Quantitative Assessment of Muscle Fatigue for FES Research Studies

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Abstract

Background: Muscle fatigue is an important issue in neuromuscular rehabilitation. Better control of this phenomenon would result in better prevention of its consequent physiological damages.

Objective: To provide a mathematical representation of muscle fatigue as a function of time.

Methods: We conducted this study by combining the EMG-based estimation methods of muscle activation with the available muscle fitness equations describing the electrically evoked muscular contractions. Two groups of experiments were devised to produce a set of isometric and dynamic contractions in two hand muscles—biceps and deltoid—in a healthy man. The relevant surface EMG signals recorded simultaneously from the target muscles, provided the data needed for this process. Secondly, a number of EMG-based fatigue indices including peak to peak amplitude, root mean square values, average rectified values, number of zero crossings and mean frequency, were evaluated for the assessment of fatigue in the devised experiments. The mentioned indices were then, plotted as a function of the calculated fatigue, so that a mathematical representation of their relationship could be achieved.

Results: The results showed an overall increase in fatigue index for both groups of contractions as time passed, and, as was expected, the calculated fatigue in dynamic experiments stood at lower levels, having some fluctuations, in comparison to the isometric ones.

Conclusion: The mathematical relationships between the time and frequency-domain fatigue indices and the proposed index were compatible with the previous experimental observations. These findings could be applied for the assessment and control of muscle fatigue in FES-research studies.

Keywords

Muscle Fatigue; Electromyogram; Quantitative measurement; EMG signal processing; Fatigue index

Introduction

Muscle fatigue can be defined as a reduction in the level of the output force produced by muscles during a sustained activity [1]. The assessment of muscle fatigue has been the basis of numerous studies, especially, in the field of neuromuscular rehabilitation and the applications of functional electrical stimulation (FES) systems. Better understanding of this phenomenon would result in better muscle force production and prevent consequent neuromuscular damages. Numerous research studies have been carried out; they investigated the changes occurring in various features including EMG signals and many qualitative indices of the development of muscle fatigue. These indices include a number of time-domain and frequency-domain fea-

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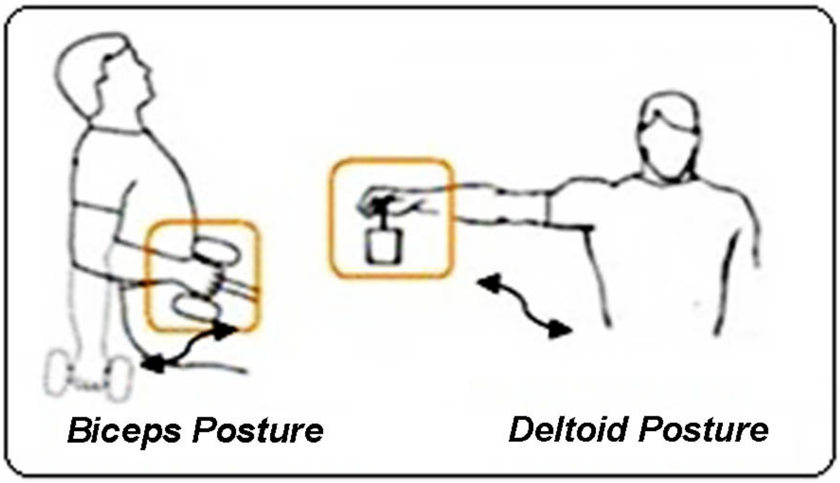

Figure 1: Left to right: the devised exercises for creating isometric and dynamic muscle contractions in biceps and deltoid muscles. The isometric conditions are shown in orange boxes.

tures of EMG signals such as root mean square values, average rectified values, the number of zero crossings, and mean and median frequency. Furthermore, many researchers performed analytical time-frequency approaches (*e.g.*, wavelet transformation) to this issue [2-17]. However, few researches have focused on providing an independent representation of muscle fatigue which would describe the alterations of this phenomenon quantitatively as a function of time. For example, Nielsen and colleagues proposed a quantitative assessment of dynamic muscle fatigue based on EMG [18]; Seibt and Schneider described muscle fatigue as a function of the instantaneous root mean square value and the median frequency of the recorded EMG signals [19]; and, Liu and colleagues proposed a quantitative assessment of the upper extremities muscle fatigue based on the repetitive task load conditions [20].

The first objective of this study was to provide an EMG-based quantitative representation of muscle fatigue as a function of time. This was done by combining the estimation methods of muscle activation with the available muscle fitness equations describing the electrically evoked muscular contractions. Secondly, a number of EMG-based fatigue indices including peak to peak amplitude, root mean square values, average rectified values, the number of zero crossings and mean frequency, were evaluated for the assessment of fatigue in the experiments. In the final step, the above-mentioned indices were plotted as a function of the calculated fatigue index, so that a mathematical representation of their relationship could be provided.

Materials and Methods

Experiment Design

Two sets of experiments were devised to produce a set of isometric and dynamic muscle contractions in two hand muscles—biceps and deltoid. Each experiment required the study subject—a 22-year-old healthy man weighing 70 kg with a height of 177.5 cm—to participate in a series of exercises in which each of the mentioned muscles underwent isometric and dynamic contractions against an opposing load of 1.5 kg.

