Qualitative Assessment of Muscle Fatigue Based on EMG

Khosravani S.[1]*, Maleki A.[2], Fallah A.[3]

[1]Master's student of Bioelectrical Engineering, Biological Systems Control Laboratory, [3]Assistant Professor at the Department of Biomedical Engineering, Department of Biomedical Engineering, Amirkabir University of Technology (Tehran Polytechnic), Tehrn, Iran

[2]Assistant Professor at the Department of Electrical and Computer Engineering, Semnan University, Semnan, Iran

*Corresponding author: Khosravani S. Master's student of Bioelectrical Engineering, Biological Systems Control Laboratory, Department of Biomedical Engineering, Amirkabir University of Technology (Tehran Polytechnic), Tehrn, Iran
E-mail: skhosravani@aut.ac.ir

ABSTRACT

Muscle fatigue assessment has been the basis of numerous studies, specifically, in neuromuscular rehabilitation and the applications of FESsystems. Various EMG-based techniques, in time and frequency domains, have been investigatedover years for the detection and evaluationof this phenomenon. The main objective of this study has beento evaluate the efficiency of applying a number of techniques which have been mostly applied to detect fatigue in isometric contractions,for the assessment ofthis phenomenon in repetitive isotonic experiments.Twogroups of tasks were devised to produce both types of contractions in two muscle groups, Biceps and Deltoid. Simultaneously, the relevant sEMG signalswere recorded anda number of time-domainindices(RMS, ARV, and ZC), together with two frequency-based features:mean and median frequency, were extracted from the recorded samples.The resulted diagramsfor all the contractionsrevealed an overall increase in the values of time domain features,and a decline in ZC and the quantities of frequencycomponents;however, the frequency-based indices represented smoother trends and, therefore, showed to be better representatives of the fatiguing phenomenon. It was also observed that, generally, the diagrams belonging to isotonic exercises stood at lower levels in comparison to the isometric ones,which mainly stem from the resting periods existing in the isotonic tasks.In the final step,theapproach utilized by Seibt and Schneider,toward representinga quantitative portrayal of muscle fatigue,was applied to the recorded signals and the deficitsinherently existing in similar approacheswerereviewed from various aspects.

Keywords

Muscle fatigue;EMG;Isometric contraction; Isotonic contraction; Signal Processing; Exercise

Introduction

As a general description, localized muscle fatigue can be defined as a reduction in the level of the output force generated by muscles during a sustained activity [1].Assessment of muscular fatigue has been the basis of numerous studies, specifically, in the field of neuromuscular rehabilitation and the applications of functional electrical stimulation (FES) systems. Betterdetection of this phenomenon results in better muscle force production and prevents possible damagescaused by excessive electrical neuromuscular stimulation.A large amount of effort has been spent over years onfinding the most suitable techniques for the detection and evaluation of muscular fatigue. These cover a wide range of methods including: near infra-red spectroscopy (NIRS), ultrasound, More-GargScale, CR Borg Scale,the use of force sensors, goniometers,accelerometers, mechanomyography, and so on; each of which containsseveral advantages and disadvantages.

Additionally,it has been 40 years since the first time when surface electromyography(sEMG) was introduced as a reliable noninvasive tool for the assessment of localized muscle fatigue. However, the concentration of most studiesin this fieldhas been on monitoringthe changes occurring in sEMGsignal characteristics recorded undervariouscontractile circumstances; the approach which providedan indirect representation of muscular fatigue with regards to the alterations taking place in muscle's electrical activity. A number of the mentioned EMGfeatures in time and frequency domains include: root mean square values (RMS), averagedrectified values (ARV), peak to peak values (PTP), the number of zero crossings (ZC), the trends of the signal's mean and median frequency, and so on [2]-[12]. Furthermore, a group of methods requiring the concurrentrecruitment of time and frequency domain analyses, named analytical time-frequency approaches,such as Cohen Class and Wavelet transformations, have also been widely applied in this area of research.A number of the relevant principalinvestigationsare as follows.In early 1990sMerletti and colleaguesreporteda number of electromyogram features capable of demonstrating muscular fatigue [13]. Soon after, Davis and his team investigated this phenomenon through analyzing the frequency components of sEMG signal [14]. In 2001, Bonato and his group studied the time-frequency parameters of surface myoelectric signal for assessing muscle fatigue during cyclic isotoniccontractions [15]. In another effort, Merletti, Rainold and Farina evaluated surface electromyography for noninvasive characterization of muscles [16]. This was followed by the work ofAsghariOskoei and his team in 2008,who studied manifestation of fatigue in the myoelectric signals belonging toisotonic contractionscreated in playing PC games [17],and the work done by Subasi and Kiymikin 2009, which focused on the detection of muscle fatigue based on EMG, by utilizing time-frequency methods, ICA and neural networks[18].

