Effects of Very Short Pauses on Electromyographic Variables Measured During Fatiguing Isometric Contractions

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Abstract— **15 healthy men (26.6 ± 4.6 years old, weight of 70.7 ± 8.6 kg, and height of 1.750 ± 0.072 m) performed three 30-seconds isometric contractions at 60% MVC, with two 10-seconds resting intervals between them. The goal was to study the effect of the resting intervals on the variables that are most commonly used to analyze surface electromyographic (S-EMG) signals (conduction velocity [CV], root mean square [RMS], average rectified value [ARV], mean power frequency [MNF], and median power frequency [MDF]). For the first 30-second contraction, the S-EMG variables behaved exactly like described in the literature. However, after the first and second pauses, the CV variable ceased to behave like in the literature. In the first contraction, the conduction velocity had a statistically significant decreasing trend, in the second contraction, it had a statistically non-significant positive trend, and, in the third contraction, a statistically significant positive trend. These results suggest that short pauses between isometric constant-force contractions lead to changes in the recruiting strategies of the muscles involved in the contraction. The causes of these changes are not yet clear, and further work is needed in order to understand this effect.**

I. INTRODUCTION

Surface electromyography is commonly used to evaluate muscle behavior due its safety and its non-invasive characteristics [1,2]. A common application of surface electromyographic (S-EMG) signals is in the study of muscle fatigue in different conditions. In some studies, S-EMG signals are measured on a muscle that performs isometric or other kinds of contractions, and these signals are used to calculate different electromyographic variables that estimate amplitude, displacement of spectral content and conduction velocity (CV) of motor unit action potentials (MUAP's). These variables can be used to assess the difference in muscle behavior in different conditions. In some applications [3,4], muscle isometric contractions with constant force and same type of contraction protocols are repeated at different moments or conditions, and the behavior of the S-EMG variables are compared. In some of these experiments [4,5,6,7], the S-EMG is measured with an interval of a few days, so that there can be a full recovery of the muscles. In some works [4,8,9], the contractions are performed with much smaller intervals. In these kinds of studies, it would be important to know how these variables behave after smaller intervals, in controlled conditions. In fact, some articles have pointed out that S-EMG variables have the tendency to return to their initial state after some time [4,8,9].

The goal of this work is to study the behavior of electromyographic variables after small rest intervals. In order to do so, the behavior of the S-EMG variables during 3 successive 30-second contractions with intervals of 10 seconds between contractions were analyzed. This study is a first step in an ongoing effort to study how the recovery of the S-EMG variables behaves as a function of time.

The *biceps brachialis* muscle is one of the most commonly used muscles in fatigue studies, because it is a large superficial muscle and it has convenient morphologic characteristics [10]. Due to these characteristics, this muscle has been chosen for this study. The goal of the current work is to study the behavior of the following S-EMG variables: average rectified value (ARV), root mean square value (RMS), mean power frequency (MNF), median power frequency (MDF), and average conduction velocity (CV) of the MUAP's. In this study, the subjects performed three successive 30-seconds contractions, with 10 seconds intervals between them. The S-EMG signal was measured, the electromyographic variables under study were calculated, and the following hypotheses are tested: (i) the mean of the slopes of the ARV and RMS variables are positive for the three successive contractions; (ii) the mean of the slopes of the MNF, MDF and CV variables are negative for the three consecutive contractions.

II. MATERIALS AND METHODS

A. Subjects

The study involved 15 healthy men (26.6 ± 4.6 years old, weight of 70.7 ± 8.6 kg, and height of 1.750 ± 0.072 m); the subjects presented mean arm circumference of 29.3 ± 3.2 cm with the arm relaxed and 30.8 ± 3.1 cm with the arm under contraction. The experimental protocol was conducted at the Digital Signal Processing Laboratory of the University of Brasília (UnB). All the volunteers were not engaged in regular physical exercise, did not present any symptoms of neuromuscular disorders or ligament problems, and were not using anti-inflammatory medication or muscle relaxants during the sessions.

