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Evaluation of Techniques for the Study of Electromyographic Signals

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Abstract — **The objective of this work was the study and the development of techniques for acquiring and processing electromyographic signals that can be used for analysis of the behavior of electromyographic variables during fatiguing dynamic activities. Two of the techniques were the RMS value and the MPF, which are commonly used for the analysis of electromyographic signals measured during isometric contractions. A new technique, called MAEC, was proposed, based on the domain of the Wavelet transform. The results showed that the combination of the three techniques together with the protocol for recording electromyographic signals lead to a useful characterization of the behavior of electromygraphic variables.**

I. INTRODUCTION

Surface electromyography is commonly used for monitoring muscle fatigue due to isometric contractions through the observation of the amplitude and power spectrum of the electromyographic signal [1]. In several applications, muscle fatigue is considered as a gradual phenomenon that starts practically at the same time as the initial muscle contraction [2]. In isometric contractions, the electrophysiological properties of muscles cause changes in the electromyographic signals [3-4]. These changes are usually associated with muscle fatigue and their study can provide useful information about muscle behavior [5].

Various digital signal processing techniques applied to the EMG signal have been used to investigate the fatigue phenomenon [2-14]. Among these techniques, two popular ones use the RMS value and the MPF (median power frequency) parameters. Christensen *et al.* [9] state that, in isometric contractions, during fatiguing contractions, the RMS value of the electromyographic variables increases, whereas the MPF decreases. This trend cannot be seen in muscle activities associated with dynamic contractions [7-8, 10]. Merletti *et al.* [10] stated that recent methods based on the time-frequency analysis of dynamic contractions have been proposed for solving this problem, and they are mainly based on wavelets and on Cohen's class [11].

This work presents a method based on digital signal processing for evaluating the changes in electromyographic signals associated with physical exercises that use dynamic muscle contractions. In this work, bipolar electrodes were used in order to acquire EMG signals of a subject that is pedaling in a bicycle. Three techniques were applied in order to evaluate the effects of muscle fatigue on the electromyographic signals. Two of them are classical techniques, employing the RMS value and the MPF. The other one, called MAEC, has originally been applied to isometric contractions [12] and is based on the Wavelets transform.

II. MATERIALS AND METHODS

Nine subjects were analyzed: 6 male and 3 female subjects. Before the experiment, a specialist in physical activities examined them, and classified them as healthy subjects. The subjects were 24.4 ± 4.3 (mean ± standard deviation) years old, and all subjects had a normal Quetelet index (height/weight^2) [15]. Before the experiment, the laboratory, the equipments and the experimental protocols were detailed to the subjects and, after that, they signed the informed consent statement.

A commercial electromyography system was used for the acquisition of the EMG signals (Delsys, model Bagnoli-2, Boston, USA). This equipment has electrodes with pre-amplification and a band-pass filter (20-400 Hz). The overall gain was 1000. The electrodes had a contact area of 1 cm x 0.1 cm and the distance between the electrodes was 1 cm. The acquired signal was transferred to the computer in real-time by a 12-bit DAQ (National Instruments, PCI 6024E, Austin-TX, USA). The sampling rate was 2.0 kHz [14] and Matlab was used to process the signal. An ergometric bicycle (Ergo-Fit, Ergo Cycle 167, Pirmasens, Germany) was used for the cycling activity.

The muscles under study were the *vastus lateralis* and the *vastus medialis* because they are important for pedaling [16]. The position of the electrodes followed Ericson´s recomentations [16] as well as the recomendations of the *International Society of Electrophysiology and Kinesiology* (ISEK) [14]. For electrode positioning, the distances between the lateral external portion (LEP) of the knee and of the femur head (FH) and between the lateral internal portion (LIP) of the knee and of the FH of the left thigh. After

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shaving, abrasion and cleaning of the skin, the electrodes were placed at distances of 1/5 of the distance between the LEP and the FH and 1/4 of the distance between the LIP and the FH, from the FH, in order to measure electromyographic signals from the vastus lateralis and from the vastus medialis muscles.

Although three physical tests were applied to the subjects, the electromyographic signals were recorded and studied only in the third test. The first test used a protocol with constant velocity and increasing load. The second test used constant load and increasing velocity. Constant velocity and constant load were used in the third test. In this last test the adopted velocity and load were defined based on the final velocity and load of the two first tests. The experiments were performed for each subject in three different days. There was a 48 hour interval between the tests.

