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Electromyostimulation and EMG real time device with muscle fatigue estimation

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Abstract

This study presents a system composed of an electromyostimulation (ES) and an electromyograph (EMG) modules which analyze in real time EMG during ES and proposes a new method based on wavelet decomposition to analyze changes in M wave. It leads to introduce a new muscular fatigue index. Different methods to filter the EMG noise are then compared. The results show that this new index gives reliable and robust results even when noise corrupts significantly the signal.

I. INTRODUCTION

The quantification of M wave changes can estimate the muscle fatigue during ES. It is proved that this wave shape evolves during ES [1], it temporally elongates and shrinks in amplitude. These changes may be used to determine the muscular fatigue [2]. The traditional muscular fatigue indexes are measuring using Peak to Peak (PTP) duration or amplitude, Root Mean Square (RMS), Mean Frequency (F_{mean}) or Median Frequency (F_{med}) [3, 4]. Quantification of muscle fatigue with wavelet treatments is much less common. It is mostly obtained by discrete wavelet transform (DWT) where classical wavelets are used [5]. In this context, this study presents a system composed of two modules devoted to ES and EMG recording which can analyze in real time the EMG signal during ES and proposes a new method, based on wavelet decomposition, to analyze changes in M wave characteristics in order to access to the muscle fatigue during ES.

II. MATERIAL

The device has been conceived to deliver constant current stimulation impulses in the range -100 mA to 100 mA [6]. It allows also to acquire EMGs with the difference between two muscular EMG electrodes and a reference erasing with one electrode laid on a bony point. A software manages the ES with some parameters which are: The current (from 0 mA to $\pm 100\text{ mA}$), the pulse duration (from $500\text{ }\mu\text{s}$ to $2000\text{ }\mu\text{s}$), the frequency (from 10 Hz to 100 Hz), the shapes of pulses (Monophasic, Biphasic, Dual Biphasic, Absorbed and Doublet Nlet [7]) and the stimulation and rest duration. The software analyzes EMGs to estimate the muscular fatigue. A NI-Daq module from National Instruments connects hardware and software to obtain a real-time system.

III. FATIGUE INDEXES

Some fatigue indexes are widely use in literature. It is the case for PTP, RMS, F_{mean} and F_{med} [3, 4]. These fatigue indexes show amplitude or frequency aspects of M wave but they do not consider the entire M wave waveform. The CWT is then used to quantify the dilatation undergone by M wave over a ES. The artifact of stimulation in EMG needs to be removed to avoid interferences in the next treatments. A thresholding method have been use to remove the artifacts [8]. The CWT use a wavelet constructed for each ES session with the first M wave, which is converted in an admissible wavelet with mean least squares optimization and a null mean eligibility condition [9]. Then, CWT is computed using this wavelet. This leads to determine the correlation which exists between any M waves and this wavelet with respect to a temporal dilation.

$$C_{a,b}(s(t), \hat{\psi}(t)) = \int_{\mathbb{R}} s(t) \frac{1}{\sqrt{a}} \hat{\psi} \left(\frac{t-b}{a} \right) dt, \quad (1)$$

with $s(t)$ is the EMG and $\hat{\psi}$ the reference wavelet from M wave. a is a scale factor and b indicates the temporal location. Then, a local maximum algorithm is applied to find the highest CWT result value for each received M wave during ES. Each detected local maxima corresponds to a value of scale factor a , which is used to construct a fatigue index. It indicates the expansion undergone by the reference wavelet between the initial M wave and the following ones. The common fatigue indexes usually decrease toward zero over time, contrary to CWT indexes which increase from 1. In order to keep the same tendency, the inverse of scale parameters are taken to find I_{CWT} fatigue index, that can be expressed as

$$I_{CWT} = \left[\underset{a}{\operatorname{argmax}} \left\{ C_{a,b} \left(s(t), \hat{\psi}(t) \right) \right\} \right]^{-1}. \quad (2)$$

TABLE I
MEAN ABSOLUTE ERROR FOR I_{CWT} (%)

EMG signal	Filter	Mean absolute error (%)
Noise free	None	1.04
With noise	None	6.69
	1D Butterworth	2.60
	1D SWT	2.86
	2D Circular averaging	2.48
	2D Butterworth	2.60

TABLE II
MEAN ABSOLUTE ERROR FOR ALL FATIGUE INDEXES(%)

Fatigue index	Noisy Signal	Butterworth Filtered	SWT Filtered
PTP	34.29	5.36	3.37
RMS	68.61	12.67	3.62
Fmean	204.48	38.60	11.61
Fmed	173.18	23.90	3.82
CWT	6.69	2.60	2.86

The validation of the system has been checked by using synthetic EMG. The construction of this signal is based on experimental M waves acquired during ES. ES was performed on the biceps brachia with a biphasic shape, a 60 mA intensity, a 1 ms pulse duration and 30 Hz, 40 Hz, 50 Hz and 60 Hz frequencies. Five M waves have been taken for each frequency. Then, these M waves are artificially extended (from 1 to 3 times) in time to mimics the expansion undergone by the M waves during a ES. All synthetic M waves are juxtaposed and attenuated exponentially in time, corresponding to a decrease from 1 to 0.1, to include the loss in amplitude which exists in a real EMG. The estimation of I_{CWT} is applied to the synthetic EMG and the efficiency of this algorithm is check by a mean absolute error with the ideal results which are beforehand known, such as