Yet, in spite of a huge number of studies whose major efforts were invested on finding the potential electromyogram features capable of properly determining the onset of muscle fatigue,the focus of another group of investigations in this field has been on providing a directquantitative portrayal ofthis phenomenon as a function of time. Nevertheless, their approach has been, again,based on the quantities of the featuresextracted from the recorded sEMG signals. As a case in point, Nielsen and colleagues proposed a quantitative method forisotonic muscle fatigue assessmentusing the values of RMS, mean power frequency and the averaged profile of electromyogram data[19]. Seibt and Schneider described this phenomenon as a function of the instantaneous RMS values and the median frequency of the recorded EMG signals [20]. Moreover, Liu and colleagues proposed a quantitative method forthe evaluation of upper limb muscle fatigue based on repetitive task load conditions by recruiting the values of typical time and frequencydomain signal features[21].

Considering the above achievements, the purpose of this study is,firstly, to assess the capabilityof applying a number of EMG-based time and frequencydomainfatigue indices, including: ARV, RMS, ZC, mean and median frequency,which have been mainly exerted to assess muscular fatigue in isometric contractions, for being applied inthe detection and evaluation of fatigue in isotonicexperiments. In order to achieve this objective, a number of isometric and isotonic contractile protocols for the contraction of two hand muscle groups, Biceps and Deltoid, were devised. Simultaneous with performing the devised exercises by the participant, the sEMG of the target muscles were recorded and processed in order to extract the mentioned features and, comparatively,analyze theirtrends in two modes of muscular contractions: isometric and isotonic modes.

Secondly, the mathematical EMG-based formulaexerted by Seibt and colleagues, was chosen as the representative of the second group of investigations,following a quantitative approach toward the assessment of muscle fatigue. In this phase, the method was applied on the recorded EMG signals,and the resulted fatigue diagrams were plottedand analyzed critically, so that a better portrayal of the advantages and disadvantages of this group of techniques could be achieved.

Methods

Experiment Design:

Two sets of experiments were devised to produce separateisometric and isotonicco-ntractions in two muscle groups:Bicepsand Deltoid. Each experiment required the subject, one healthy man (age: 22 years, weight: 70 kg, height: 177.5 cm), to participate in a series of exercises, in which each of the mentioned muscles underwent different types of contractions against an opposing load of 1.5 kg.In fact, Biceps isometric test required the 90 degree flexion of elbow joint, and Deltoid isometric experiment required the 90 degree abduction of the participant's arm. In addition, the isotonic tests were made up of rhythmic movements performedunder equal temporal intervals;this means,repetitive 90 degree flexion and extension of elbow joint and the periodic 90 degreeabduction andadduction of the subject's arm, respectively for the repetitive isotonic contraction of Biceps and Deltoid muscles.Each of the four tasks was performed to the phase where the subject was no more able to continue his performance and maintain the load in the pre-determined posture. The devised experimentsare depicted from left to rightin Fig. 1,respectively.The postures for performing the isometric contractions are shown in the orange boxes.

Electromyogram Recordings:

Along with performing the mentioned exercises, the surface EMG signalsof the target muscles were recorded usingPowerLAB data acquisition system, with the sampling ratio of 2000 samples per second.Considering the bandwidth of a typical electromyogram (6-500 Hz), whose energy is mainly concentrated between 20 and 150 Hz, the signals were simultaneously filtered with the band-pass filter embedded within the device with the cut-off frequencies of 0.3 and 500 Hz. This was followed by using a 4th order high-pass Butterworth Filter, with the cut-off frequency of 10 Hz, for the removal of motion artefacts and other unwanted signals.

