Changes of HD-sEMG Maps of the Upper Limb During Isometric Endurance Contractions

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Abstract— **Recent research in the field of surface EMG recorded with 2D electrode arrays have shown muscle adaptations as reflected on the spatial activation of motor units in response to pain, direction of movement or fatigue. The purpose of this study was to evaluate time- changes in the activation maps of upper limb muscles during endurance tasks associated with the degrees of freedom at the elbow joint. Preliminary results show time-variations in the distribution of intensity, that is, in the spatial recruitment of motor units, and that such changes may be dependent on the type of task.**

I. Introduction

Motor unit activity registered by surface EMG is commonly used to assess fatigue both in normal and pathological conditions. It is well known that the spectral and amplitude characteristics of the signal are affected during fatigue because of physiological changes occurring in the muscle fiber membrane leading to a reduction in the conduction velocity of the potentials as well as to changes in central nervous system's recruitment strategies regarding timing and frequency of activation of motor units [1], [2].

More recently, different research studies based on High Density surface EMG (HD-sEMG) recorded by 2D electrodes arrays have focused on investigating the adaptations to fatigue occurring within different regions of the muscle [3], [4]. For example, in [4] it was shown that motor units in the cranial region of the trapezius muscle became progressively more active during fatigue than their counterparts in the caudal region in non-pathological subjects. In addition, the same authors have attributed such changes to a spatial dependency in the control of motor units that is necessary for maintaining the mechanical output of the muscle [5]. Therefore, myoelectric fatigue also affects Central Nervous System' recruitment strategies at regional level at least, in spiral muscles.

The purpose of this study is to analyze regional changes in the activation of motor units in muscles of the upper limb during isometric endurance contractions. Different directions of movement at the elbow joint were analyzed.

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II. Methodology

A. HD-sEMG recording

Five muscles were assessed: Triceps and Biceps in the upper arm and Brachio Radialis, Anconeo and Pronator Teres in the forearm. Monopolar surface EMG signals were recorded with three EMG amplifiers (EMG-USB, 3dB bandwidth 10-750 Hz, fs=2048 Hz, LISiN-OT Bioelettronica with synchronized sampling). A Driven Right Leg (DRL) circuit was used for reduction of power line interference. Purposed built 2D eyelet-electrode (ϕ=5mm) arrays were used for the recording of the signals: two arrays (15 columns × 8 rows) were used to cover the surface of biceps and triceps in the anterior and posterior regions of the upper arm respectively, and one array (19 × 6) was used for the assessment of the three forearm's muscles. Inter-electrode distance was set to 10 mm in both directions. Midpoints of the arrays were aligned with anatomical landmarks recommended by SENIAM project, that is, at the relative distance from the origin to the insertion of the muscle and above an imaginary line connecting those points [6].

Four male volunteers (age, 32.3 ± 3.8 years; height: 175.2 ± 3.8 cm; weight: 69.3 ± 4.7 kg) without history of neuromuscular disorders participated in the experiment. Subjects sat with the dominant arm placed in a mechanical brace with the elbow joint flexed at 45º, shoulder abducted at 90º (parallel to the Sagittal plane), and forearm twisted 90º (midway between supination and pronation). In this position, subjects were asked to exert isometric contractions at 50% of maximal voluntary up to exhaustion. The mechanical brace was capable of measuring torque produced at right and left sides of the elbow joint. Four movement intentions were considered: flexion, extension, supination and pronation of the forearm. Every contraction was followed by 10 minutes rest to avoid effects of cumulative fatigue and the four contractions were performed in randomized order.

B. Signal processing

Signals were offline filtered in forward and backward directions to avoid zero-lag (4th order Butterworth filter, 12-350 Hz), and inspected for possible artifacts using the algorithm described in [7]. The EMG signals were divided into non-overlapping epochs of 500 ms for the calculation of topographical maps as (1)

$$I_{i,j}(ep) = RMS(s_{i,j}) \tag{1}$$

where $s_{i,j}$ is the EMG signal recorded in the channel (i,j) of the electrode array and I defines an *intensity* map for each epoch (ep) across the total duration of the contraction.

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TABLE 1. SLOPE OF THE LINEAR REGRESIÓN OF $\bar{I}_{bip}$ AND $\bar{I}_{map}$ AS FUNCTION OF THE TOTAL DURATION OF THE CONTRACTION. RESULTS ARE PRESENTED AS **MEDIAN** AND (*MIN, MAX*) FOR EACH MUSCLE AND CONTRACTION. THE CONTRACTIONS WERE EACH MUSCLE IS EXPECTED TO BE ACTIVE ACCORDING TO [8] ARE UNDERLINED.

