the subjects IEMG shows an increase during a set before levelling off or in some subjects may remain roughly flat. In our exercise we asked to subject to continue the exercise a further into the fatigue period till the subject was clearly inclined to discontinue the activity. It was found that this fatigue stage showed up in the IEMG graphs in terms of either rapid rise or fall. Our study shows that even in the case of the same subject both fast rise or decline are possible during isokinetic exercises.

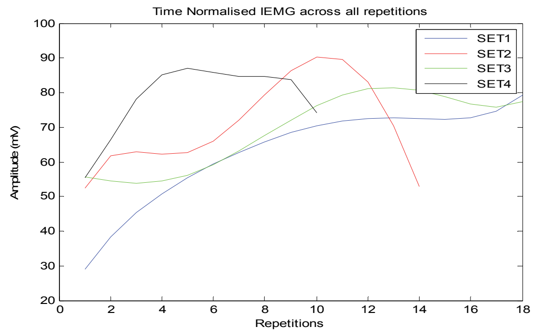

Figure 2: Superimposed IEMG (mV) best fit curves for different sets for Subject 1.

4.2 Mean Power Frequency (MPF) Trends

Fig. 3 shows the superimposed mean power frequency graphs (MPF) for each subject. Usual statistical parameters used to describe the frequency shift in data are median frequency and mean power frequency. Consistent with the previous studies (Hwaang et al., 2106; Allison and Fujiwara, 2002; Zaman et al., 2007) the mean power frequency determined for each set in our study decreased in a non-linear fashion as fatigue set in the muscle. Congruent to the results obtained from time analysis of data, the MPF value for each set shows either a sharper decline or an abrupt increase in its value after 70% of the total endurance time has passed and this indicates onset to fatigue.

We observed that the MPF value varied from subject to subject. However, for an individual set it was observed that the MPF at the failure point tends to fall to a value that lie in close range of a fraction of the maximum MPF value. This ratio varies in the range of 0.6 to 0.7 depending on the individual. This is concurrent to the observation stated in (Hwaang et al., 2016) that the MPF falls to 60% of its initial value as 100% fatigue sets in the muscle. This can be determined using the following equation.

$$n = f_{max}/f_t \tag{5}$$

Here n is the threshold factor, f_{max} is the peak MPF value and f_t is the MPF value at the failure point.This is fairly stable for an individual and hence can be used for prediction of failure point.