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B. *Experimental Protocol*

The experimental protocol has been approved by the Ethics Research Committee of the Medical School of the University of Brasilia (process no. 029/2011). The experimental procedure was explained to every subject, and every subject signed an informed consent form.

In the experimental procedure, each volunteer seated in front of the equipment with the elbow rested on a support. The arm was positioned with an elbow angle of 90°, with the forearm in supine position, as shown in Figure 1 [4, 11,12]. With the fingers flexed, the subject held an anatomic handgrip coupled to a load cell by a steel cable, and the load cell was connected to a point on the floor by another steel cable. The force was monitored by the load cell (TS model, manufactured by AEPH, São Paulo, Brazil) with a maximum load of 50 Kgf. The signal from the load cell was amplified by a differential amplifier, and the analog signal was converted to the digital form by a 12-bit analog-to-digital converter integrated in a MISO II biomechanical signal amplifier (OT Bioelettronica, Turin, Italy). The software that controls the MISO II (OT Bioelettronica, Turin, Italy) controlled the acquisition of the force signal and provided visual feedback for the subject. The software allowed, in a first stage, to acquire the maximum voluntary contraction (MVC), and, in the following stage, the acquisition of force and the provision of a visual feedback system with a target force and the actual force being exerted by the subject.

In the experiment, the subject would seat as shown in Figure 1, and, on command, would perform an isometric contraction, trying to match a target force. In the first stage of the experiment, the MVC of the subject is determined. The subject is positioned on the chair, and instructed to exert, on command, the maximum force he can. The experimenter starts the program and provides verbal encouragement to reach the maximum force, for a period of 5 seconds, and, after 5 seconds, the maximum force is recorded. This procedure is repeated 3 times, and the highest of the 3 forces is recorded as the MVC for the subject.

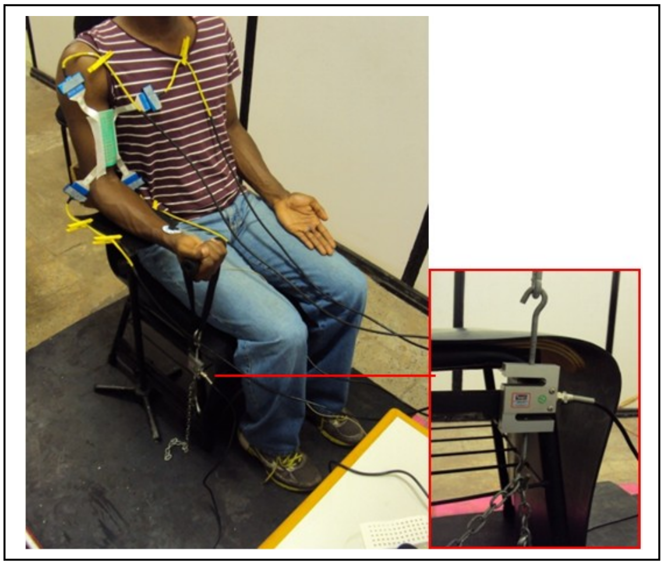

Figure 1. Subject position in the experimental protocol

In the second stage, the subject is also positioned as shown in Figure 1, and a force target with 60% of the intensity of the MVC is presented to the subject. The acquisition software is started, and the subject tries to match the target, aided by a visual feedback tool. The isometric contraction has a duration of 30 seconds, and is followed by a 10 seconds rest pause. Three contractions were performed, with two 10 seconds pauses between them. Electromyographic signals were recorded during the whole process, as described in the next subsection.

C. *Electromyhographic Signal Aquisition*

EMG signals were acquired using a matrix of Ag/AgCl electrodes with adhesive tapes for electrode fixation in the skin (OT Bioelettronica, Turin Italy). The matrix contains 64 electrodes disposed in 4 lines with 13 electrodes and 1 line with 12 electrodes, resulting in a 5x13 matrix in which the position (1,1) is missing, due to the 12 electrode column. The interelectrode distance was 8 mm. Surface matrix electrodes were applied following appropriate skin preparation to reduce skin impedance, the skin was cleaned with water and soup without trichotomy. The matrix was placed on the biceps brachii muscle, aligned with the direction of the muscle fibers, following SENIAM recommendations [13]. After placement, the ring electrodes were filled with conductive electrolitic gel (Mercur, Santa Cruz do Sul, Brazil).