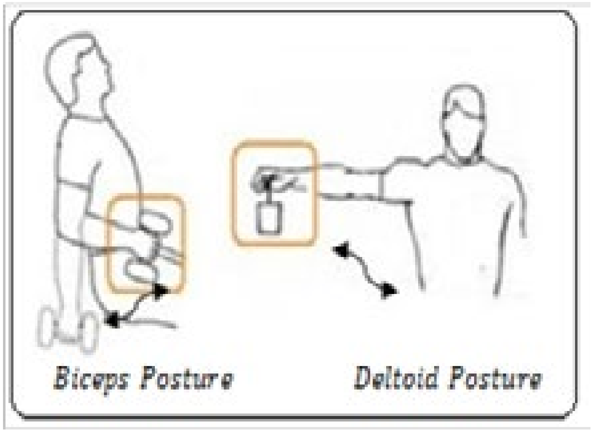

Figure 1: Exercise postures for Deltoid and Biceps muscle in the devised isometric and isotonic muscle contractions.

Signal Processing:

In this step, the high-pass filtered EMG signals belonging to each of the tasks werenormalized and equally divided to sequential data windows. For isotonic tests, however, data window selection process was based on only selecting the intervals in which the target muscles were actively contracting. This means that the low amplitude signals belonging to the muscles' resting periods, inevitably located in the transition phases from abductions/flexions to adductions/extensions and vice versa, were not included. Moreover, the onsets of the repetitive contractions in each of the isotonictaskswere adjusted based on a rhythmic pattern with equal intervals, so that all the contraction periods in a specific task could be of similar length, and consequently, the number of the samplesselected for each of the data windowscouldbe almost equal.

In the next step, the samples inside each data window were processed, and a number of time-based features including: root mean square values, averaged rectified values andthe number of zero crossings, together with mean frequency and median frequency (the frequency where the sum of all power densities below this point is equal to the sum of all power densities above), were extracted for each data section.The mathematical relation used for the estimation of mean frequency values is also described in equation 1. In this equation, "p" refers to power spectral density and "f" represents frequency in Hz.

$$Mean\ Frequency = \frac{sum(f \times p)}{sum(p)} \qquad (1)$$

Next, the features,calculatedseparately for each of the single data windows,were normalized to their maximum values and plotted sequentiallyversus the number of the data sections, so that theoverall trend for each of the indices could be achieved, and the relevant changes could be monitoredover time.

Results

Part One:

The raw EMGsignals are represented in Fig. 2 and 3.

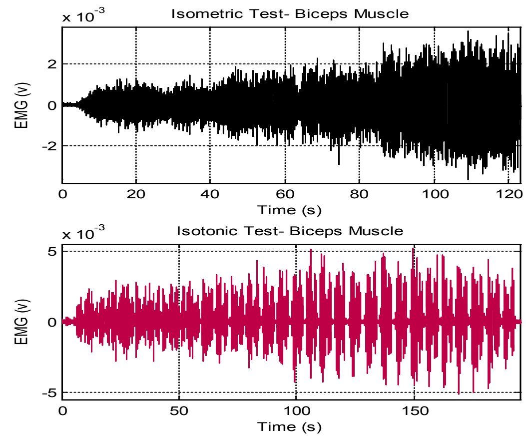

Figure 2: Raw EMG signals forBiceps muscle, recorded from isometric and isotonic contractile experiments.

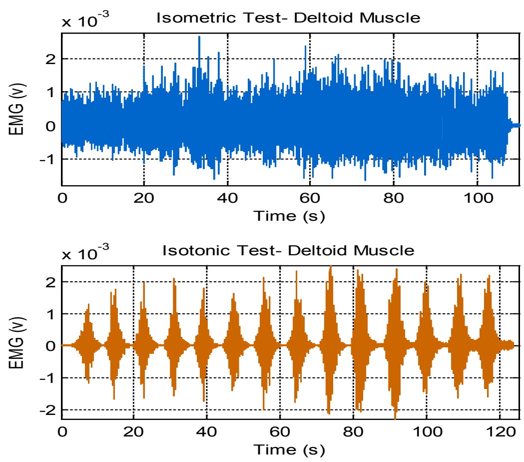

Figure 3: Raw EMG signals for Deltoid muscle, recorded from isometric and isotonic contractile experiments.

