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Characterization of Laplacian Surface Electromyographic Signals during Isometric Contraction in Biceps Brachii

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Abstract*— Surface electromyography (sEMG) is a noninvasive technique for monitoring the electrical activity produced by the muscles. Usually, sEMG is performed by carrying out monopolar or bipolar recordings by means of conventional Ag/AgCl electrodes. In contrast, Laplacian recordings of sEMG could also be obtained by using coaxial ring electrodes. Laplacian recordings increase spatial resolution and attenuate other distant bioelectric interferences. Nevertheless, the spectral characteristics of this kind of recordings have been scarcely studied. The objective of this paper is to characterize the sEMG signals recorded with a Laplacian ring electrode and to compare them with traditional bipolar recordings with disc electrodes. Both kinds of signals were collected simultaneously in two healthy subjects during resting and sustained isometric voluntary contraction activities in biceps brachii. The conducted study computed the cumulative percentage of the power spectrum of sEMG so as to determine the energy bandwidth of the two kinds of recordings and the signal to noise ratio in different bands of the sEMG spectrum. Also, muscle fatigue, a condition when muscle force is reduced, was assessed using indexes from amplitude and frequency domain. The results of this study suggest that Laplacian sEMG has higher spectral bandwidth but a lower signal to noise ratio in comparison to bipolar sEMG. In addition, frequency fatigue indexes showed that Laplacian recording had better response than bipolar recording, which suggests that Laplacian electrode can be useful to study muscular fatigue due to better spatial resolution.

I. Introduction

Surface electromyography (sEMG) is the non-invasive recording of electrical activity generated by muscle fibers and captured from the skin surface of the body by electrodes. sEMG has shown being a promising technique in clinical diagnosis [1], rehabilitation and prosthetic technologies [2]. Clinical and research practice use commonly the classical silver chloride electrode (Ag/AgCl) as the gold standard electrode to collect sEMG. In spite of being widely used, Ag/AgCl electrodes, which are generally disposables, have the drawback of affecting signal quality, as it dries up and also, some skin reactions can be present due to their use [3]. In addition, the poor spatial resolution of conventional monopolar or bipolar electrode configuration, which produces a blurring effect on the volume conductor, is another concern. In contrast, expressed as the second spatial derivative of the surface potential, the Laplacian configuration increases the spatial resolution of the bioelectrical signal [4] and hence, it attenuates bioelectrical interferences, such as the electrocardiogram (ECG) signal in sEMG recordings [5].

Laplacian of surface potential can be obtained by active Laplacian electrodes. These electrodes are commonly dry and they are made up of a central disc with one or more concentric outer [4], [6]. The picked up signal is usually preamplified close to the electrode. Nowadays, the development of the Laplacian electrodes is an ongoing challenge, resulting in the appearance of improvements in their design [6], [7]. The daily clinical practice can be benefited of reducing the time patient preparation and better spatial resolution by using this kind of electrodes. Furthermore, Laplacian electrodes have been used in the study of other bioelectrical signals as electroencephalogram (EEG) [8], ECG [9], electrohysterogram (EHG) [10] and electroenterogram (EEnG) [5] signals.

The present study aims to characterize the sEMG collected by a Laplacian electrode. With this intention this signal was compared with the sEMG acquired with conventional disc Ag/AgCl electrodes. The study was carried out during resting and sustained isometric voluntary contractions on biceps brachii. In addition, muscle fatigue on that muscle was considered. Described as a physiology change in the muscle, which produces the inability to perform a physical task, muscle fatigue is extensively studied in sEMG [2]. It manifests changes in the motor unit firing rates and decreases in the fiber conduction velocity. Traditionally, fatigue indexes from amplitude and frequency domain are useful to describe muscle fatigue over time. Median power frequency shifts to lower frequencies, whereas the Dimitrov's index [11] and the averaged rectified value increase in time [12], [13]. Fatigue indexes derived from bipolar and Laplacian sEMG recordings will also be studied.

