Evaluation of HD-sEMG Probability Density Function Deformations in Ramp Exercise

M. Al Harrach, S. Boudaoud, D. Gamet, J.F. Grosset and F. Marin

Abstract— **the aim of the present study is to propose a subject-specific screening approach of High Density surface EMG (HD-sEMG) Probability Density Function (PDF) shape evolution in experimental conditions following a ramp exercise from 0% to 50% of the Maximum Voluntary Contraction (MVC) during 25 seconds of isometric contractions of the Biceps Brachii from six healthy subjects. This method uses High Order Statistics (HOS), namely the kurtosis and the skewness for PDF shape screening examined on selectively positioned Laplacian sEMG channels obtained on an 8x8 HD-sEMG grid. For each subject, the position of the Laplacian channels was chosen based on the level of muscle activation obtained from the Signal to Noise Ratio (SNR) matrix computed for the 64 sEMG signals of the grid in order to obtain independent Laplacian configurations localized in areas with high SNRs indicating high muscle activation. Afterwards, we used the Principal Component Analysis (PCA) to obtain the principal trend of the kurtosis and the skewness computed from the selected Laplacian signals according to force level variation. The obtained results show a globally common increasing HOS trend according to force increase from 0% to 50% MVC for all the subjects regardless of the anatomical, instrumental and physiological variability that usually strongly influences these trends.**

I. INTRODUCTION

The surface electromyography (sEMG) is a noninvasive technique to measure the electrical currents generated in muscles during contraction following a neural command[1]. This complex electrophysiological signal depends on various parameters: anatomical, neural, instrumental…[1]. Another instrumental variability is the electrode arrangement (monopolar, bipolar) and location that have a strong influence on the measured sEMG signals. In recent years, HD-EMG recording techniques have emerged as an alternative for classical bipolar electrodes, thus, taking into account aspects of spatial distribution of potentials and eliminating the electrode position variability by covering the active muscle zone with a grid of electrodes with minimal inter-electrode spacing (high spatial resolution).

Classical sEMG amplitude descriptors are generally based on the first and second order moments[1]. However, these parameters are not sufficient to study PDF shape variation of the sEMG signals since the assumption of the Gaussianity has been proven invalid in many contexts (contraction level, fatigue, electrode arrangement)[1][2]. Recent studies focused on the proficiency of High Order Statistics (HOS) in tracking the shape variation of the sEMG PDF and consequently these parameters have been used in EMG classification [3], force classification [1], muscle contraction determination [4]. Concerning the HOS/force relationship definition, even if some studies obtained promising results [1],[2],[5] in both simulation and experimentation, there is not yet a clear consensus on the nature of this relationship due to the described types of variability.

This study describes a subject-specific method, including both Laplacian channel selection and PCA decomposition, for the evaluation of the HOS/force relationship on an experimental database collected from six subjects, using an 8x8 HD-EMG grid under isometric contractions during ramp exercise (0-50% MVC).

II. MATERIALS AND METHODS

A. Experimental Data Recording and Processing

Six healthy male subjects (mean± std, age: 22.2±1.3 years; stature: 176.7±5.5 cm; body mass: 71.1±5.8 kg) participated in the study. The sEMG signals obtained from a two dimensional adhesive array consisting of 64 electrodes of circular shape were recorded from the Biceps Brachii (BB), during isometric voluntary contractions with the elbow flexed at 90°. The adhesive array was placed either proximally (~1.5 cm) from the main IZ (Innervation Zone) location supposed to be in the middle of the BB muscle (Fig. 1). The reference and the ground electrodes were placed on the elbow bone and around the wrist respectively.

The 64 monopolar sEMG signals were acquired using TMSI REFA acquisition system (Netherlands), and recorded with specific software with a 2048 Hz sampling frequency. A force signal was measured simultaneously with the sEMG signals by a strain gauge, and displayed in real-time on an oscilloscope for visual feedback purpose to the subjects.

The protocol begins by measuring the reference Maximum Voluntary Contraction (MVC) of the subjects after recording three MVC elbow flexion contractions lasting five seconds and choosing the highest as the reference. Then the subjects were requested to perform a series of isometric force ramps from 0%MVC to 50%MVC lasting 25 seconds by following the reference force ramp on the oscilloscope screen. Few ramps were performed before the beginning of the protocol to train the subjects to track the ramp target.