Fig. 4-6,display the trends of the fatigue indices extracted from Biceps muscle's electromyogram.As it can be observed, Fig. 4 and 5, belonging to isometric tasks, demonstrate the same diagrams differing from one another just in terms of the length of the windows the recorded sEMGs are devided to. The windows in Fig. 4 comprise1000 samples (0.5 sec) which provides a better representation of the subtle fluctuations, and the windows in Fig. 5 are made up of 12000 samples (6 sec) which provides the possibility of displaying the overall trendsof the features more smoothly. It should be noted that, this type of analysis was not applicable to isotonic tasks, since for this group, the creation of data windows was confined to only selectingthe active periods of the recorded sEMG signals.

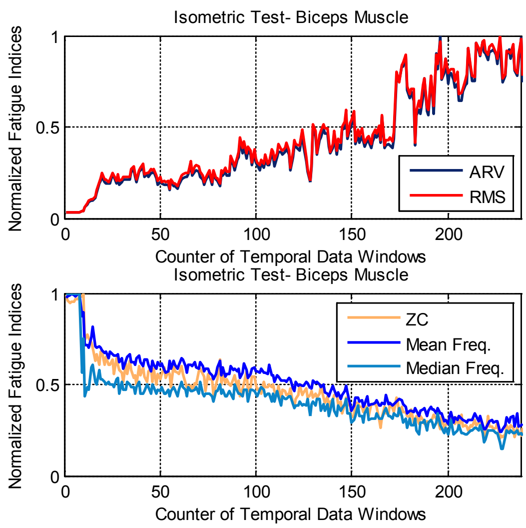

Figure 4: The trends of time and frequency domain indices versus time. Biceps muscle, isometric test, 1000 sample data window.

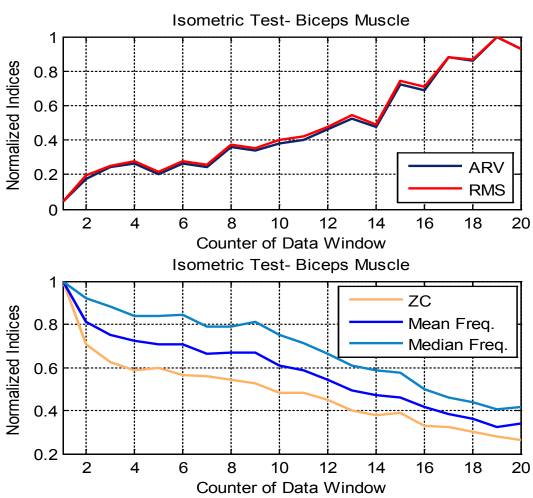

Figure 5: The trends of time and frequency domain indices versus time. Biceps muscle, ismetric test, 12000 sample data window.

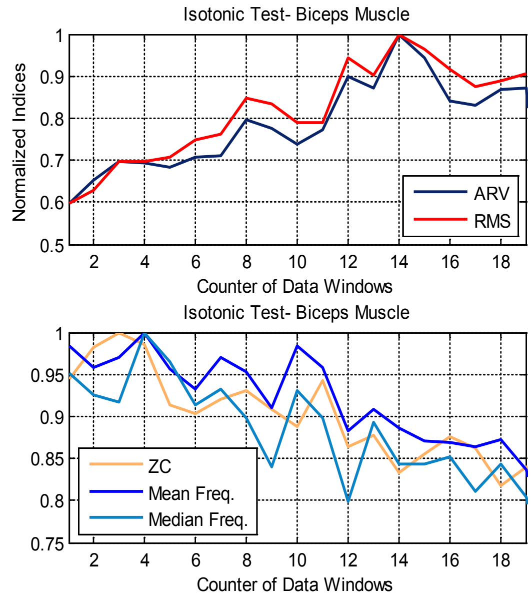

Figure 6: The trends of time and frequency domain indices versus time. Biceps muscle, isotonic test, 12000 sample data window.

Fig. 7-9, show the trends of the mentioned fatigue indices extracted from Deltoid muscle sEMG signalsover time.