Slope- *m* of the regression *(min, max)*	**Biceps** $\bar{I}_{bip}$	**Biceps** $\bar{I}_{map}$	**Triceps** $\bar{I}_{bip}$	**Triceps** $\bar{I}_{map}$	**Anconeo** $\bar{I}_{bip}$	**Anconeo** $\bar{I}_{map}$	**Brachioradialis** $\bar{I}_{bip}$	**Brachioradialis** $\bar{I}_{map}$	**Pronator Teres** $\bar{I}_{bip}$	**Pronator Teres** $\bar{I}_{map}$
Flexion	**0.2**	**0.6**	**0.2**	**0.5**	**0.2**	**0.3**	**0.03**	**0.6**	**0.4**	**0.4**
	(0.01, 1)	*(0.2, 0.8)*	*(0.06, 0.2)*	*(0.4, 0.5)*	*(-0.2, 0.4)*	*(0.05, 0.4)*	*(-0.4, 0.2)*	*(0.3, 1)*	*(0.09, 0.5)*	*(0.4, 0.7)*
Extension	**-0.1**	**0.2**	**0.1**	**-0.03**	**-0.3**	**0.4**	**0.8**	**0.4**	**1**	**0.6**
	(-0.8, 0.2)	*(0.08, 0.3)*	*(0.09, 0.3)*	*(-0.2, 0.05)*	*(-0.6, 0.3)*	*(0.09, 1)*	*(-0.06, 1)*	*(0.06, 2)*	*(0.8, 2)*	*(0.07, 2)*
Supination	**0.2**	**0.7**	**0.4**	**0.6**	**0.5**	**0.8**	**0.6**	**0.8**	**0.3**	**0.8**
	(0.02, 0.5)	*(0.3, 0.9)*	*(0.2, 0.9)*	*(0.2, 1)*	*(0.2, 0.6)*	*(0.3, 1)*	*(-0.06, 1)*	*(0.5, 1)*	*(0.03, 1)*	*(0.3, 1)*
Pronation	**0.1**	**0.05**	**-0.06**	**0.1**	**0.4**	**0.1**	**-0.3**	**0.2**	**-0.1**	**-0.1**
	(-0.4, 0.2)	*(-0.3, 2)*	*(-0.2, 0.8)*	*(-0.2, 1)*	*(-0.4, 0.8)*	*(-0.3, 0.5)*	*(-0.6, 0.9)*	*(-0.2, 0.8)*	*(-0.3, 0.1)*	*(-0.3, 0.6)*

Each activation map I was segmented as in [7] for obtaining the most significant region of activation for each muscle. Two features were extracted from each map, Eq. (2 and 3): 1. the *mean intensity*- $\bar{I}_{map}$ (2) and, 2. the *center of gravity*- $CG_{x,y}$ (3), in order to analyze intensity and spatial changes during the contraction.

$$\bar{I}_{map}(ep) = \frac{1}{N}\left(\sum_{x=i}\sum_{y=j} I_{x,y}(ep)\right) \tag{2}$$

$$CG_{x,y}(ep) = \frac{\left[\sum_{x=i}\sum_{y=j} I_{i,j}(ep)\times i, \sum_{x=i}\sum_{y=j} I_{i,j}(ep)\times j\right]}{\sum_{x=i}\sum_{y=j} I_{x,y}(ep)} \tag{3}$$

where N is the total number of segmented channels (i.e. *pixels*) after the segmentation, and y (rows) and x (columns) refers to the coordinates of the electrode located in the positions [*i, j*] of the electrode array.

On the other hand, changes in the intensity of the maps were compared to that observed with traditional bipolar signals. For this purpose, the two monopolar channels (inter-electrode distance=10 mm) more proximal to the landmarks described by SENIAM recommendations [6] were used to obtain a bipolar signal for each muscle. The RMS for the same epochs as in the intensity maps was calculated for these signals (4).

$$\bar{I}_{bip}(ep) = RMS(s_{bip}) \tag{4}$$

where s_{bip} is the bipolar signal calculated off-line from the monopolar channels previously described.

The trend of the different variables, that is, $\bar{I}_{map}$ and $CG_{x,y}$ of the maps and $\bar{I}_{bip}$ of the bipolar signals were analyzed through the rate of change (m) of its linear regression as function of the number of epochs. In order to be able to compare between different subjects, the duration of the contraction was normalized with respect to the total duration test (TDT), that is, between 0 and 100%. In addition, the trends of $\bar{I}_{map}$ and $\bar{I}_{bip}$ were normalized with respect to their initial value. Similarly, the coordinates of the center of gravity were normalized with respect to the circumference and length of the arm segments (upper- arm or forearm) in the x and y- axes respectively, and changes were referred to the center of gravity at the beginning of the contraction, that is, at *t=0*, *ep=0.*

III. RESULTS

A. Intensity changes

The total duration for the 4 subjects in each test (TDT) was as follows (mean ± std): flexion 69.3 ± 23 s, extension 110.8 ± 61.6 s, supination 94 ± 69 s and pronation 87.8 ± 50 s.