EMG-S signals were acquired using an EMG-128 data acquisition system (OT Bioelettronica, Turin Italy). The sampling frequency used was 2048 Hz, the band-pass filter was set to 10–500 Hz, and the amplification gain was 2000. The signal-to-noise ratio was measured without load to verify the quality of the measured signal. The recorded signals were saved on a computer and transferred to dedicated software packages for off-line processing and analysis.

D. *EMG signal processing*

Segmentation of the raw signal was performed using the OT Biolab software. The segmented signals were processed in the Matlab 2008 environment (Mathworks Inc., South Natick, MA, USA), using a set of tools developed at the University of Brasilia [3,14], in which the MDF, MNF, RMS, ARV and CV variables were estimated and plotted against time. The power spectrum was calculated using a 1-second Hamming sliding window. For the MDF, MNF, RMS and ARV, windows with 0.5-second overlap were used. The CV was estimated, for each signal epoch, with 50 evenly spaced CV points.

For each subject, one linear triplet with the best possible quality (smallest signal to noise ratio, within the physiological range from 4 to 6 m/s, and with highest correlation – preferably above 70%) has been chosen. From these signals, the estimations from the RMS, ARV MDF, MNF e CV were calculated. When the estimators of each variable are plotted against time, typically, the curve can be divided in three segments with approximate linear behavior. In the processing stage, these three segments are cut and the three best fitting straight lines for these segments are determined. After that, the amplitude at the beginning of the first straight line (y-intercept) is calculated, and the whole curve is divided by this value, so that the whole curve is normalized in such a way that the initial amplitude of the first best-fitting line is 1. Two examples of normalized results are shown in Figure 2.

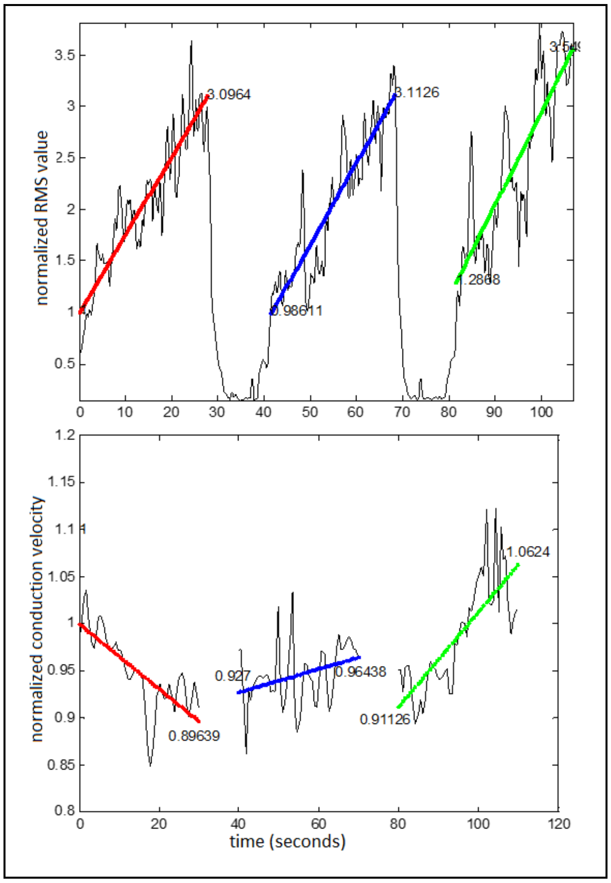

Figure 2. Plots with examples of the obtained curves. Upper plot: normalized CV curve; lower plot: normalized RMS curve. Similar plots were obtained for the ARV, MNF and MDF variables.