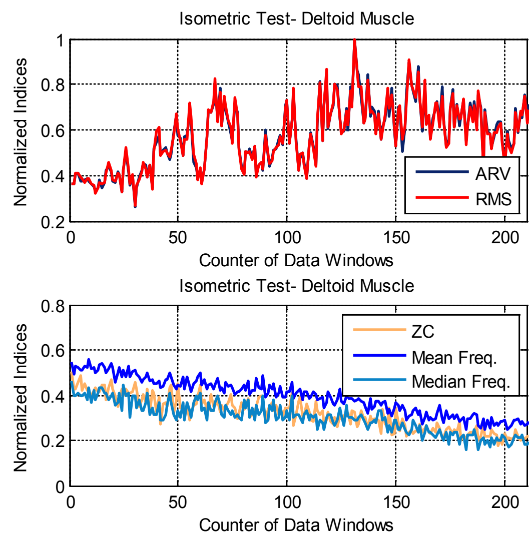

Figure 7: The trends of time and frequency domain indices versus time. Deltoid muscle, isometric test, 1000 sample data window.

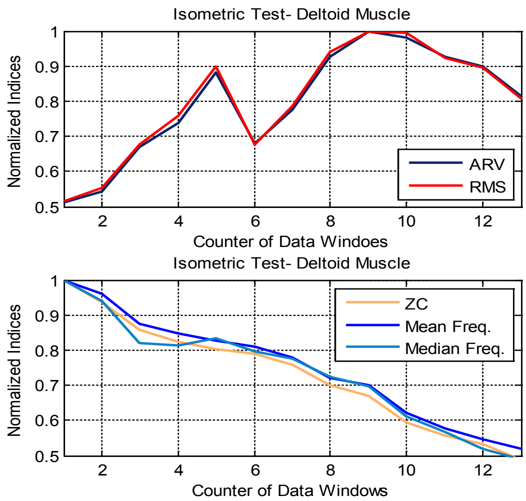

Figure 8: The trends of time and frequency domain indices versus time. Deltoid muscle, isometric test, 16000 sample data window.

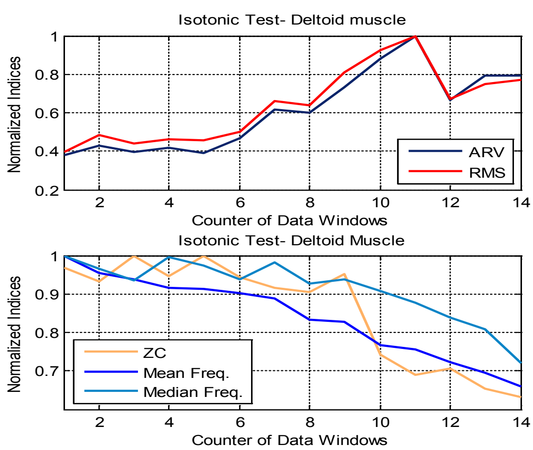

Figure 9: The trends of time and frequency domain indices versus time. Deltoid muscle, isotonictest, 16000 sample data window.

Part Two:

Fig. 10, represents the fatigue diagrams achieved through applying the method utilized by Seibt and colleagues. The formula isillustrated in equation 2.

$$Fatigue = (\frac{EA}{EA_z} - 1) \times (-1) \times (\frac{MF}{MF_z} - 1) \qquad (2)$$

In this equation, EA represents the “Electrical Activity” of musclesand is defined the same as RMS.Additionally, MF stands for “Median Frequency”. EA_z and MF_z are the values of electrical activity and median frequency in non-fatigue state,andare severly subject dependent; in this study, these were initialized by the values of RMS and MF, extracted from one of the initial data windows (one of the first three windows), the state in whichthe subject was not yet experiencing the emergence of muscle fatigue.Furthermore, the reason Biceps muscle’s fatigue diagram has been plotted separately is that, as it can be observed, the range of the relevant fatigue values for this groupsignificantly differ from the three others, and this separation provides a better representations of the quantities.