Table 1 shows the slope (m) of the regression of $\bar{I}_{bip}$ and $\bar{I}_{map}$ normalized with respect to their initial value. Results are presented as the median and (*min, max*) for the four subjects in the study and for each muscle during flexion, extension, supination and pronation. Note that in the majority of the cases, the trend is positive and that higher slope values were

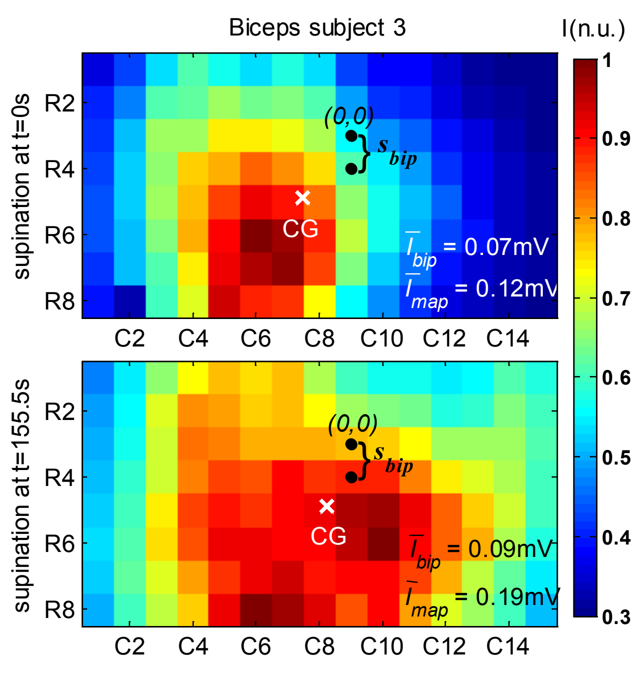

Figure 1. Activation maps for supination in the Biceps at the beginning (top) and end of the contraction (bottom). The location of the channels used for obtaining s_{bip} and the location of CG as well as $\bar{I}_{map}$ and $\bar{I}_{bip}$ in the two time instants are also shown.

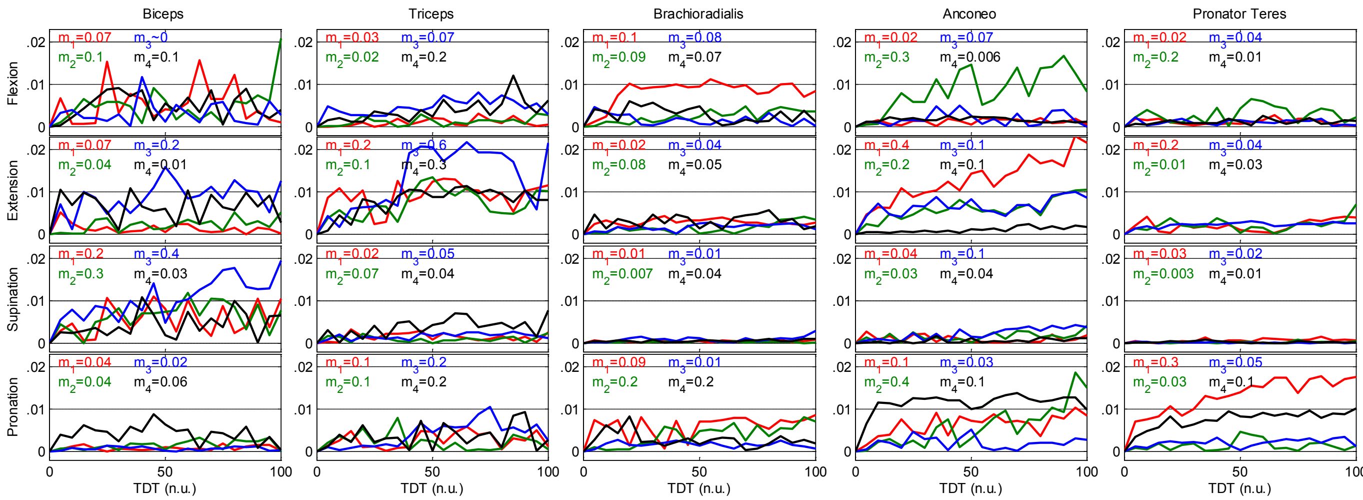

Figure 2. Trend of CG_x for each muscle and contraction as function of the total duration of the contraction (*TDT* in normalized units, from 0 to 100% of test duration). Results are presented for each subject independently (in different colors). The slope of the linear regression (*m*) is also shown.

obtained for the intensity of the maps, than for the RMS of the bipolar signals.