The following data were extracted from each figure: the initial magnitude of each of the 3 best fittings straight lines (I_1, I_2, and I_3), and the final magnitude of each of the 3 straight lines (F_1, F_2, and F_3) (these values are shown in the examples in figure 1). These parameters, together with the initial and final moments of the straight lines, were used to calculate the slopes (m_1, m_3, and m_3) of each best-fitting straight line.

E. *Statistical analysis*

The goal of this work was to study how these variables behave during the isometric contraction, and mainly, how the 10 seconds pauses affect these variables. The main analysis intended to check the signs (positive or negative) of the slopes for each variable, for each of the 3 contractions. From literature, it is expected that the slopes for the ARV and RMS variables tend to have positive slopes, and that MNF, MDF and CV tend to have negative slopes. To check these properties, each set of slopes of the three successive curves, for each variable, are compared with a zero mean. To do so, first a normality test (Lilliefors test, performed with Matlab) was performed, the t-test was used if the data set was found to be Gaussian and the Wilcoxon test was used if the data set was found to be non-Gaussian.

III. RESULTS

23 subjects have been evaluated. However, some subjects have been excluded due the following reasons: i) three of the signals had a bad signal to noise ratio; ii) two subjects were not able to follow the target MVC during the test; iii) three other subjects were classified as trained. Consequently, 15 subjects composed the sample.

Table I shows the mean values of the normalized slopes of the three isometric contractions. The numbers between parentheses indicate the p-value. The threshold adopted to indicate statistical significant was $p<0.05$.

TABLE I. RESULTS

variable	**average value of the variable (p-variable)**		
	m_1	m_1	m_3
CV	-0.00145 (0.0103)	0.00097 (0.1822)	0.00383 (0.0479)
RMS	0.031747 (0.0108)	0.09602 (0.0020)	0.04688 (0.0037)
ARV	0.03244 (0.0084)	0.09701 (0.0020)	0.04779 (0.0034)
MNF	-0.00672 (<0.0001)	-0.00311 (0.0002)	-0.00575 (0.0017)
MDF	-0.00586 (<0.0001)	-0.0033 (0.0001)	-0.00651 (0.0013)

The mean values of the normalized variables are shown outside the parentheses. Each variable has been compared with the zero mean, and the numbers between parentheses indicate the p-value.

IV. DISCUSSION AND CONCLUSION

The results shown in Table I indicate significant values of p for several variables ($p<0.05$). This finding was expected, since results from previous works in the specialized literature predict it [7,8,9]. For example, for the first slopes, m_1, many works in the literature report that this slope tend to be, in untrained subjects, negative for CV, MDF, and MNF, and positive for ARV and RMS. The results in the first column of table corroborate this expectation: the signs of the mean values are compatible to the ones found in the literature, and the results are all statistically significant. Consequently, for the first contraction, the results were in total agreement with the literature.

For the second and third contractions it is not possible to compare the results with those of other works in the literature because, to our knowledge, no other work performed this kind of study. However, it is reasonable to expect that the second and third contractions could have a behavior that is similar to the behavior of the first contraction. In the following paragraphs, we will analyze if the second and third contractions behaved similarly to the single contraction experiments in other works.

For the second and third contractions, some of the results were also compatible with the single contraction experiments in the literature: the slopes of the ARV and RMS variables were positive and statistically significant, and the slopes of the MNF and MDF values were negative and statistically significant.

However, for the CV variable, the behavior of the second and third contractions changed in an unexpected way. While for the first contraction the mean value of the slope was negative and statistically significant, for the second contraction, the mean value of the slope was positive, but not significant (p=0.18), and, for the third contraction, the mean was positive and statistically significant (p=0.048). An additional information clarifies this behavior: for the first contraction, 13 out of the 15 contractions had negative slope; for the second contraction, 9 out of 15 had positive slope; for the third contraction, 11 out of 15 had positive slope. These results suggest that these 10-seconds pauses after a substantial fatiguing activity cause changes in the recruiting pattern of the muscle. At this point, it is difficult to explain this behavior. However, it is possible to make hypotheses that may be used to guide future research, and this is done in the following paragraphs.