Conclusion

In this research, firstly, a number of time domain and frequency domain electromyogram-based fatigue indices including: ARV, RMS, ZC, mean and median frequency, were extracted for typicalisometric and isotonic contractile circumstances in two hand muscle groups, Biceps and Deltoid.Figures 4-9 depictthe behaviour of the mentionedfeatures belonging to the devised experiments. Compatible with the previous experimental findings, the values of ARV and RMS, in both target muscles, gradually increased and the number of zero crossings (ZC), progressively decreased as muscle fatigue emerged. Moreover, the frequency components of the sequential data windows in all the experiments were transferred to lower quantities over time.Additionally, precise observation of the trends of the frequency indices,revealed smoother alterations with fewer fluctuations,compared with thetrends of the time domain features; the quality which makes the first group more reliable for being used for the detection of muscle fatigue.Comparing the trends of the extracted time and frequency domain fatigue indices between

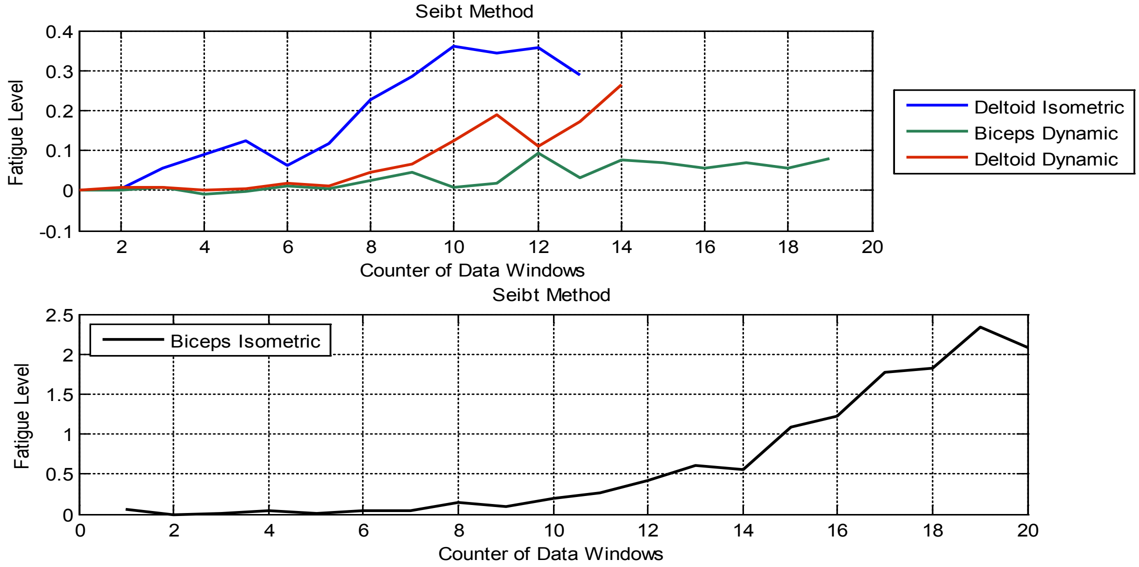

Figure 10: Quantitative fatigue diagrams, based on Seibt and colleagues method, plotted as a function of data windows.

isometric and isotonic muscular contractions also revealed that the features' values in isotonic muscle contractions stood at lower levels in comparison to the isometric ones,since the nature of isotonicexercises provided resting periods in which, the target muscles could approximately recover their lost stamina.

Fig. 10, displays the calculated fatigue values, acquired based on the method utilised by Seibt and colleagues which provides a quantitative perception of muscle fatigue phenomenon. Compatible with the previous section, it can be observed that the values of muscle fatiguein isometric exercises are of larger values and rise more sharply, in comparison to the isotonic experiments. However, it should be noted that the accuracy of such methods, using the instant values of EMG features for the quantitative assessment of muscle fatigue,can be criticized from various aspects. Firstly, there are a wide range of algorithms available for the calculation of sEMG features e.g., RMS and median frequency; the situationwhich might result in considerable differences in the quantities of the calculated values.Moreover, the values of a number of theamplitude-relevant features, such as RMS, are severely influenced by the accuracy and stability of physical circumstances such as electrode placement. Furthermore, utilizing spectrum estimation techniquesentails the data windows to be sufficiently large for obtaining high resolution estimated values;the issue which, inevitably,reduces the total number of data sections. The above facts strengthen the necessity of looking for a quantification method,preferably, with the least dependence on spectrum estimation techniques, which could be capable ofquantitativelyassessing localized muscle fatigue phenomenon from the relevant electromyogramdata.