$$ER = \frac{100}{n} \sum_{i=1}^n \frac{|FR_i - IR_i|}{IR_i}, \quad (3)$$

where ER is the mean of error, FR are found results and IR are ideal results. n represents the number of analyzed M waves. The mean absolute error is shown in the Table I at the line "without noise". The error of 1.04% indicates that the I_{CWT} is reliable, as the dilated wavelet reference fits well synthetic M waves. EMG signals may be very little signals, so its noise sensitivity must be studied. To check the I_{CWT} noise sensitivity, synthetic EMGs previously created are used with a standard uniform noise distribution on the interval $\pm 10\%$ of $V_{EMG_{max}}$. After fatigue estimation, the error of noiseless EMG is 1.04% and EMG with noise is 6.69% which show that the noise affects the I_{CWT} . To reduce the noise impact on I_{CWT} , four filters have been implemented, which can be applied directly to the EMG (a low pass 1D Butterworth and a 1D discrete stationary wavelet transform (SWT) filters) or applied to the CWT coefficients (a low pass 2D Butterworth and a circular averaging of radius 10 filters). The filters are applied and averages of errors have been computed thanks to the eq. (3) in order to quantify filters efficiency. On table I, the results of denoising treatment on synthetic EMG have been listed. The best filter is the image processing inspired one with a decrease of error from 6.69% to 2.48%. On table II, the same tests on the sensitivity to noise has been performed for the all fatigue indexes. Obviously, the 2D filtering cannot be applied as no CWT has been made. The error difference between the results of an unfiltered signal and a filtered one is very significant and show that I_{CWT} is less dependent to a noise than literature indexes even without denoising.

IV. EXPERIMENTAL RESULTS

The I_{CWT} processing has been applied to EMG signals obtained under experimental ES exercises on the right biceps brachial of several subjects. Many ES parameters have been chosen for our experiment: intensity from 30 mA to 60 mA, pulse train frequencies from 20 Hz to 60 Hz, pulse shapes propose in II and a total duration of stimulation of 10 s. An example of result is shown in Fig. 1.a. A decreasing of I_{CWT} can be observed during the ES which corresponds to a dilation of M waves over time. It can be interpreted as a sign of muscle fatigue [10]. It illustrates that this index based on CWT is indeed a indicator of fatigue usable on EMG during ES.

V. CONCLUSION

This article presents a new muscle fatigue index which is based on continuous wavelet transform. The changes of shape of M waves are then analyzed to determine their dilations throughout the ES. The results shows that this CWT index could be a suitable fatigue index as it quantifies the M wave elongation during a ES. In addition, the calculated error ratio indicates that the CWT fatigue index is not very disturbed by noise. It implies that I_{CWT} is less subject to noise than indexes based on the frequency or amplitude. A future study would be useful to measure differences in those parameters for a large number of subjects and stimulations.

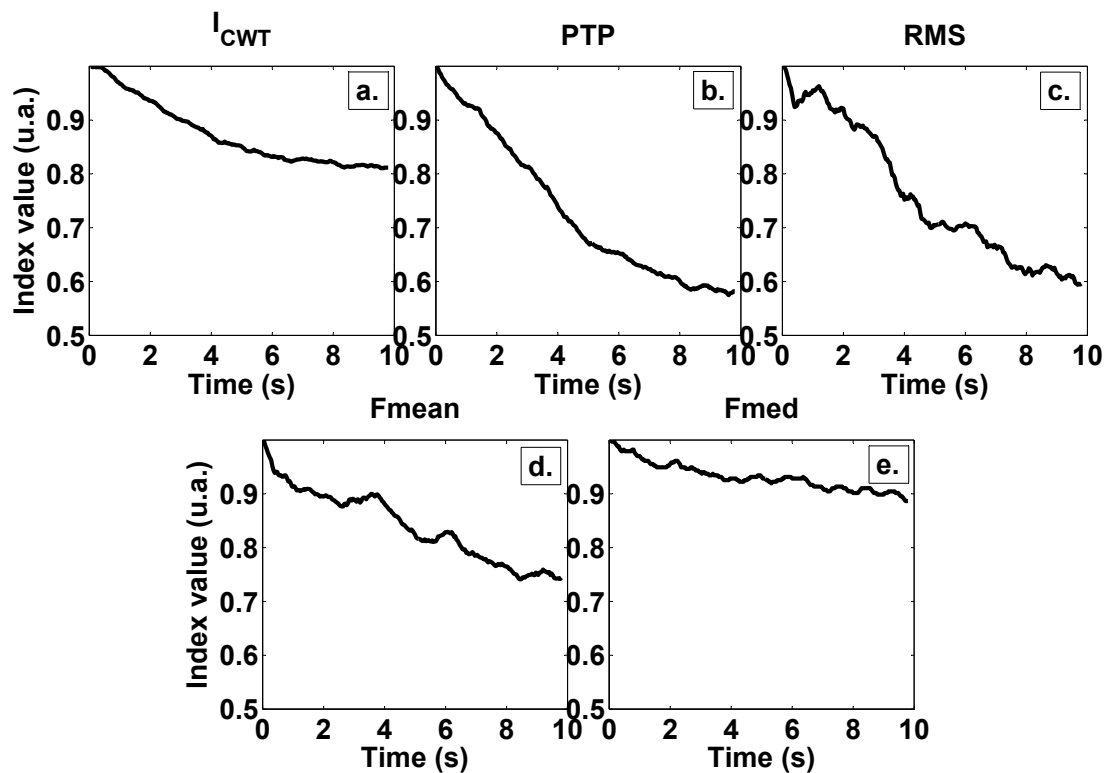


Fig. 1. Example of fatigue indexes corresponding to a biphasic symmetric stimulation with a 60 mA intensity, a 1 ms pulse duration and a 50 Hz pulse train frequency: a. I_{CWT} , b. PTP, c. RMS, d. F_{mean} , e. F_{med} .

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