II. Material and Methods

A. Experimental procedure

sEMG was collected from the biceps brachii muscle of the right arm during recordings sessions, each consisting of one resting task followed by one sustained isometric contraction with a high load.

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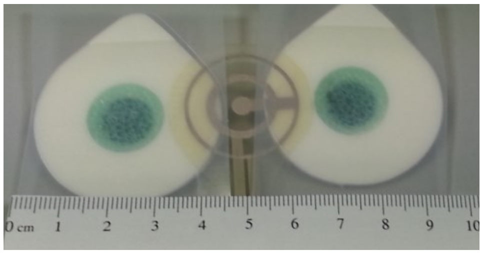

Figure 1. Concentric ring electrode for laplacian sEMG recording (middle), and 2 monopolar disposable disc electrodes (both sides) for bipolar sEMG recording.

The study was carried out with two healthy subjects, seated with the arm close to the trunk and holding an 18 kg dumbbell. The angle between the forearm and the upper arm was set at 90º. Tasks per subject lasted 30 s.

B. Signal recording

The skin was abraded with gel (Nuprep, Weaver and Company, USA) and cleaned with alcohol. Circular disposable Ag Ag/Cl electrodes (foam electrode 50/PK – EL501, Biopac Systems Inc, Santa Barbara, CA, USA), 10 mm diameter with 50 mm inter-electrode distance were placed halfway between endplate zone and distal tendon, according to SENIAM Project guidelines [14]. Tripolar Laplacian electrode in bipolar configuration (24 mm outer diameter) with a signal conditioner (filter and preamplifier) developed by our research group in previous studies [5] was placed between the two monopolar electrodes, attached with an adhesive plaster as is illustrated in Fig. 1. A reference electrode was placed at the wrist. Signals were acquired using a data acquisition system (EMG 100C, Biopac Systems Inc, Santa Barbara, CA, USA), using a gain of 500, a 1 to 500 Hz analog band-pass filter and 2000 Hz sampling rate. No notch filter was used to remove 50 Hz interference. Data were monitored and stored on a computer using Acknowledge software (v.3.2, Santa Barbara, CA, USA).

C. Signal preprocessing and analysis

sEMG signals were digitally band-pass filtered between 10 and 500 Hz with a Butterworth bidirectional filter of order 4, prior to their analysis. The mean value of the signals was removed. Power spectral density (PSD) estimation was computed using Welch's averaged modified periodogram (Hamming window, 0.4 seconds length, 4096 - point FFT, and 50 % overlap) in segments of one second length. The signal to noise ratio (SNR) was used to compare the quality of bipolar and Laplacian sEMG spectrum. It was calculated as the ratio between the energy of a 5 seconds window of the sustained isometric contraction (E_I) and the resting task (E_0).

$$SNR = 10log_{10}\left(\frac{E_I}{E_0}\right) \tag{1}$$

The SNR was analyzed in sub-bands of 10 Hz between 10 and 300 Hz of the sEMG spectrum.

Cumulative percentage of the power spectrum of sEMG was used to compare the spectral distribution of bipolar and Laplacian sEMG power. It was computed as follows:

$$CmPs(f) = \frac{\int_{f_1}^{f} PS(f)df}{\int_{f_1}^{f_2} PS(f)df} \cdot 100 \tag{2}$$

where $PS(f)$ is the power spectrum of the sEMG signal under study, and f_1 (10 Hz) and f_2 (300 Hz) are the low and high frequencies considered.

To study muscle fatigue, the following amplitude and frequency fatigue indexes were computed for bipolar and Laplacian sEMG recordings.

1) Average rectified value (ARV) is an amplitude parameter, expressed as the averaged of the absolute value of sEMG.

$$ARV = \frac{1}{n}\sum_{i=1}^{n}|x_n| \tag{2}$$

where x_n are the values of SMEG, and n is the total number of samples.