References

1. Al-Mulla MR, Sepulveda F, Colley M. A review of non-invasive techniques to detect and predict localized muscle fatigue.*Sensors* 2011: 2545-2594.
2. Konrad P. *The ABC of EMG: a practical introduction to kinesiological electromyography.* USA: Noraxon, Inc.; 2005.
3. Herberts P, Kadefors R, Broman H. Arm positioning in manual tasks. An electromyographic study of localized muscle fatigue.*Ergonomics* 1980; **23**:655–665.
4. Outten AG, Roberts SJ, Stokes MJ. Analysis of human muscle activity.*IEE Colloquium on Artificial*

Intelligence Methods for Biomedical Data Processing 1996: 7/1-7/6.

5. Micera S, Sabatini AM, Dario P. An algorithm for detecting the onset of muscle contraction by EMG signal processing. *Medical Engineering and Physics* 2011; **20**: 211-215
6. K. Manal, Gonzalez RV, Lloyd DG, Buchanan TS. *A real-time EMG-driven virtual arm. Computers in Biology and Medicine* 2002; **32**: 25-36.
7. Vollestad NK. Measurement of human muscle fatigue.*Neuroscience Methods* 1997; **74**: 219-227.
8. Potvin JR, Bent LR. A validation of techniques using surface EMG signals from isotonic contractions to quantify muscle fatigue during repetitive tasks. *Electromyography and Kinesiology* 1997; **7**: 131-139.
9. Chen JJ, Yu N, Huang DG, JuMSh, HusehTCh. Muscle fatigue study in FES induces isotonic cycling movement. *IEEE* 1995.
10. Mizrahi J, Levy M, Ring H, Isakov E, Liberson A. EMG as an indicator of isometrically FES-activated paralyzed muscles. IEEE Trans. *On Rehabilitation Engineering* 1994; **2**: 57-65.
11. Buchanan TS, Lloyd DG, Manal K, Besier TF. Neuromusculoskeletal modelling: estimation of muscle forces and joint moments and movements from measurements of neural command.*Applied Biomechanics* 2004; **20**(4).
12. Riener R, Fuhr T, Patient-driven control of FES-sSupported standing up: asimulation study. *IEEE Trans on Rehabilitation Engineering* 1998; **6**: 113 – 124.
13. Merletti R, Lo Conte LR, Orizio C. Indices of muscle fatigue. *Electromyography and Kinesiology* 1991; **1**: 20-33.
14. Davis MR, Reisman SS. Time frequency analysis of electrmyogram during fatigue. *Proc. of 20th Annual Northeast Bioengineering Conference* 1994: 93-95.
15. Bonato P, Roy SH, Knaflitz M, De Luca CJ. Time frequency parameters of the surface myoelectric signal for assessing muscle fatigue during cyclic isotonic contractions. IEEE Trans. *On Biomedical Engineering* 2001; **48**: 745-753.
16. Merletti R, Rainold A, Farina D. Surface electromyography for noninvasive characterization of muscle. *Exercise Sport Science Rev* 2001, **29**: 20–25, 2001.
17. AsghariOskoei M, Hu H, Gan JQ. Manifestation of fatigue in myoelectric signals of isotonic contractions produced during playing PC games. *Proceedings of the 30th annual international IEEE EMBS conference*: 2008: 315–318.
18. Subasi A, Kiymik MK, Muscle fatigue detection in EMG using tie-frequency methods, ICA and neural networks. *Journal of Medical Systems* 2010; **34**: 777-785.
19. Nielsen L, Sinkjaer T. *Quantitative assessment of isotonicmuscle fatigue by electromyographicmeasurements.* Pros. of 7thMeeting of the European Society of Biomechanics; 1990.
20. Seibt R, Shneider J. *A new method for quantification of muscular force and fatigue by using surface electromyographicalmeasurements.*
21. Liu D, Tokarski T, Wojcik K. Quantitative assessment of upper limb muscle fatigue depending on the conditions of repetitive task load. *Journal of Electromyography and Kinesiology* 2004; **14**(6): 671-682.