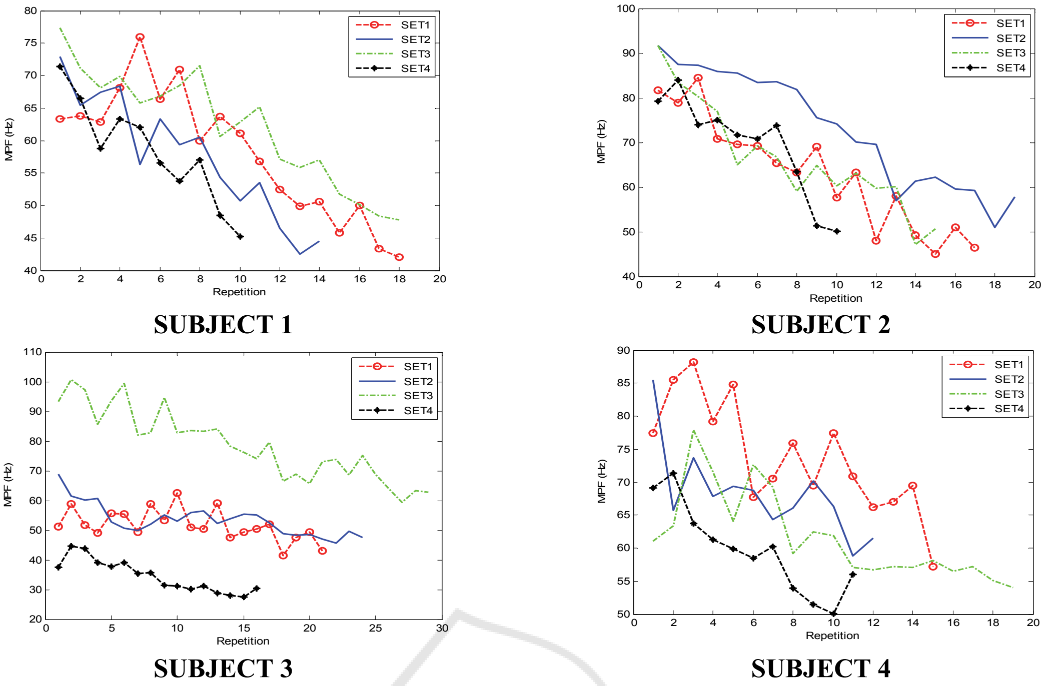

Figure 3: Superimposed MPF graphs of four different sets at different muscle rest condition for subject 1, 2, 3 and 4 respectively.

The variation in the initial starting values of each set for the subjects was observed to be less for relatively trained subjects i.e. subject 1 and subject 2 which lie in the range of 10-13 Hz as compared to novice subjects .i.e. subject 3 and subject 4 in which the variation amongst the starting values of performed sets lie in the range of 22-44 Hz. This indicates that the variation in trends of MPF tends to become more predictable and easier to model with the increase in performance training. The variation in the shape of the curves and absolute values under different muscle conditions becomes less fluctuating with training.

The trend observed in the MPF graphs is pre-dominantly that of progressive decline. However, initial rise in the MPF value was also observed in some trails. It is proposed that progressively declining stage of the graph be regarded as the transition to fatigue phase. Portion of the graph before the MPF peaks off can be regarded as non-fatigue phase.

Using this definition of transition to fatigue, it is proposed that prediction of time to fatigue (number of repetitions left to total fatigue) can be done after the onset of transition to fatigue. This can be done by estimating the MPF value at the failure point and the average slope of the MPF curve during the transition to fatigue stage. This is shown in Fig. 4. At any time after entering the transition to fatigue stage, the decreasing trend in the MPF curve may be extrapolated using the estimated slope of the transition to fatigue phase to the estimated failure point MPF level. The failure point MPF can be estimated using the peak of MPF curve in a set and threshold factor. A rough first estimate of the average slope may be obtained by evaluating the average instantaneous slope till the current point. As the transition to fatigue stage will progress the average instantaneous slope will come closer in value to final average slope of this phase and the accuracy of prediction is expected to improve. Table. 1 shows the average threshold factor *n* determined for each subject, the standard deviation and the average slope.

Our method is expected to yield better prediction than in (Al-Mulla et al., 2012) because the time to failure in (Al-Mulla et al., 2012) is assumed to remain the same for a given subject. However, our study confirm that depending on the energy condition this time to failure varies in reality and can be observed from the graphs. Our approach being more adaptive to the ongoing trend is expected to be more accurate.

Table 1: Calculated threshold factor and average slope for each subject.

Subject	Average Threshold *(n)*	St. dev in *(n)*	Average Slope
1	0.6035	0.0199	-2.4421
2	0.5443	0.0313	-3.3943
3	0.6440	0.0564	-1.3225
4	0.7073	0.0194	-2.2975

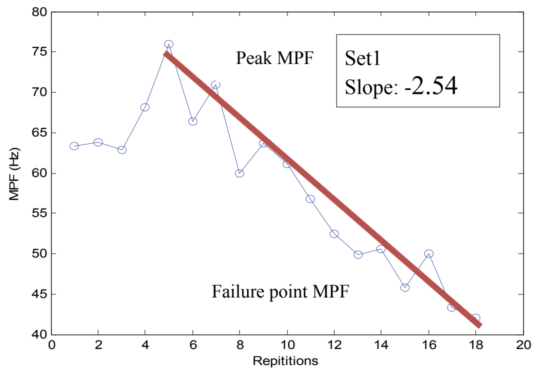

Figure 4: Slope of MPF curve to predict time to fatigue.