The devised exercises for the creation of the desired muscle contractions in biceps and deltoid muscles are shown from left to right in Figure 1, respectively. The arm postures for performing the isometric contractions are shown in the orange boxes. Each separate ex-

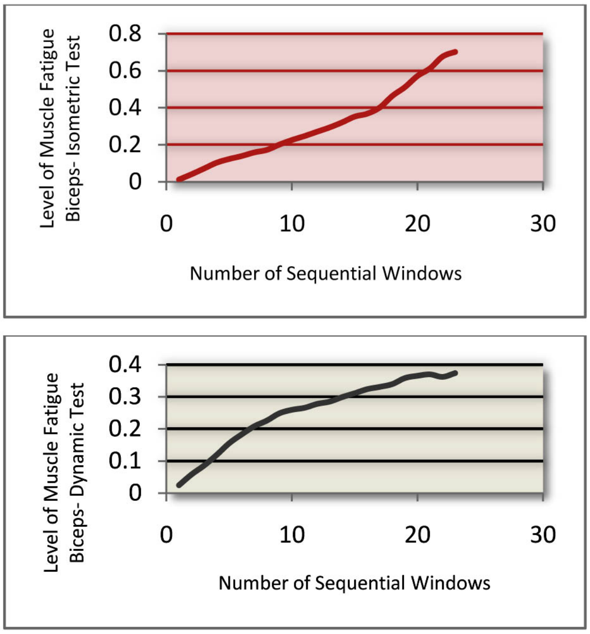

Figure 2: The average fatigue calculated for each of the sequential data windows. The upper diagram shows isometric test for biceps muscle; the lower diagram depicts dynamic test for biceps muscle.

ercise was performed to the point where the subject was not able to continue his performance anymore.

EMG Recordings

During the mentioned exercises, the surface EMG signals of the target muscles were also recorded by a PowerLAB data acquisition system at a rate of 2000 samples per second. Considering the bandwidth of a typical EMG (6–500 Hz) the energy of which is mainly concentrated between 20 and 150 Hz, the signals were simultaneously filtered with an embedded band-pass filter with a cut-off frequencies of 0.3 and 500 Hz. This was followed by using a 4th order high-pass Butterworth filter, with a cut-off frequency of 10 Hz, for the removal of motion artefacts and other unwanted signals.

The Extraction of Muscle Activation from EMG

After the pre-processing steps, each series of signals were rectified, normalized to unity and filtered using a low-pass Butterworth fil-

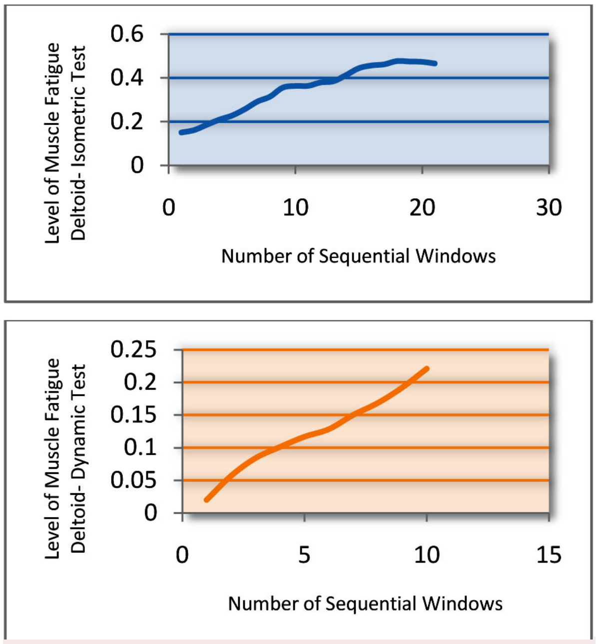

Figure 3: The average fatigue calculated for each of the sequential data windows. The upper diagram shows isometric test for deltoid muscle; the lower diagram depicts dynamic test for deltoid muscle.

ter with a cut-off frequency of 4 Hz. At this point—one step before achieving the neural activation parameter of the muscles—the signal was designated as *e(t)*.

When a muscle fiber is stimulated by an action potential, a spastic response the so-called “twitch” is produced which can be estimated by a second order differential equation. This would be the basis for the formation of the following relationship between the neural activation parameter, *u(t)*, and *e(t)*, proposed by Rabiner and Gold in 1975 (equ 1):

$$u(t) = \alpha \times e(t-d) - \beta_1 \times u(t-1) - \beta_2 \times u(t-2) \qquad (1)$$

where, *d*, is the electromechanical time delay and α, β_1 and β_2 are the coefficients defining the second order dynamics of this relationship and should satisfy the following constraints for achieving a stable equation.