The results for the second and the third contractions were somehow unexpected. We thought of possible explanations for this behavior. In the beginning of the work, we implicitly took two assumptions for granted: (i) in the contraction, the dominant muscle is the biceps brachialis, and the antagonist and auxiliary muscles have little influence in the process; (ii) the pause does not cause any change in the recruiting strategy of the muscle. However, it is possible that, in a biceps contraction, there is co-contraction of other muscles, such as the triceps brachialis. If a co-contraction happens, it is possible that the biceps brachialis have to exert a stronger force than in a contraction with no co-contraction. If this happens, it is well known that the increase in force is usually achieved through the recruitment of motor units with increasingly higher conduction velocity. These new motor units will join the already active ones, who, due to fatigue, may have decreasing conduction velocity. Since there are two opposing effects (some fibers are slowing down and the new recruited fibers are speeding up), it is possible that, for some subjects, the speeding up effects become dominant, causing an increase instead of a decrease in mean conduction velocity for the second and third contractions. However, in order to study this hypothesis, it would be necessary to repeat the experiment, but, this time, monitoring antagonist muscles (and auxiliary muscles, if possible). This new experiment could help in the acquisition of a better understanding of the observed effects.

Other aspect of the results also caught our attention: for the second and third contractions, even though there was a tendency for a positive slope of the CV, there was an increasing (and statistically significant) trend of a negative slope for the MNF and MDF variables. At first sight this results might seem contradictory, since it is reasonable to expect that the increase in conduction velocity should be linked to the increase in the MDF and MNF, since the spectrum depends strongly on the conduction velocity and very little in the train of pulses that control the triggering of the MUAPs. However, several works in the literature make it clear that this is not always true (Solomonov 1990, Merletti e Parker 2004): the clear relation between conduction velocity is only perfect for invasive electromyography. For surface electromyography, it is possible, in several cases, that there is an increase in conduction velocity while having a decrease in the MDF and in the MNF. This effect can be caused by geometric factors and by the attenuation characteristics of the volume conductor, as well as by the occurrence of synchronization of the firing moments of different MUAPs, that happen for high contraction levels.

Theoretically, a behavior that could be expected would be the one described as follows. In the beginning, of an isometric contraction, only a percentage of fibers is recruited. As time passes, some fibers start losing strength, and, in parallel, the average CV of their MUAPs start to decrease. To compensate for this loss of strength, new fibers start being recruited, and this new fibers tend to have increasingly higher conduction velocity. In this situation, there are two opposing effects, one that leads to an increase and another that leads to a decrease in CV. In the majority of the works in the literature, in which only a single contraction is performed, without pauses, there is a decreasing trend. Thus, it seems that, for the first contraction the effect that causes the decrease in conduction velocity is dominant. In the current study, it seems that the 10-seconds pauses generated a disturbance that caused changes in the recruiting pattern, and changed this balance.

It is also relevant to add that several works in the literature report an increase of the conduction velocity concomitant with a decrease in MNF and MDF. The usual explanation is that the volume conductor causes selective attenuation of higher frequencies, but has little effect on the CV. Thus, the recruitment of deeper MUAPs may be responsible by this effect. However, none of these works provides a conclusive explanation to this effect and, to our knowledge; this is still an open issue. It is important to mention that EMG representations depend not only on muscle activation levels but also on muscle recovery velocity, muscle of interest, fatigue level, and the mechanisms involved in the transition from normal operative condition to fatigue, among other factors. These factors should be taken into account in future works. For example, different MVC's could be tested in order to assess the influence of fatigue level. Moreover, invasive electromyography be used in order to minimize interference of other muscles. As mentioned before, careful monitoring of opposing and auxiliary muscles could give a better idea about the influence of other muscles in the results.

As a conclusion, this work explored what happens with the surface electromyographic variables if short pauses are included between an isometric contraction. The results have shown that if a short pause is included after a fatiguing isometric contraction, when the contraction is resumed, the recruiting pattern of the contracting muscles tend to change. We believe that it might be worth studying the reason for this behavior in future works.

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