2) Median frequency (MDF), defined as the frequency that divides the sEMG spectrum in two parts of equal power

$$\int_{f_1}^{MDF} PS(f) \cdot df = \int_{MDF}^{f_2} PS(f) \cdot df \tag{3}$$

3) Dimitrov's fatigue index, defined between the signal spectral moment of order (-1) and the spectral moment of order (5) [11].

$$FInsm5 = \frac{\int_{f_1}^{f_2} f^{-1} \cdot PS(f) \cdot df}{\int_{f_1}^{f_2} f^{5} \cdot PS(f) \cdot df} \tag{4}$$

All parameters were computed using a moving window of one second. A linear regression was performed to study the trend of the parameters during the contraction task. The *ARV* and *FInsm5* were normalized with respect to their values at the beginning of the study. All instructions were implemented in MATLAB (v. R2011b, Natick, Massachusetts, USA).

III. Results

An example of 10-sec sEMG signal recorded by bipolar and Laplacian electrodes, during resting and a sustained isometric voluntary contraction, is illustrated in Fig. 2. Note that units in Laplacian recording are scaled considering its mean radius as described in [5] . In the resting signals, only for visual analysis of ECG interference, sEMG were also digitally band-pass filtered between 10 Hz and 40 Hz with a Butterworth bidirectional filter of order 4. These filtered signals are showed in red color. It can be observed that bipolar recording during resting task (Fig. 2a) is more affected by the ECG interference than Laplacian recording (Fig. 2c). In the case of the sustained isometric contractions, the signal amplitude increased due to the muscular activity (Fig. 2b and 2d).

The cumulative percentage of sEMG power spectrum (CmPS(f)) is represented in Fig. 3 for resting task and sustained isometric contraction. At rest, cumulative power of bipolar electrode showed an exponential trend, with a fast accumulation of power (more than 70% approximately) from 10 Hz to 150 Hz and a slow accumulation of power from 150 Hz to 300 Hz. On the other hand, cumulative power of Laplacian signals at rest showed a linear trend which can be associated to white background noise. Both

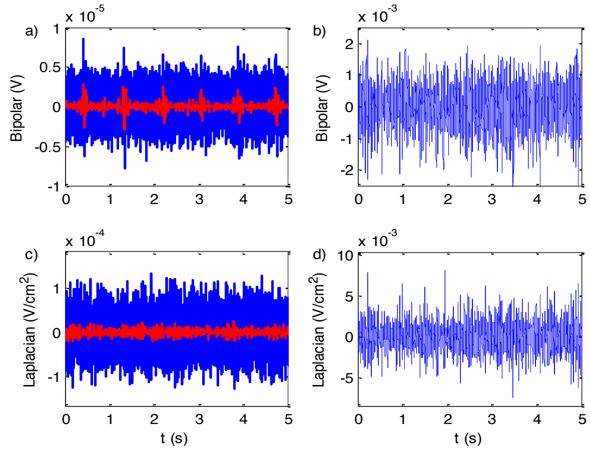

Figure 2. Example of sEMG recordings corresponding to bipolar and Laplacian electrodes from subject 1 for a resting task (a and c, respectively) and a sustained isometric voluntary contraction task (b and d, respectively). In red color: sEMG after a 10-40Hz band-pass filter.

electrodes show abrupt increases in CmPs at 50 Hz and 150 Hz, but they are higher in bipolar recordings reflecting a more significant contribution of power-line interference to the signal energy in these conditions. Regarding CmPs during isometric contraction, it can be appreciated in Fig 3b that the energy of Laplacian signals extends to higher frequencies than bipolar. Table I shows the frequencies that include the energy between 5% and 95% of the total power ($f_{5\%}$ and $f_{95\%}$, respectively) during resting and isometric tasks for bipolar and Laplacian recordings.