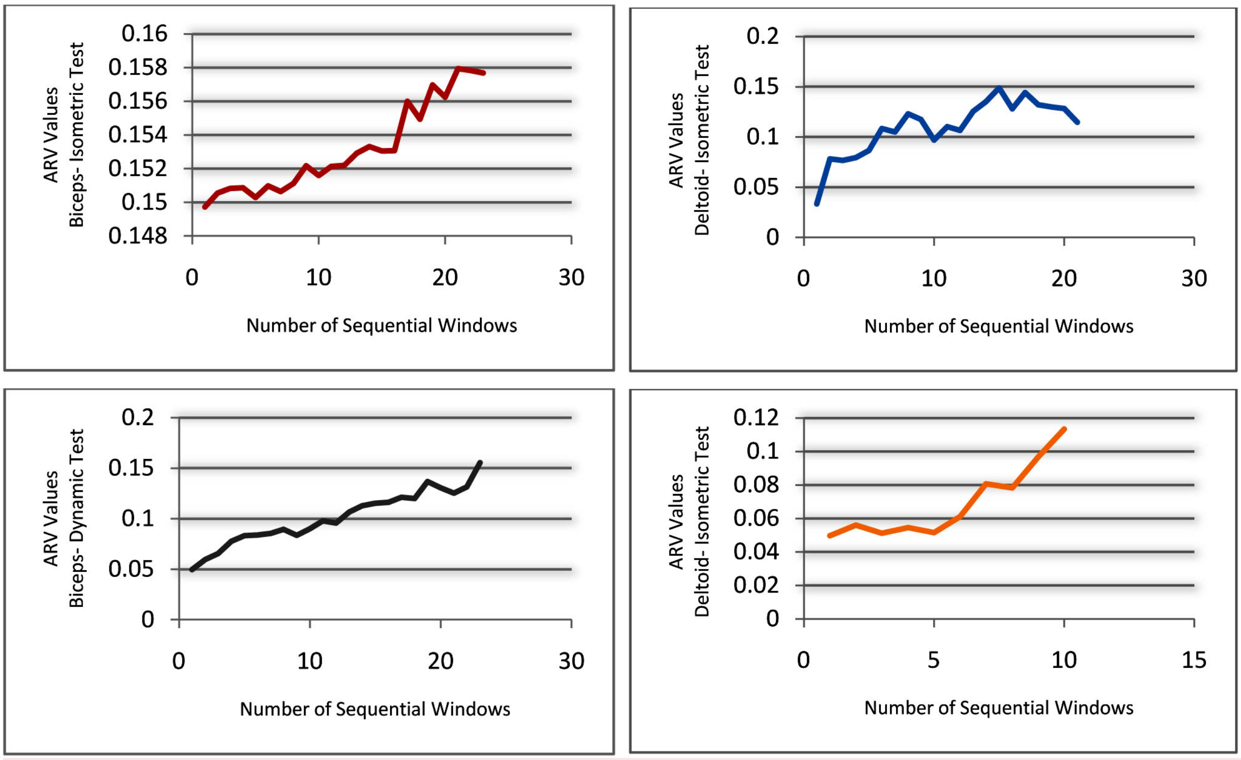

Figure 4: The changes in ARV index in the sequential data windows based on the recorded EMG signals. From top to bottom: isometric test for biceps muscle; dynamic test for biceps muscle; isometric test for deltoid muscle; and dynamic test for deltoid muscle.

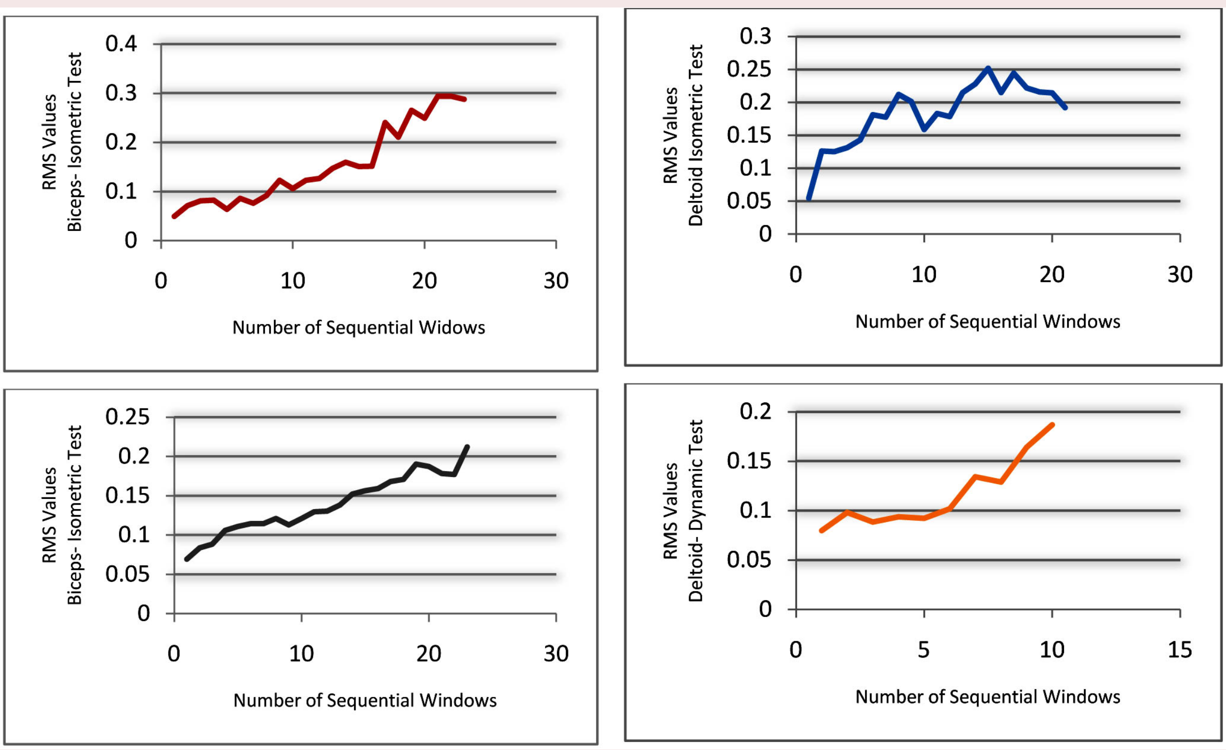

Figure 5: The changes in RMS values in the sequential data windows based on the recorded EMG signals. From top to bottom: isometric test for biceps muscle; dynamic test for biceps muscle; isometric test for deltoid muscle; and dynamic test for deltoid muscle.