This work was carried out and funded in the framework of the Labex MS2T. It was supported by the French Government, through the program “Investments for the future” managed by the National Agency for Research (Reference ANR-11-IDEX-0004-02)

M. AL Harrach, S. Boudaoud, D. Gamet, J.F. Grosset and F. Marin are with Université de Technologie de Compiègne, CNRS UMR 7338 BMBI, 60200 Compiègne, France, (e-mail: mariam.al-harrach@utc.fr, sofiane.boudaoud@utc.fr, didier.gamet@utc.fr, jean-francois.grosset@utc.fr frederic.marin@utc.fr).

978-1-4244-7929-0/14/$26.00 ©2014 IEEE

For the processing algorithm, signals of 25.5s in duration were used wherein we took the first part of the recordings (0.5s) where there is no contraction as an estimation of the observed noise in order to calculate the SNR.

B. HOS parameters

To study the variation of sEMG amplitude with the increase of Force intensity from 0%MVC to 50%MVC in an isometric ramp exercise we used HOS parameters, the skewness (asymmetry) and the kurtosis (flatness), that track indirectly the PDF shape modifications of the sEMG signal. We recall briefly the definitions of both normalized parameters in the following equations for the sEMG amplitude:

$$\mathrm{Skew}(\mathrm{sEMG})=\frac{E\left[(\mathrm{sEMG}-\mu)^{3}\right]}{\left(E\left[(\mathrm{sEMG}-\mu)^{2}\right]\right)^{\frac{3}{2}}} \tag{1}$$

$$\mathrm{Kur}(\mathrm{sEMG})=\frac{E\left[(\mathrm{sEMG}-\mu)^{4}\right]}{\left(E\left[(\mathrm{sEMG}-\mu)^{2}\right]\right)^{2}}-3 \tag{2}$$

Where E(.) is defined as the expectation operator, and μ is the mean value of the sEMG signal amplitude. It is important here to note that these high moments are invariant to the mean value and variance variability. These parameters were computed on a 2.5s moving window (5000 samples) covering the 25s force ramp without overlapping to obtain acceptable estimation accuracy.

C. Laplacian channels selection procedure

The selection of the Laplacian matrices for each subject was done automatically after channel selection. Since not all the channels of the grid have the same Signal to Noise Ratio (SNR) we find some channels with high level of noise superposition (power line noise, white Gaussian noise, movement artifacts…) hence a low SNR, therefore, we start by computing the SNR of all the channels of the grid according to:

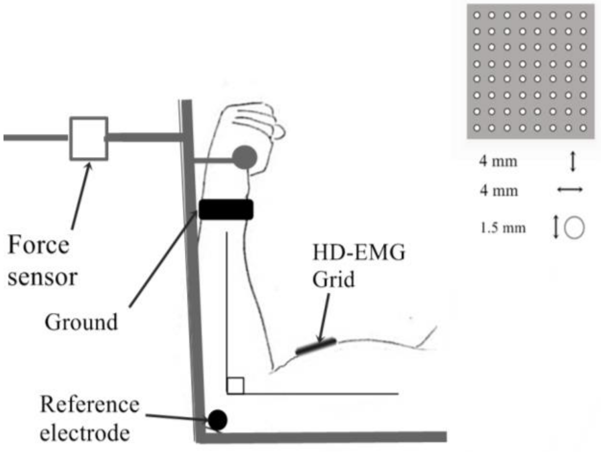


Figure 1. The experimental protocol

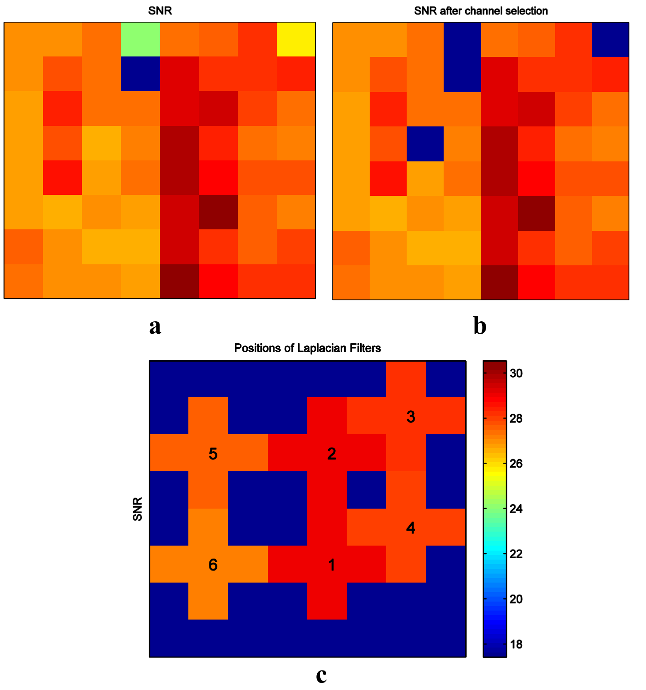


Figure 2. 2.a.The SNR matrix of the grid 2.b.The SNR matrix of the grid after channel selection (suppressed channels in blue) 2.c. The Laplacian channel positions according to higher muscle activation areas for subject 1.