The initial part of the first test consisted on a warming up period of at most 4 minutes, at a velocity of 30 km/h and a power of 30 W. After this initial part, a velocity of 30 km/h and a power of 150 W were kept constant. During the test, an increase of 50 W in the power was applied after periods of 30 s periods, until the subject decided to quit the activity due to fatigue.

For the second test, the warming up procedure was the same as in the first test. The load was chosen to be 70 % of the highest load reached in the first test. The experiment began at a velocity of 30 km/h, and was increased for each 30 s period, until the subjects decided to quit the activity due to fatigue.

In the third day, after the warming up period, a load of 70% of the maximum load reached in the first day for each subject was chosen. The velocity was chosen to be 70 % of the peak velocity in the second protocol. Thus, we defined a protocol with constant load and velocity and high intensity, that ended when the subjects quit due to fatigue.

In the analysis, only a small part of the electromyographic signal was used. This part corresponded to 20 % of the period of each pedaling cycle, engulfing the section of the electromyographic activity with highest amplitude. Successive windows were then combined, forming a single signal. This approach was used because, in dynamic contractions, in order to minimize the effects of variation in muscle length, in the force applied during the pedaling cycle and in the position of the electrode with respect to the muscle, only a small section of the signal is taken into account. Finally, the techniques using the RMS, MPF and MAEC parameters were applied to the resulting signal in a 500 ms period.

The first technique used the Root Mean Square (RMS) value of the signal, which is commonly used for estimating the amplitude of EMG signals acquired during fatiguing activities in isometric contractions [10]. The second technique uses the median power frequency (MPF). This parameter is widely used for assessing the displacement of the power spectrum of electromyographic signals measured during isometric conditions [10].

The third technique will be called the mean of acumulated energy curve (MAEC) and it is obtained in the wavelet domain. Previous studies showed that the continuous wavelet transform (CWT), Daubechies-4, is a good tool for decomposition in the transformed space [11], [17]. Karlsson *et al.* [11] showed that the CWT has a better performance that the short Fourier transform for analyzing EMG signals.

The MAEC starts with calculation of the CWT of each 500 ms window of the assembled EMG signal. Later, we obtain the wavelet periodogram (Figure 1b) and the quantization in 100 amplitude levels. Later, we plot a 2-dimensional curve that shows the number of times each amplitude occurred in the normalized periodogram. Then, the number of times each amplitude occurred is multiplied by the amplitude itself. Thus, we obtain the curve of accumulated energy (CAE) as shown in Figure 1c and Equation 1.

$$CAE(k) = nk \cdot k \tag{1}$$

where nk is the number of times that the amplitude k [1-100] appears in the wavelet periodogram. Finally, with the CAE, we obtain the median of the accumulated energy curve (MAEC), shown in Figure 1c. The application of this technique in successive 500 ms windows shows how the balance of the high and low wavelet coefficients changes during the exercise.

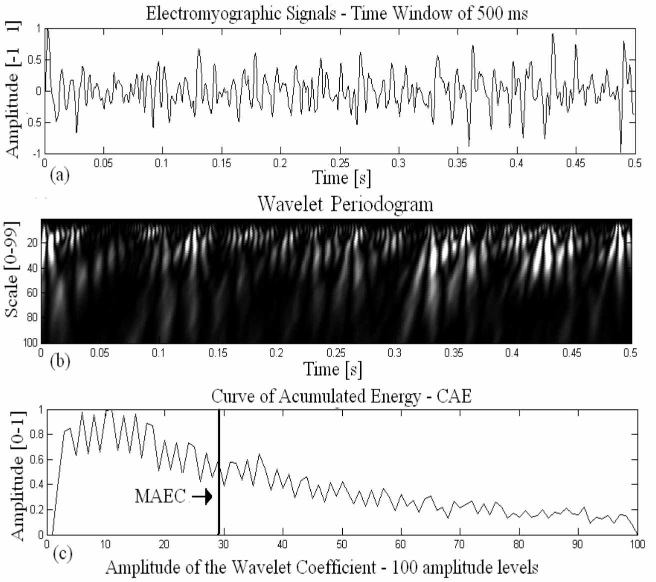

Figure 1: (a) typical EMG signal, (b) wavelet periodogram of the EMG signal, (c) MEC with the MAEC indicated.