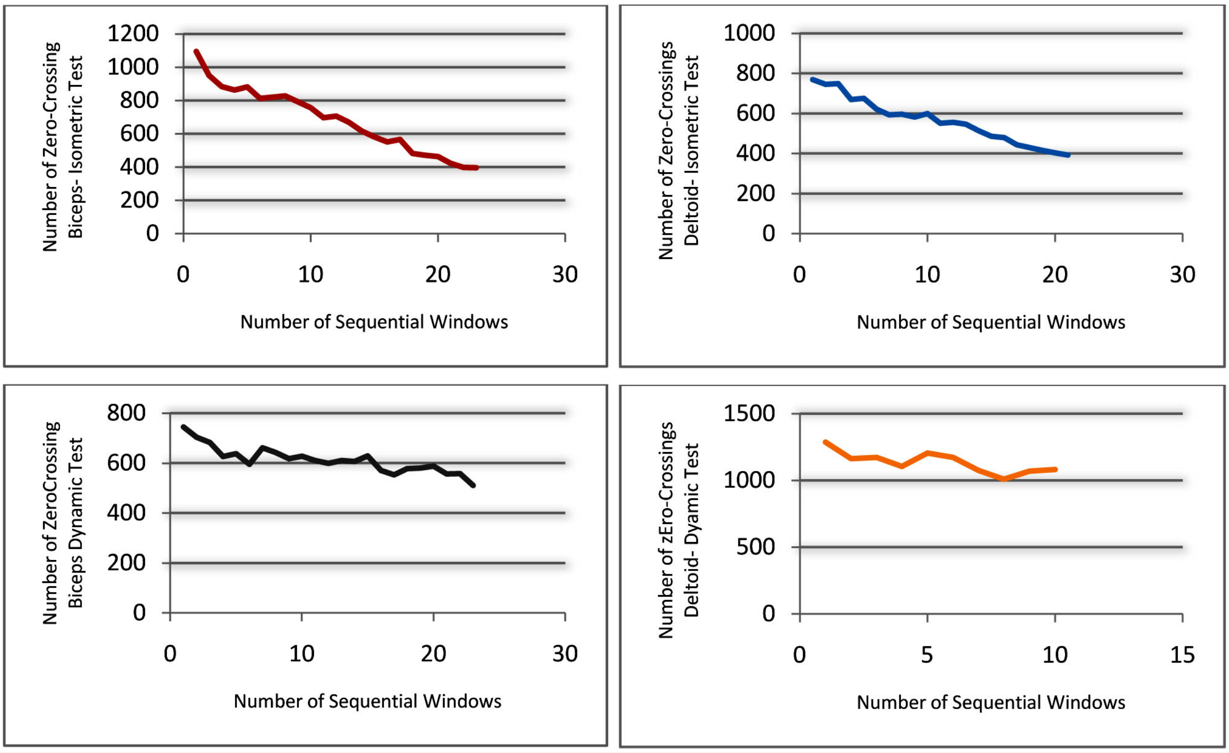

Figure 6: The changes in the number of zero-crossings in the sequential data windows based on the recorded EMG signals. From top to bottom: isometric test for biceps muscle; dynamic test for biceps muscle; isometric test for deltoid muscle; and dynamic test for deltoid muscle.