$$\mathrm{SNR}=20\times\mathrm{Log}_{10}\left(\frac{\sum|s_i(t)|}{\sum|b_i(t)|}\right) \tag{3}$$

Where $s_i(t)$ is the *i*th EMG signal of the grid and $b_i(t)$ is the corresponding noise obtained from the first 0.5s of the signal recorded without any muscular contraction (visual check). Both signals were computed on 500 samples.

Then, we eliminate the channels with an SNR lower than a threshold defined as:

$$\mathrm{Thr}=\frac{1}{64}\sum_{i=1}^{64}\mathrm{SNR}_i-\sigma_{\mathrm{SNR}} \tag{4}$$

Where SNR_i is the SNR of the ith channel of the grid and σ_{SNR} is the standard deviation of the SNR throughout the grid. Then, the Laplacian matrices were automatically placed so that we obtain independent channels localized in areas with maximum muscle activation (areas with maximum SNR) as shown in Fig. 2 for one of the six subjects.

D. Principal Components Analysis

In this study, the PCA algorithm was used to obtain the principal trends of the HOS parameters. We recall the steps of PCA as follows:

If we consider X the observation matrix (in our case the HOS parameter for the different Laplacian signals), α the vector of the Eigen values and V the matrix of Eigen vectors.

$$R_x=X\times X^{T} \tag{5}$$

The Eigen values of the matrix R_x can be determined by finding the roots of the characteristic polynomial $\det(R_x - \alpha I)$. Then the corresponding eigenvectors are obtained by finding non-zero solutions of the eigenvalue equation. The final step is taking the transpose of the matrix V after elimination of the Eigen vectors corresponding to an Eigen values with a less than 5% of total contribution and multiplying it to the initial observation matrix X as shown in (6).

$$X_{new} = V^{T} \times X \qquad (6)$$

Where X_{new} is the new data vector and V^T is the transposed vector of V[6]. Then we chose the first component of X_{new} as representative of the HOS trend for both skewness and kurtosis since it has usually the majority of the weight (percentage of the Eigen value >70%) as checked in Table.1.

III. RESULTS

For each subject, Laplacian channel position selection procedure was applied as previously described. Afterwards, we computed the classical amplitude estimators, the average rectified value (ARV) and the Root Mean Square (RMS), along with the HOS parameters, the skewness and the kurtosis, for each of the Laplacian signals obtained after finding the optimum position that reflects the highest muscle activation locations. The results of the variation of the four parameter trends with force increase from 0% to 50% MVC for subject 1 are presented in Fig.3. For this subject, the Laplacian channel positions corresponding to the different trends are presented in Fig. 2.c. As we can clearly see in Fig. 3, we have different trends for the kurtosis and skewness with a strong sensitivity to the position of the Laplacian channel in the grid. However, for the ARV and the RMS we have almost the same profile for all the Laplacian signals but with different variation dynamic that depends on the amount of activity for the corresponding Laplacian channel position (MU recruitment).