The process is stochastic and non-stationary, and if a polynomial approximation were used to fit the MAEC, the result would be too sensitive to noise. In order to minimize the local effect of non-linear fitting polynomials in the mathematical approximation, we used linear regression, where the window is the whole duration of the experiment.

In isometric conditions, muscle fatigue is associated with the negative slope of the MPF [9,10] and with the positive slope of the RMS value [9,10,13] and the MAEC [12]. The increase in the RMS value and in the MAEC is associated primarily with the recruiting of new motor units [10, 13].

The decrease in the MPF curve is usually attributed, among other factor, to a reduction in the conduction velocity of the muscle fiber that occurs during fatigue [10]. The t-student test ($p<0.05$) was used to check if the slopes of the MAEC and RMS value curves were positive and if the slopes of the MPF curves were negative in the experiments.

III. RESULTS

Figures 2 and 3 show the curve values for MPF, RMS value and MAEC for the nine subjects, for the *vastus lateralis* and *vastus medialis* muscles. Table 1 shows the the slopes of the curves shown in Figures 2 and 3.

Figure 4 shows a plot of the values of the slopes of the linear regressions for each subject and for the three techniques as a function of time. This is done for each muscle in the study. These parameters are also shown in Table 1.

When applied to the data shown in Table 1, the t-student test showed that the hypotheses for negative and positive slopes for the MPF, RMS and MAEC operators are significant at the level of $p<0.05$.

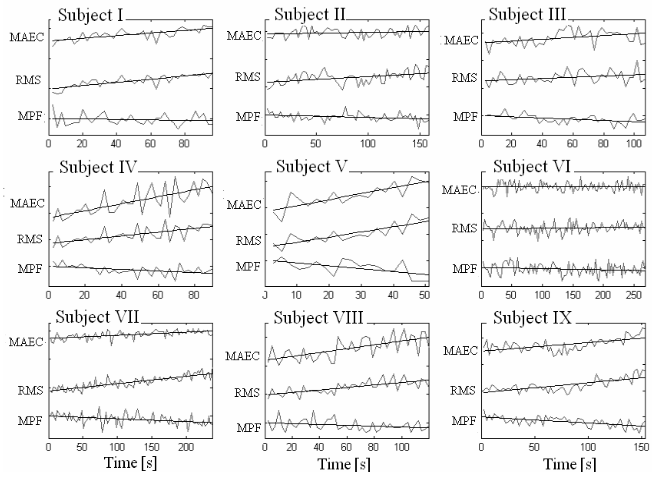

Figure 2: Normalized curves: MPF, RMS and MAEC of the vastus lateralis and regression lines.

IV. DISCUSSION

The results showed that the proposed parameters (MPF, RMS and MAEC) increase or decrease gradually in fatiguing dynamic activities. The results in figures 2, 3 and 4 and in Table 1 suggest that these parameters could be correlated with the process of muscle fatigue [9,10,13]. The characteristics of the protocol show that the gradual increase in RMS and MAEC, in the observation window, is not associated with increase in speed or in load. It is clearly associated with factors that are inherent to muscle behavior, possibly factors such as increase in the recruiting in motor units, which increases the energy of the signal [10, 13].

The increase in the MAEC shows that the muscle fatigue process tends to increase the distance between the coefficients of high and low amplitude .This result cannot be seen with the RMS value. This happens due to the fact that the RMS shows only the change in the whole energy of the signal in the time domain. This phenomenon is possibly due to the recruiting of new motor units and to changes in conduction velocity.

The CAE curve (Figure 1) may be useful in order to see how the different energy ranges of the wavelet coefficients behave with the recruiting of new motor units. Thus, one can investigate the fatigue phenomenon in a different manner using this curve. It is interesting to notice that the slope of the regression line of the MAEC is higher than that of the regression line of the RMS value. Futhermore, the MAEC has the highest slope variance and in order to show whether there is difference of the ability (MAEC versus RMS) more subjects might be necessary to address this point.