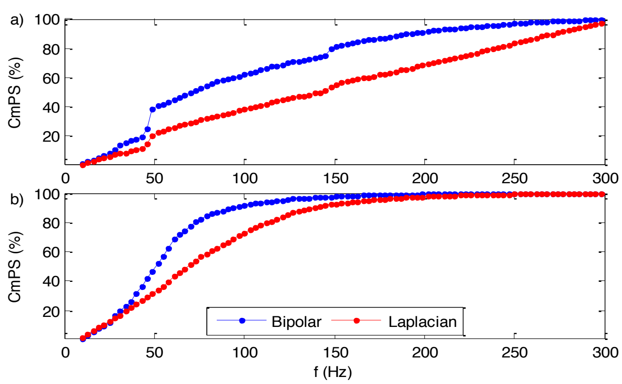

Figure 3. Cumulative percentage of bipolar and Laplacian sEMG power spectrum corresponding to subject 1 during a) resting task and b) sustained isometric contraction.

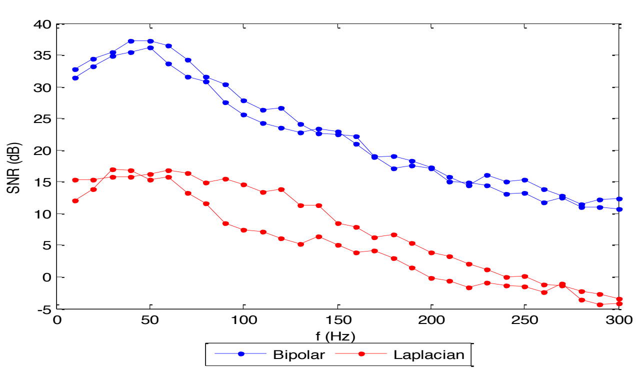

Figure 4. SNR response in sEMG spectrum for bipolar and Laplacian electrodes for the two studied subjects.

The results confirm that sEMG Laplacian signals during isometric contractions present a wider bandwidth than bipolar signals ($f_{95\%}$=164.86 Hz vs 128.30 Hz, respectively). The SNR of the two subjects for bipolar and a Laplacian recording are represented in Fig. 4. For both recording techniques the higher the frequency range, the lower the SNR. Nevertheless, it is clearly appreciated that bipolar recordings with conventional disc electrodes had a higher SNR than Laplacian recordings.

Fig. 5 depicts the ARV, MDF and FInsm5 used to study the evolution of muscular fatigue over the time. In each case, linear regression was plotted to show the tendency of the fatigue indexes. In Table II it is shown the slope (rate of change) of the ARV, MDF and FInsm5 fatigue indexes. Data were normalized respected to the first value and represented as percentages to obtain a better representation. In addition, in Table II it was presented the averaged of the first five values of the MDF. Fatigue indexes from bipolar and Laplacian signals presented similar trends. Nevertheless the slopes of MDF and FInsm5 from Laplacian signals are higher than those of bipolar signals.

TABLE I
FREQUENCIES CORRESPONDING TO 5% AND 95% OF THE TOTAL POWER DURING RESTING AND SUSTAINED ISOMETRIC CONTRACTION TASKS

Resting	Bipolar		Laplacian	
Subject	$f_{5\%}$ (Hz)	$f_{95\%}$ (Hz)	$f_{5\%}$ (Hz)	$f_{95\%}$ (Hz)
1	17.74	224.60	21.85	286.21
2	23.95	208.80	12.74	287.70
Mean	20.85	216.70	17.30	286.96
Isometric	Bipolar		Laplacian	
Subject	$f_{5\%}$ (Hz)	$f_{95\%}$ (Hz)	$f_{5\%}$ (Hz)	$f_{95\%}$ (Hz)
1	15.39	119.80	14.52	168.31
2	15.14	136.80	16.04	161.40
Mean	15.27	128.30	15.28	164.86