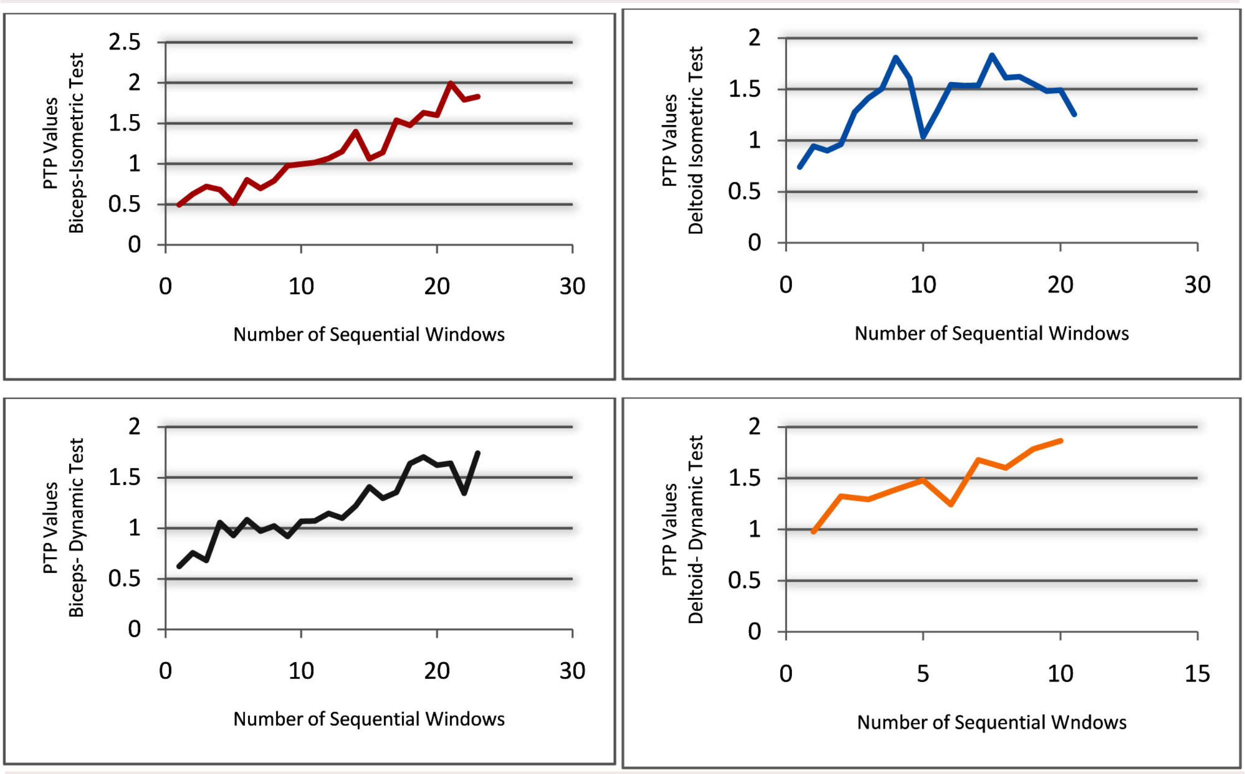

Figure 7: The changes of PTP index in the sequential data windows based on the recorded EMG signals. From top to bottom: isometric test for biceps muscle; dynamic test for biceps muscle; isometric test for deltoid muscle; and dynamic test for deltoid muscle.

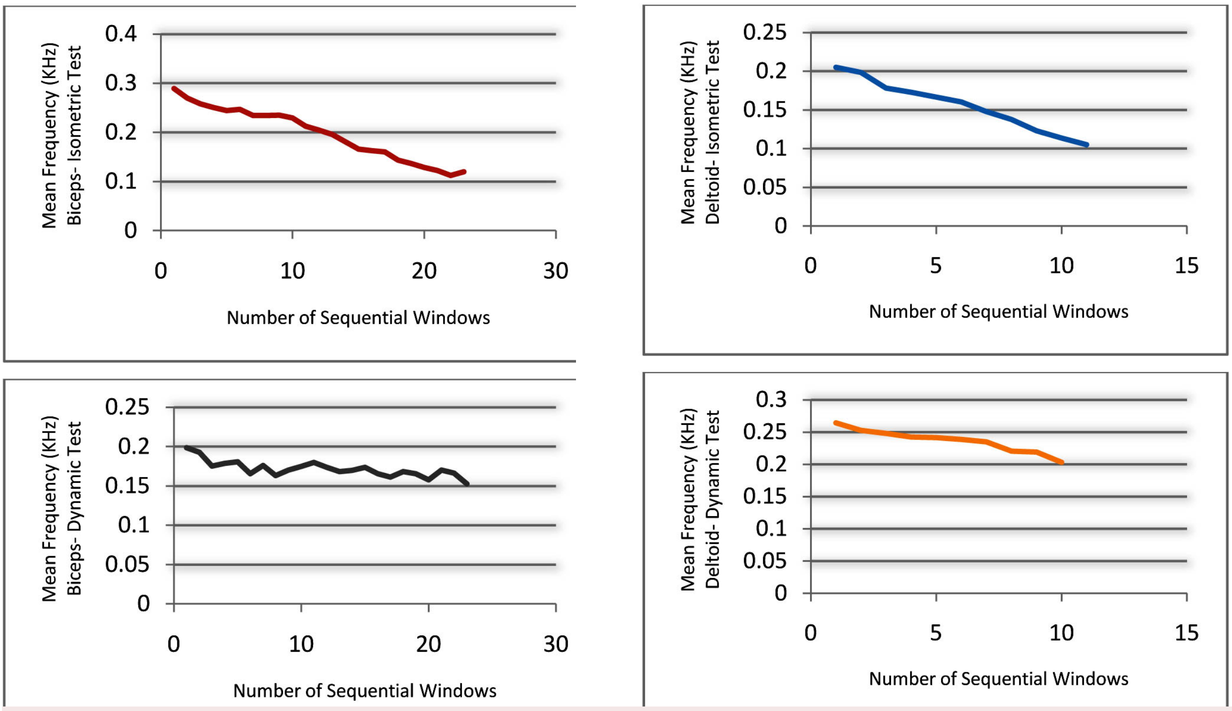

Figure 8: The changes in mean frequency in the sequential data windows based on the recorded EMG signals. From top to bottom: isometric test for biceps muscle; dynamic test for biceps muscle; isometric test for deltoid muscle; and dynamic test for deltoid muscle.