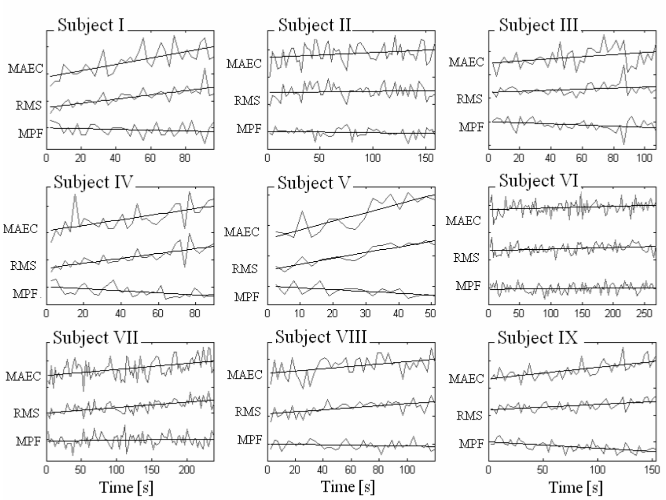

Figure 3: Normalized curves: MPF, RMS and MAEC of the vastus medialis and regression lines.

Table 1: Slope of the curves, based on regression lines of the MPF, RMS and MAEC curves.

Sub	**vastus lateralis**			**vastus medialis**		
	MAEC $*10^{-3}$	RMS $*10^{-3}$	MPF $*10^{-3}$	MAEC $*10^{-3}$	RMS $*10^{-3}$	MPF $*10^{-3}$
I	5,49	6,77	-1,02	14,91	9,89	-1,79
II	0,78	2,61	-1,13	2,23	0,60	-0,70
III	4,23	2,83	-2,91	5,82	2,88	-3,15
IV	16,75	9,16	-3,75	13,31	11,56	-5,09
V	29,97	26,15	-14,42	37,88	25,37	-7,99
VI	0,03	0,35	-0,55	0,75	0,72	0,28
VII	1,39	3,29	-1,26	2,96	2,64	0,41
VIII	8,55	5,54	-1,89	5,30	4,59	-0,90
IX	4,12	4,75	-2,94	5,36	2,49	-2,98
MAEC (μ ± σ) = 8,88 ± 10,40 RMS (μ ± σ) = 6,79 ± 7,60 MPF (μ ± σ) = -2,88 ± 3,53						

Previous works have reported the study of dynamic activities using protocols with higher duration and lower intensity, and did not use linear regression to fit the experimental data and, probably, because of that, they could not observe the gradual spectral displacement of the MPF. The results hint that the choice of a short, high intensity protocol, using linear regression may be more efficient for observing changes in the electromyographic variables.

The results in Figure 4 also showed that the slopes associated with the curves are higher for subject who had worse physical performance scores. In the experiments, one of the volunteers, which was excluded in the tests and in the calculation of IM and FM, in Figure 4, had a result that was very different from those of the group. However, this subject had the worst physical performance during the tests and the highest slope values. These observations clearly serve as a motivation for continuing the studies with the proposed protocol and with the adopted techniques, and investing in its improvement and in the better understanding of how these parameters are associated with muscle fatigue.

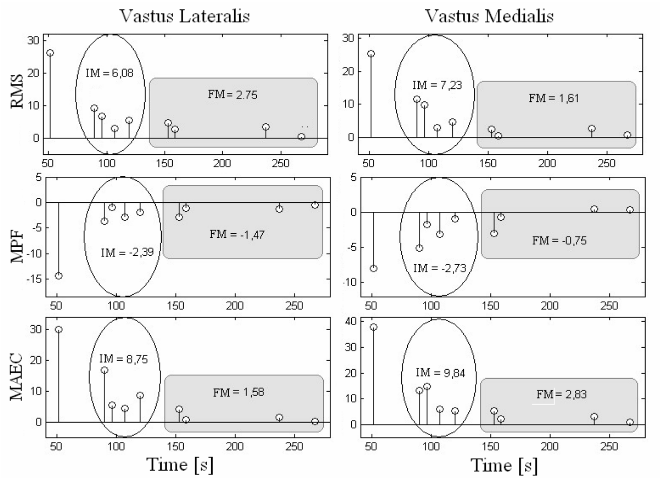

Figure 4: Slopes of the linear regression curves for the MPF, RMS and MAEC parameters, for each subject, in the execution time. IM = initial mean, FM = final mean.

V. CONCLUSION

This work presented a protocol for acquisition of EMG signals in dynamic physical activities, and methodologies for observing the gradual change in the characteristics of this signal. The protocol proposed used constant velocity and constant load, also used the MPF, RMS and MAEC parameters. The EMG parameters had values that changed gradually in time, in an approximately linear manner. The MAEC index showed the highest slope.

The results hint that it is worth trying to improve the protocol, and trying to get a better understanding of the relationships between the behavior of the EMG variables and the muscle fatigue.

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