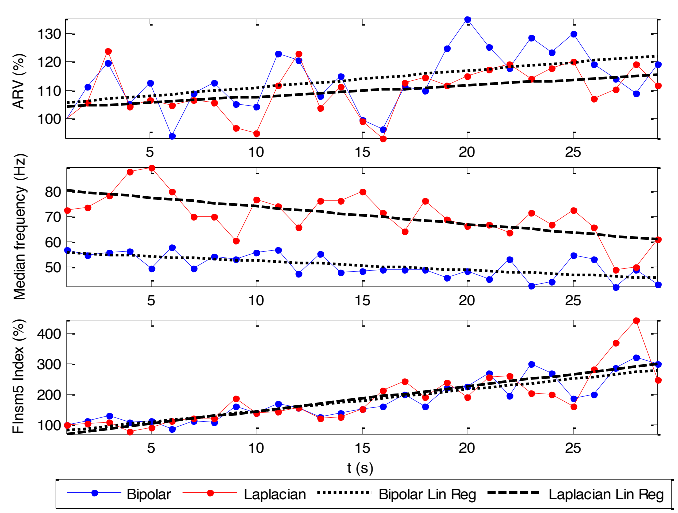

Figure 5. ARV, MDF and FInsm5 fatigue indexes from bipolar and Laplacian recordings during sustained isometric contraction, corresponding to subject 1.

TABLE II
SLOPE OF ARV, SLOPE AND INITIAL VALUE OF MDF, AND SLOPE OF FINSM5 FOR BIPOLAR AND LAPLACIAN RECORDINGS

	ARV		MDF				FInsm5	
Subj.	Slope (%/s)		Initial (Hz)		Slope (%/s)		Slope (%/s)	
	Bip.	Lap.	Bip.	Lap.	Bip.	Lap.	Bip.	Lap.
1	0.59	0.39	54.79	80.57	-0.63	-0.96	7.10	8.13
2	0.49	0.25	52.73	53.32	-0.38	-0.67	2.00	2.82

IV. DISCUSSION

Our experiences showed that sEMG recordings obtained with Laplacian electrodes are less affected by the ECG interference. This is in agreement with previous studies that performed surface recordings of other bioelectrical signals on the abdomen [5, 10]. It is probably related to the increased spatial resolution of Laplacian techniques which makes this kind of recordings less sensitive to bioelectrical sources far from the recording area. The analysis of sEMG power spectrum reflected that the Laplacian signals covers higher frequencies than bipolar signals; presenting a bandwidth more similar to that of recordings with needle electrodes [15]. This could be due to the spatial filter transfer function associated to the concentric ring structure of the Laplacian electrode [16].

This can be an advantage of this kind of recordings in comparison to bipolar recordings with disc electrodes, since it could facilitate the identification of single motor units action potential [16]. However, our results showed that SNR of bipolar signals is clearly higher than that of Laplacian signals. The fact that the interelectrode distance between the disc electrodes is much higher than the distance between the rings of the Laplacian electrode, provokes that the amplitude of Laplacian signals is greatly reduced, yielding these lower SNR values. This could also explain that the ARV parameter, which is related to signal amplitude, presents better performance (higher slope) to monitor muscle fatigue in bipolar recordings. Finally, a similar behavior during the evolution of fatigue indexes over time in bipolar and Laplacian recordings was observed. The ARV and the FInsm5 increase, while the mean frequency decreases, which are classic manifestations of fatigue according to literature [11–13]. Nevertheless, it is noticeable that the capability of Laplacian recordings to pick up EMG components of higher frequencies enhances the fatigue monitoring, in the sense of providing greater changes of spectral parameters (MDF and FInsm5) throughout time during sustained isometric contractions.

V. CONCLUSION

The outcomes of this work suggest that sEMG recordings with a Laplacian electrode present a wider spectrum in comparison to bipolar recordings with conventional disc electrodes. However, quality of Laplacian recording is inferior to bipolar recording in terms of SNR.

Reducing interferences is an important issue when interpreting signals. In the present study, sEMG signal recorded by Laplacian electrodes has been less affected by the ECG and electrical line interferences in comparison to conventional bipolar recordings. Additionally, during muscular fatigue, Laplacian electrode has shown a remarkable response during sustained isometric contractions. More subjects should be studied to confirm these findings. Furthermore, additional studies have to be developed to investigate the performance of Laplacian electrodes in other muscles and in different conditions such as during dynamic contractions.

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