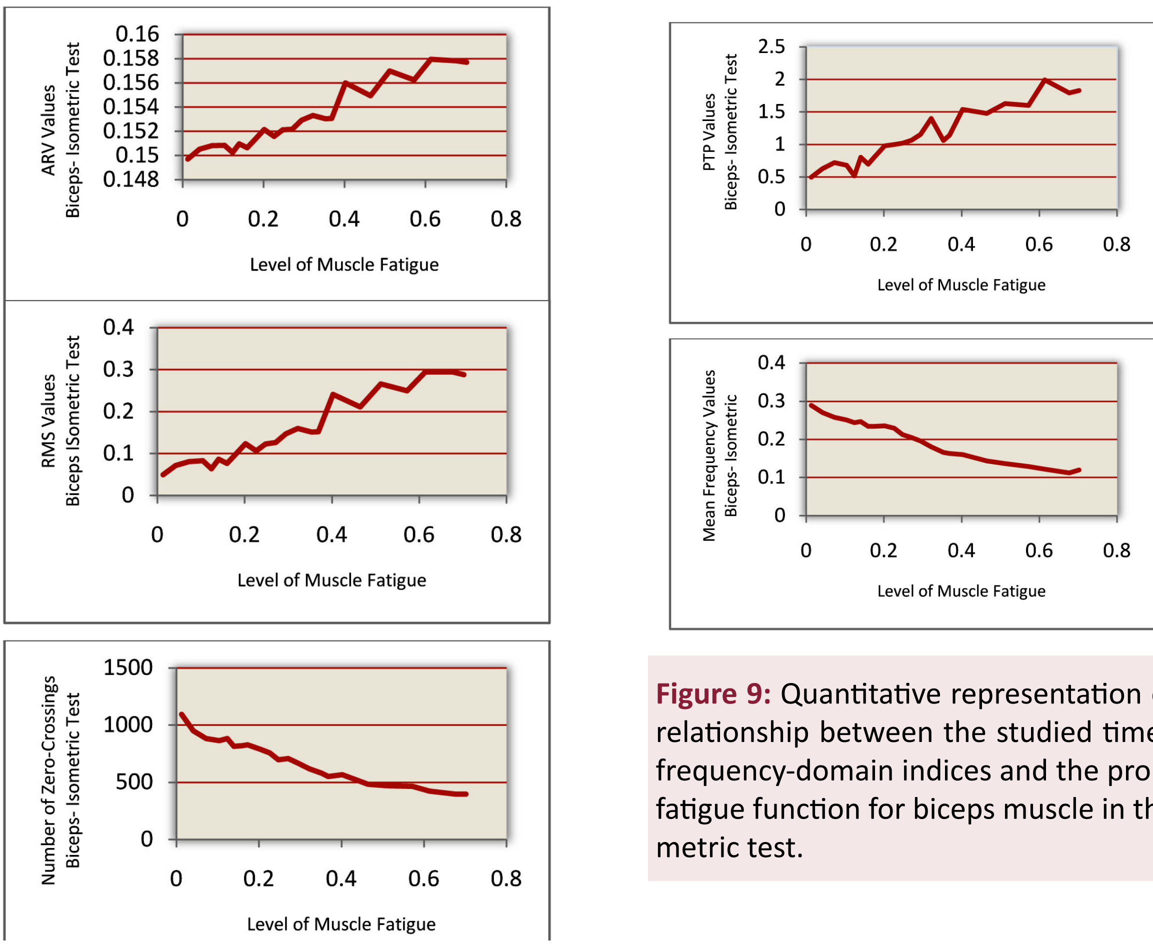

Figure 9: Quantitative representation of the relationship between the studied time- and frequency-domain indices and the proposed fatigue function for biceps muscle in the isometric test.

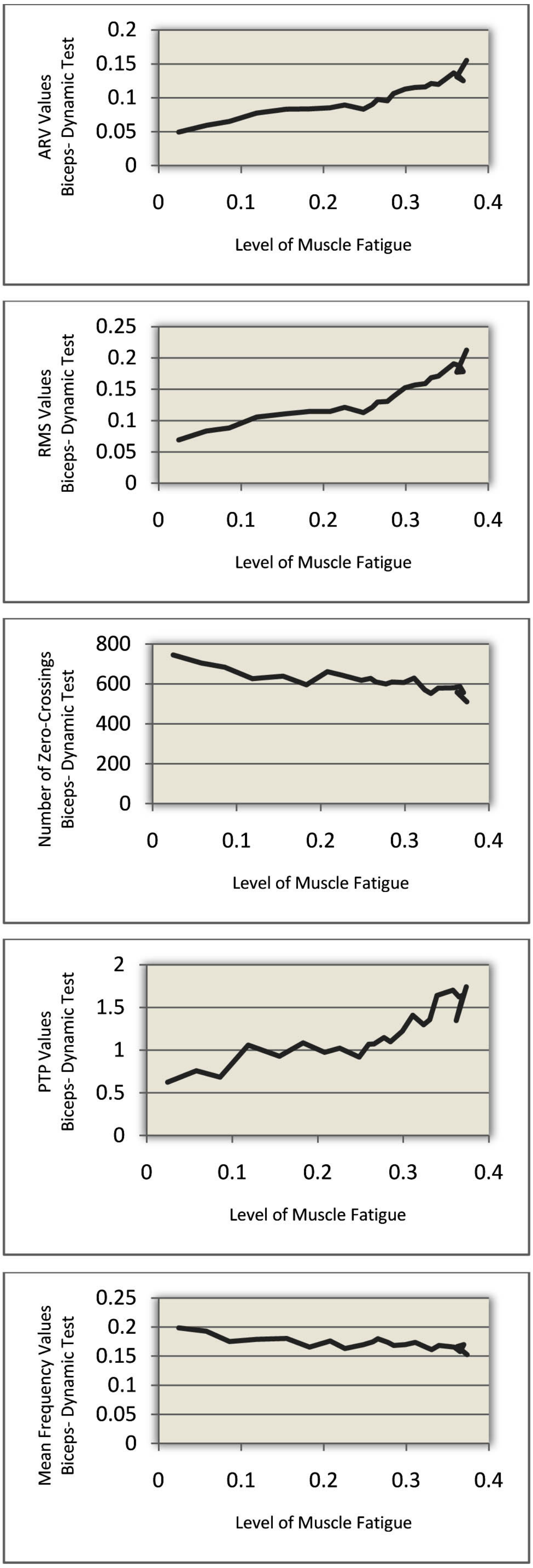

Figure 10: Quantitative representation of the relationship between the studied time- and frequency-domain indices and the proposed fatigue function for biceps muscle in the dynamic test.