In order to predict the transition to fatigue in EMG waveform (Ullah et al., 2012) has used just the instantaneous slope of MPF to identify transition to fatigue stage. The onset of this stage is indicated if the slope exceeds a certain threshold. Looking to the fluctuations in slope in EMG real-life data overall only using the instantaneous slope criteria may not be enough to reliably detect the transition to fatigue stage. With regard to detection of transition to fatigue and prediction of time to failure point training a classifier with machine learning approach for prediction is more suitable rather than using a deterministic approach evaluating one or two features.

(Hwaang et al., 2016) proposed a method of making a global EMG index map to simultaneously predict muscle fatigue and force from real-time EMG signal with arbitrary MVC levels for repeated isokinetic dumbbell curls. The mean IEMG value and mean frequency values were co-plotted for this purpose. In our case IEMG vs MPF plots for our four subjects only for a 35% MVC are shown in Fig. 5. Linear curve has been fit over points corresponding to transition to fatigue stage. Looking at the spread of these points and different slopes of the best-fit lines for each fatigue bout, it can be concluded from our results that defining an accurate global-index curves even for individual subjects would be not be realistic given the non-stationary nature of EMG signal. Such curves can only be used describe a very coarse and general trend of MPF vs IEMG values at different force levels but predicting the force levels can yield inaccurate results.

5 CONCLUSIONS

The conclusion of this study is that IEMG and MPF curves show considerable inter-subject variation through EMG data collected in different trails from an individual as well as some repeatable characteristics. Hence the scope of person-specific autonomous systems only trained on individual person data is advocated for attaining accuracy than a generally-trained system based on these characteristics. The study indicate that MPF frequency trend starts showing

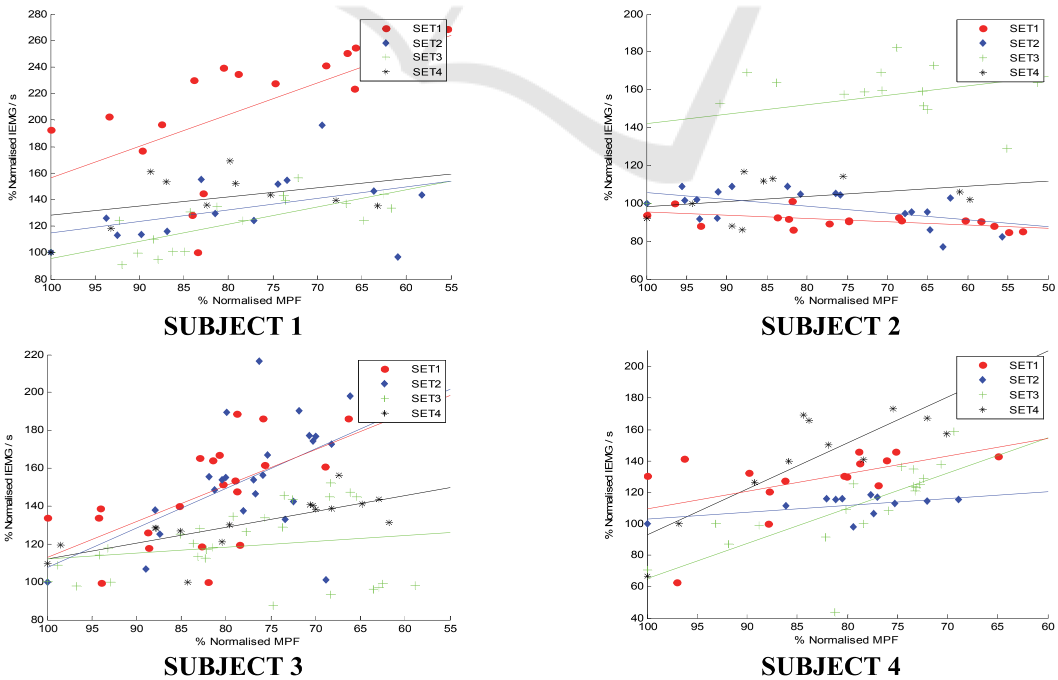

Figure 5: MPF vs. IEMG graphs of four different sets at different muscle condition for subject 1, 2, 3 and 4 respectively.