This difference may be explained as result of the progressive activation of motor units in different areas of the muscle as the contraction evolves. An example is presented in Fig. 1 showing two activation maps normalized with respect to their maximum intensity. The resultant torque (T) at [right, left] of the mechanical brace for the two displayed epochs was $T_{t=0s}$ = [4.02, 0.13] N·m and $T_{t=155s}$=[4.54, 0.34] N·m. The SENIAM reference landmark (0, 0) and the channels used for the calculation on the bipolar signal are also shown (s_{bip} in black). Maps correspond to biceps of subject 3 during supination at the beginning and at the end of contraction.

Note that at the beginning (t=0 s), the main intensity of the map is constrained between rows R4-R8 and columns C4-C8 while at the end of the contraction (t=155 s), the main intensity spreads outside of this region, even when the direction of torque changed only by 2.5º and its magnitude remained within similar values. The described amplitude behavior cannot be observed with bipolar signals and therefore its rate of change is not as large as in the case of the mean intensity of the maps (see values of $\bar{I}_{map}$ and $\bar{I}_{bip}$ for *t=0 s* and *t=155 s* displayed on Fig. 1).

In addition, the rate of change is different for different contractions. For example, the slope for the Anconeo during flexion (median: 0.3, [*min: 0.05, max: 0.4*]) is lower than during supination (0.8, [*0.3, 1*])

B. Spatial changes

In addition to changes in the spread of intensity described in the previous paragraph, it is possible to observe two "*peaks*" of activation in Fig. 1, one near (*R8, C6*) and the other near (*R10, C6)* at the end of the contraction, while at the beginning only one (*R6, C6*) is observed. This change is reflected in the center of gravity of the maps which is also displayed on Fig. 1 (*CG* in white).

Besides, Fig. 2 shows the time trends of the coordinate x (columns) of the center of gravity for each muscle. For simplicity, only this coordinate will be analyzed, although similar patterns were observed in the y- coordinate. Results are presented for each subject independently (in different colors) and the value of slope (m) is also presented for each subject 1 to 4. Different subjects presented different trends, however the location of the CG varied consistently among subjects, particularly in the contractions associated to the principal functions of the muscles [8]: in Biceps, the larger changes were registered for the contraction *supination*, in Triceps and Anconeo for *extension*, in Brachioradialis for *flexion*, and in Pronator Teres for *pronation*. However, as in the case of intensity, the rate of change was different for different contractions: for example in biceps, the slope m was higher during supination than during flexion. The same behavior was observed for Anconeo during *extension* and *pronation* and in Pronator teres when comparing *pronation* and *flexion*. What is more, the *CG* also changed in contractions where some of the muscles behave as antagonists, as in the case of Triceps and Anconeo during *flexion* or the Biceps and Brachioradialis during *extension*.

IV. Discussion and Conclusions

This study analyzed the spatial characteristics of the activation of motor units during an endurance contraction. Results are consistent with previous observations on spiral muscles, although muscles in this analysis presented different architectures. Preliminary results in four different subjects show different time-activation patterns associated with the amplitude of motor unit action potentials and its spatial distribution. Furthermore, such changes may be related to the type of task (flexion, extension, pronation and supination in this work) pointing to motor units' activation strategies that depends on this factor or on the co-activation with other muscles. A similar behavior, was observed in [4] for the trapezius and it was attributed to a progressive activation of motor units in a muscle region that was not active at the beginning of the contraction in response to fatigue. However, such finding for other types of muscles like the ones proposed in our study needs to be confirmed with a bigger database.

In addition, it was observed that changes in amplitude, which reflect the number and firing frequency of active motor units, were best assessed from RMS activation maps than from bipolar signals, given that the latter is constrained to a delimited volume of the muscle. Although simulated bipolar recordings in this study may be biased because of the size of the electrodes (5 mm), such bias should not affect the rate of change of the amplitude of the EMG signal but the estimation of the amplitude itself, that is, similar bias can be expected along the duration of the exercise. This consideration, however, should be taken in further studies.

Future work will comprise the use of a bigger database and the extraction of features associated with similarity between maps like mutual information or 2D cross-correlation.

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