$$\beta_1 = \gamma_1 + \gamma_2$$
$$\beta_2 = \gamma_1 \times \gamma_2$$
$$|\gamma_1| < 1$$
$$|\gamma_2| < 1$$

Equation 1 can also be interpreted as a recursive filter whose current value is dependent on the current EMG data and the last two values of *u(t)*. Moreover, in order to avoid the neural activation values to exceed the maximum of one, the following equation should also be satisfied:

$$\alpha - \beta_1 - \beta_2 = 1$$

Although a group of researchers believe that *u(t)* would provide a suitable estimation of muscle activation (a_m), a more precise representation of this parameter could be achieved using the following equation, in which A defines the degree of non-linearity between a_m and u that is adjusted between 3 and 0 [21].

$$a_m(t) = \frac{e^{Au(t)} - 1}{e^{A} - 1}$$

The Relation between Muscle Activation and Muscle Fatigue

In this research, the model used by Riener and colleagues [22] for the estimation of muscle fitness in electrically evoked muscle contractions has been recruited as the main core for estimation of muscle fatigue from the calculated muscle activation. The model is described in the following equations.

$$\frac{dfit}{dt} = \frac{\left(fit_{\min} - fit(t)\right) a(t) \times \lambda}{\tau_{fat}} + \frac{(1 - fit) \times (1 - \lambda a)}{\tau_{rec}}$$

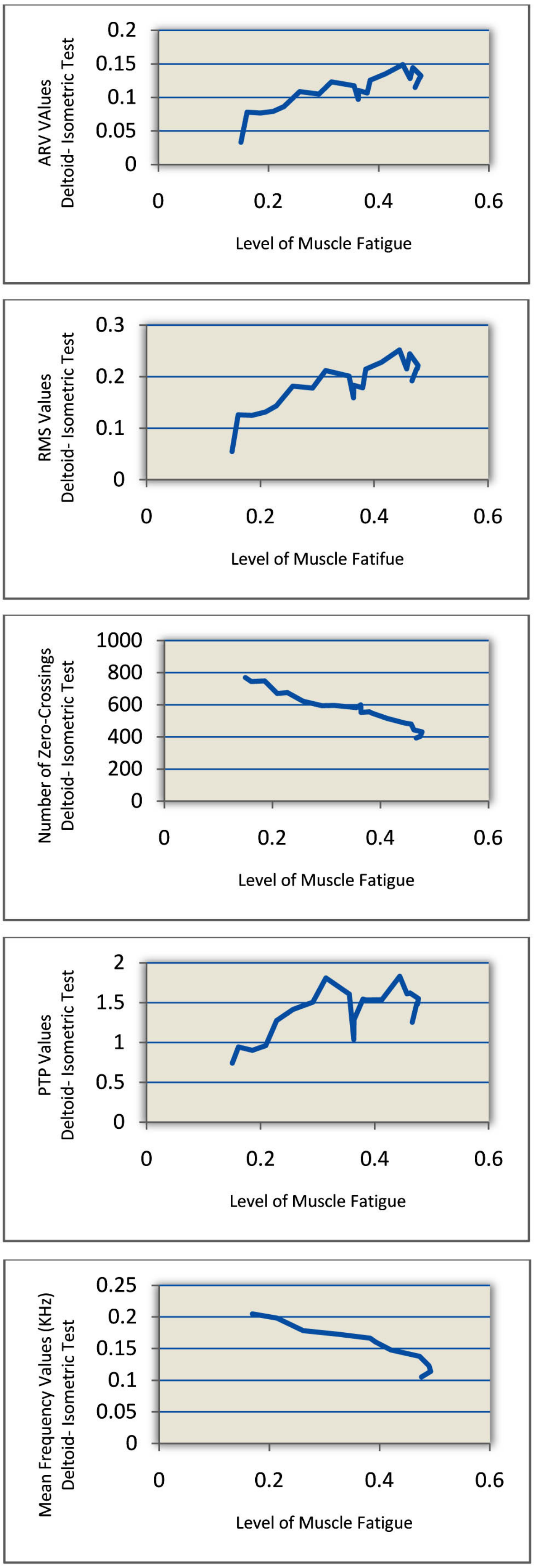

Figure 11: Quantitative representation of the relationship between the studied time- and frequency-domain indices and the proposed fatigue function for deltoid muscle in the isometric test.

where, $\tau_{rec} = \tau_{fat}$ and fit_{min} represent the recovery time constant, the fatiguing time constant, and the minimum fitness of the target muscles, respectively, and

$$a_m(t) = a(t) \times fit(t)$$

$$\lambda = 1 - \beta + \beta\left(\frac{f}{100}\right)^2$$

Solving the above-mentioned system of differential equation by applying the muscle activation values estimated in the previous steps, muscle fitness can be calculated as a function of time. However, in order to combine the Riener's equations, which have been proposed for the estimation of muscle fatigue in the contractions evoked by electrical stimulation, with the previous estimations of muscle activation, which were carried out based on voluntary muscle contractions, the parameter λ should be set to one, so that the effects of the artificial electrical stimulation could be omitted. Finally, the muscle fatigue can be defined as $1 - fit(t)$