predictability earlier with little training compared to mean EMG and IEMG in which the effect of fatigue and unpredictability of trends remain dominant till later stage of training. Thus MPF values (frequency analysis) are more sensitive to intra-subject variation than time domain metrics like mean and IEMG and hence carry more scope in developing an autonomous system.

We have pointed that features like slope during transition-to-fatigue stage can be used to predict time-to-failure as the final failure point is about 60%-70% of the maximum MPF frequency. The recovery of starting frequency from fatigue even in case of somewhat experienced subject is very fast and is complete in almost 10 minutes. Moreover, our study does not verify the utility of a general global fatigue index as they have not taken in to consideration the intra-subject and inter-subject variations.

REFERENCES

J. W. Yates, J. T. Kearney, M. P. Noland, W. M. Felts, 1987. *Recovery of dynamic muscular endurance*, European Journal of Applied Physiology, 56: 662-667.

M. W. Cornwall, L. P. Krock, L. M. Wagner, 1994. *Muscular fatigue and recovery following alternating isometric contractions at different levels of force*, Aviat. Space Environ. Med, 65: 309 -14.

V. P. Singh; D. K. Kumar; D. Djuwari; B. Polus; S. Fraser; J. Hawley; S. L. Giudice, 2004, *Strategies to identify muscle fatigue from SEMG during cycling*, Proceedings of the 2004 Intelligent Sensors, Sensor Networks and Information Processing Conference.

H. J Hwaang, W. H Chung, J. H Song, J. K Lim and H. S Kim, 2016. *Prediction of biceps muscle fatigue and force using electromyography signal analysis for repeated isokinetic dumbbell curl exercise*. Journal of Mechanical Science and Technology, 30(11), Pp. 5329~5336.

F. Zaheer, S.H. Roy, C. J De Luca, 2012. *Preferred sensor sites for surface EMG signal decomposition*, Physiol Meas; 33(2): 195–206

G. T. Allison, T. Fujiwara, 2002. *The relationship between EMG median frequency and low frequency band amplitude changes at different levels of muscle capacity*. Clinical Biomechanics 17/:464–469

Y. Hotta, K. Ito, 2013. *Detection of EMG-based muscle fatigue during cyclic dynamic contraction using a monopolar configuration*. 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC) .

J. M Willardson, 2006. *A Brief Review: How Much Rest between Sets?*, Kinesiology and Sports Studies Department, Eastern Illinois University, Charleston, Illinois.

R. A. Conwit, D.Stashuk, H. Suzuki , N. Lynch, M. Schrager, E. J. Metter, 2000. *Fatigue Effects on Motor Unit Activity During Submaximal Contractions*, Arch Phys Med Rehabil, 81:1211-6.

A. A. Zaman, T. Sharmin, M. A. A Khan, M. Ferdjallah, 2007. *Muscle fatigue analysis in young adults at different MVC levels using EMG metrics*, *Proceedings 2007 IEEE SoutheastCon*, Richmond, VA, pp. 390-394.

M. R. Al-Mulla, F. Sepulveda and M. Colley, 2012. *sEMG Techniques to Detect and Predict Localised Muscle Fatigue*, EMG Methods for Evaluating Muscle and Nerve Function, Mark Schwartz, IntechOpen.

J. G. Ullah, H. Yu, S. Gyan, P. Rangel, O. Adeoye, N. V. Hernandez, 2012. *A mathematical Model to Predict Transition-to-Fatigue During Isometric Exercise on Muscles of the Lower Extremities*. Engineering, Vol. 4, No. 10, pp. 16-19.