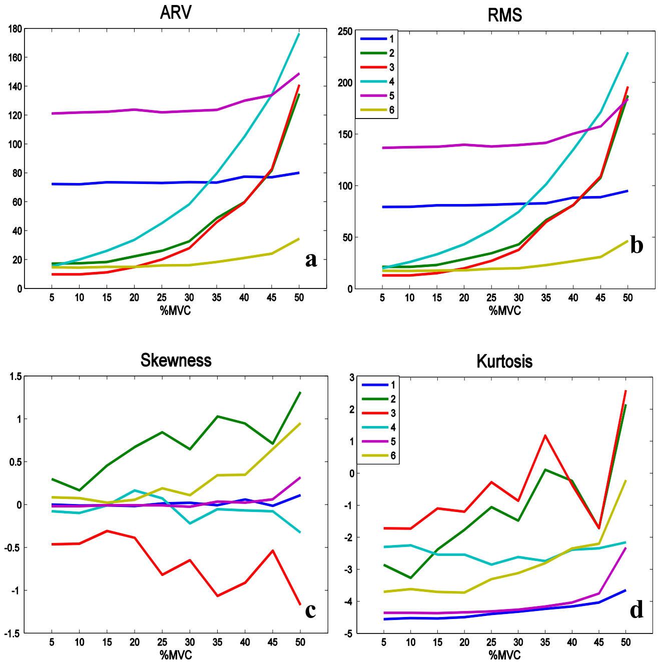
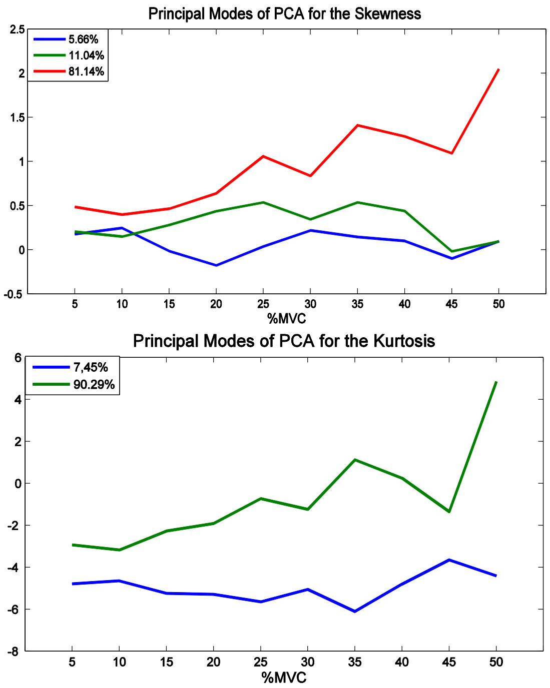

ARV
RMS
Skewness
Kurtosis

Figure 3. The Averaged rectified value (ARV)(3.a), The Root Mean Square (RMS)(3.b), The Skewness (3.c) and The Kurtosis (3.d) variation for the six Laplacian signals according to force level increase from 0% to 50%MVC for subject 1 (Fig.2.c).


Principal Modes of PCA for the Skewness

Principal Modes of PCA for the Kurtosis

Figure 4. The variation of the obtained principal modes of the Kurtosis (up) and the Skewness (bottom) with force intensity increase from 0% to 50%MVC for subject 1.

According to Fig. 3.a and 3.b, we obtained the biggest dynamics for Laplacian 2, 3 and 4.

Then, the PCA algorithm previously described is performed to obtain the dominant trend for both HOS parameters. The trends of the skewness and the kurtosis after reconstruction from their respective principal modes having Eigen value weights above 5% are presented in Fig. 4 for subject 1. We can clearly observe that we have a dominant shape variation profile (an increase with force intensity increase) for both HOS parameters (principal mode).

Eventually, this procedure was applied to all six ramps collected from six different subjects with different

TABLE I. PERCENTAGE OF PRINCIPAL MODE CONTRIBUTION

	Kurtosis (%)	Skewness (%)
Subject 1	90.29	81.14
Subject 2	89.61	80.57
Subject 3	76.68	77.43
Subject 4	76.93	88.68
Subject 5	71.23	78.70
Subject 6	74.86	72.64

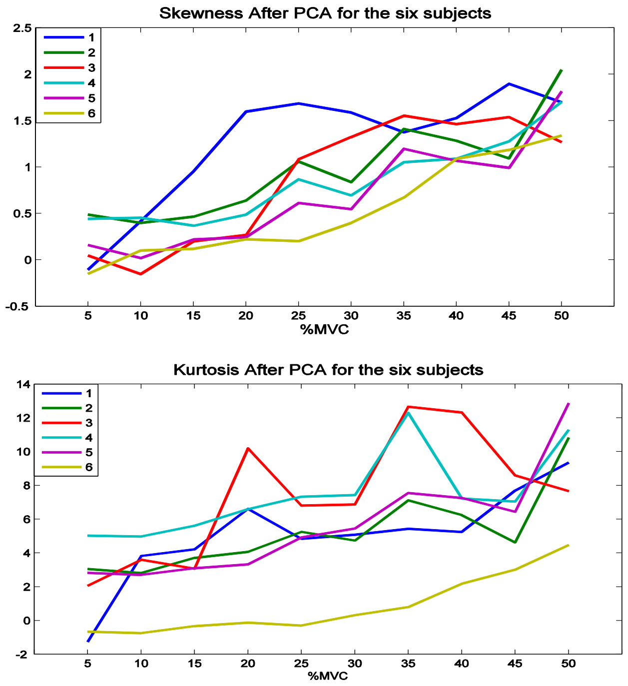


Figure 5. Trends of the Skewness (up) and the Kurtosis (bottom) for the six subjects with force intensity increase from 0% to 50% MVC.

anatomical (ex: MU number, type and position), physiological (ex: conduction velocity), neural (ex: MU recruitment pattern) and instrumental (ex: grid position according to IZ) properties. The results are presented in Fig.5 and Table I. Fig.5 presents the trends of the principal mode for the skewness and the kurtosis for the six subjects according to continuous force intensity increase (ramp exercise) after PCA where the weight percentage of this principal mode for each subject and each HOS parameter is presented in Table I. By observing Fig.5, we can observe that we retrieve the increasing trend observed previously for both HOS parameters.