The Evaluation of EMG-Based Time-Domain and Frequency-Domain Muscle Fatigue Indices

In a parallel analysis, the normalized high-pass filtered EMG signals belonging to each of the target muscles were divided into sequential data windows. Then, the signals inside each data window were processed and a number of time-based features including peak to peak amplitude of the recorded EMG signal (PTP), root mean square value (RMS), average rectified value (ARV), and the number of zero crossings, plus a frequency-based feature—mean frequencies—were measured for every single window. Then, the overall trend

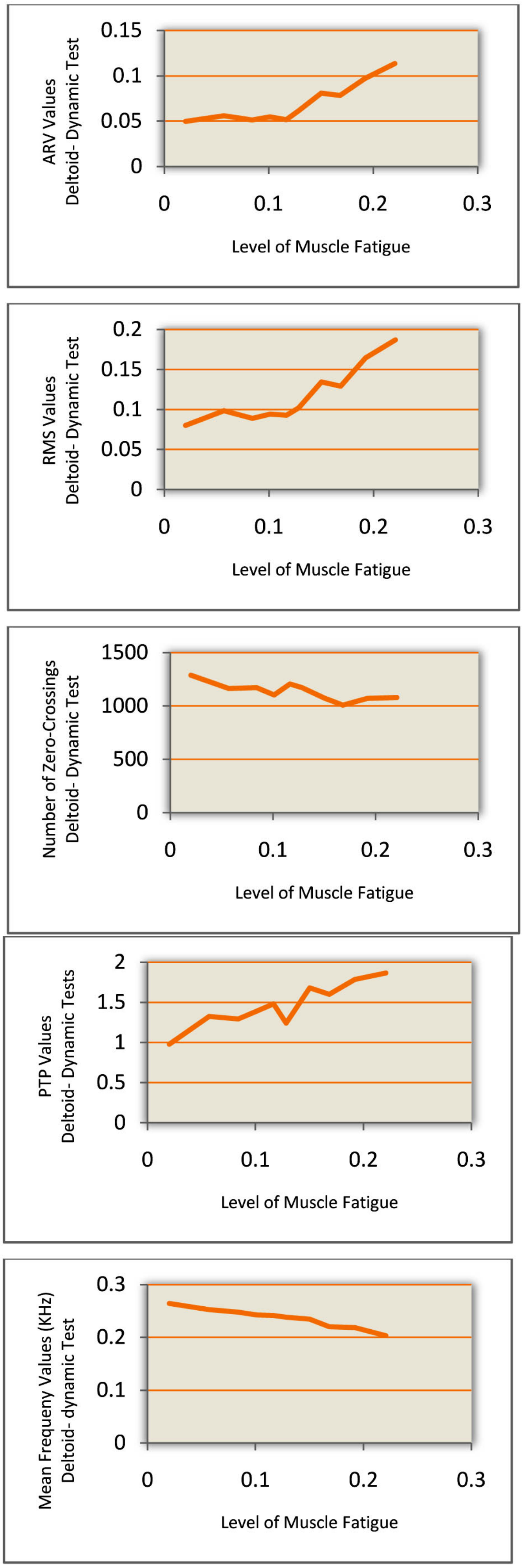

Figure 12: Quantitative representation of the relationship between the studied time- and frequency-domain indices and the proposed fatigue function for deltoid muscle in the dynamic test.

for each feature in the sequential widows was plotted so that the relevant changes could be analyzed over time. Finally, each of the mentioned indices was plotted as a function of the proposed muscle fatigue index and its behavior was observed and analyzed over time.

Results

The fatigue index calculated for each of the contractions is shown in Figures 2 and 3.

The studied time-domain and frequency-domain indices of muscle fatigue plotted for the sequential data windows, are shown in Figures 4 to 8.

Figures 9 to 12 show the relationship between the studied time-domain and frequency-domain indices and the calculated fatigue index.

Discussion

Muscle fatigue rose quantitatively as a function of time in all experiments (Figs. 1 and 2). As was expected, the values of the calculated fatigue index remained at lower levels in dynamic muscle contractions in comparison to isometric contractions, because dynamic exercises provided resting periods, during which, target muscles could approximately recover their lost stamina. Figures 3 to 8 show the behaviour of a number of EMG-based time- and frequency-domain fatigue indices as a function of time, during the devised exercises. As was proven in the previous experimental studies, the values of ARV, RMS and PTP indices increased gradually and the number of zero-crossings decreased in both groups of contractions as muscle fatigue emerged. Moreover, the frequency components of the sequential data windows moved toward the lower values over time in all experiments. Figures 9 to 12 provide a mathematical representation of the relationship between the studied fatigue indices and the quantitatively measured fatigue index. This provides the opportunity to monitor the behavior of the studied indices during muscle fatigue, not only by experimentally observing the consequent muscular symptoms of muscle fatigue, but also by quantitative measurement of the produced muscle fatigue over time.

In conclusion, we proposed a method for quantitative measurement of muscle fatigue by combining EMG-based signal processing methods. The results of this study can be used in FES research studies and control of muscle fatigue in FES-based rehabilitation systems to avoid the consequent effects of muscle fatigue especially in patients with spinal cord injury.

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