However, although we have a global trend, we can clearly observe an important variability in the shape of these trends among subjects.

IV. DISCUSSION AND CONCLUSION

The objective of this study was the evaluation of possible trends of the HOS parameters, indicating reproducible shape modifications of the sEMG PDF, according to continuous force increase (ramp) exercise in isometric contractions for different subjects. This interest is motivated by recent studies that pointed, with no consensus on its nature, a possible non-Gaussianity behavior of the sEMG signal amplitude according to force increase [1],[3],[5]. However, this behavior is difficult to observe in presence of several sources of variability. For this purpose, we developed a subject-specific procedure that allows the extraction of HOS trends from a grid of 64 monopolar channels by combining channel selection, Laplacian arrangement, and PCA algorithm. The main obtained result of the proposed study is the estimation of a common trend for both HOS parameters despite the presence of the described variability. This trend represents an increase in non-Gaussianity when the measured force increases from 0% to 50% MVC. This trend has been observed in recent studies in simulation and experimentation but not systematically for all subjects as in this study [1], [2]. An attempt to physiologically explain this trend should be linked to the MU recruitment strategies. In fact, with force increase, more fast type MU, localized closer to the surface for the Biceps Brachii, are recruited [7], which results in relative high amplitude MU action potential trains. And since the Laplacian arrangement generates highly asymmetric MU action potentials with important positive wave, the direct consequence should be the apparition of PDF shape deformation toward positive amplitude sEMG values explaining the positive skewness and kurtosis according to force increase. This proposed hypothesis should be clearly demonstrated in future works. Another application of this study should be a better definition of the sEMG/force relationship including robust functional PDF shape parameters related to sEMG signal amplitude [8].

REFERENCES

[1] B. S. Fouaz Sofiane Ayachi, "Evaluation of Muscle Force Classification Using Shape Analysis of the sEMG Probability Density Function: A simulation study," *Med. Amp Biol. Eng. Amp Comput.*, 2013.

[2] K. Nazarpour, A. H. Al-Timemy, G. Bugmann, and A. Jackson, "A note on the probability distribution function of the surface electromyogram signal," *Brain Res. Bull.*, vol. 90, pp. 88–91, Jan. 2013.

[3] K. Nazarpour, A.-R. Sharafat, and S. M. P. Firoozabadi, "Application of Higher Order Statistics to Surface Electromyogram Signal Classification," *IEEE Trans. Biomed. Eng.*, vol. 54, no. 10, pp. 1762–1769, Oct. 2007.

[4] M. s. Hussain, M. b. i. Reaz, F. Mohd-Yasin, and M. i. Ibrahimy, "Electromyography signal analysis using wavelet transform and higher order statistics to determine muscle contraction," *Expert Syst.*, vol. 26, no. 1, pp. 35–48, 2009.

[5] F. Ayachi, S. Boudaoud, J. F. Grosset, and C.Marque, "Study of the Muscular Force/HOS Parameters Relationship from the Surface Electromyogram," in *15th Nordic-Baltic Conference on Biomedical Engineering and Medical Physics (NBC 2011)*, K. Dremstrup, S. Rees, and M. Ø. Jensen, Eds. Springer Berlin Heidelberg, 2011, pp. 187–190.

[6] M. Al Harrach, F. S. Ayachi, S. Boudaoud, J. Laforet, and F. Marin, "Sensitivity evaluation of HOS parameters by data fusion from HD-sEMG grid," in *2013 2nd International Conference on Advances in Biomedical Engineering (ICABME)*, 2013, pp. 97–100.

[7] H. Cao, S. Boudaoud, F. Marin, C. Marque. "Surface EMG-force modelling for the biceps brachii and its experimental evaluation during isometric isotonic contractions." Comp. Meth in Biomech. & Biomed. Eng. 01/2014.

[8] S. Boudaoud, H. Rix, M. AL Harrach, and F. Marin. "Robust Functional Statistics applied to Probability Density Function Shape screening of sEMG data" submitted to 36th IEEE EMBS Conf., Chicago, U.S.A, 2014.