QUANTIFICATION OF MUSCLE FATIGUE WITH WAVELET ANALYSIS BASED ON EMG DURING MYOELECTRICAL STIMULATION

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Abstract: We propose a device dedicated to real time analysis of electromyograms (EMG) under myoelectrical stimulation (ES). The muscular fatigue analysis, which is obtained by the use of a dedicated analog circuit and a processing part, is the main purpose of this study. The description of a hardware device which incorporates an electro-stimulator and an electromyogram amplifier combined to a computer is detailed. Then, we present a muscular fatigue analysis part based on wavelet decomposition in order to extract a fatigue index, which is confronted with synthetic and experimental data. We conclude that the CWT index applies well to M waves. The noise sensitivity is investigated.

1 INTRODUCTION

Devices using the myoelectrical stimulation (ES) and the analysis of electromyograms (EMG) become more sophisticated and their applications continue to grow. It is the case especially for muscular rehabilitation systems (Chilibeck et al., 1999) for people who have had nerves trauma like paraplegics or hemiplegics and for people who have had a temporary immobilization of one or more limbs leading up to muscle atrophies. Other applications allow FES assisted gait (Matjai et al., 2003; Iwami et al., 2009; Hunt and Stone, 2004), equally in medicine with the intention of search myasthenia or muscular degenerations (Stein and Mushahwar, 2005). The ES retards and even inverses the muscular atrophy. The first goal is to increase the muscle mass by artificial contractions of muscles. In this way, muscles react as during a real exercise and create more muscular tissues (Erika Scremin et al., 1999).

Electrical stimulators have considerably changed since their discovery (Dolhem, 2008) and some follow a predefined program with current controlled injection (Velloso and Souza, 2007). EMGs allow obtaining some informations about the muscle contractions. These informations can give the state of a muscle or its changes over time. Recent works show the use of those indexes in order to manage a dedicated

electrical stimulation (Yeom and Chang, 2010; Sinkjaer et al., 2003). The fatigue analysis during a muscular effort can be essential. When a patient does not feel the fatigue, it can be transcribed by an index resulting from the evaluation of EMG (Mizrahi et al., 2002). During ES, a typical electrical response appears on EMGs: the M Waves (Chesler and Durfee, 1997). This is usually a biphasic wave. It is proved that those wave shapes are changing during an electrical stimulation (Thomas, 1997). It is these changes which are used to determine the muscular fatigue (Knaflitz and Deluca, 1990).

Various indices of muscle fatigue are available with different types of signals. The most common are performed on EMGs which are acquired during voluntary or electrically stimulated contractions (Mizmhi, 1997). Others indexes use the muscle strength developed (Tepavac and Schwirtlich, 1997). In our case, for EMGs, one can cite the Peak to Peak (PTP), Root Mean Square (RMS), Mean Frequency (F_{mean}) and Median Frequency (F_{med}) or also the power spectral density and the zero crossing (Mizmhi, 1997; Tepavac and Schwirtlich, 1997; Chesler and Durfee, 1997).

Some recent articles apply wavelet treatments for fatigue analysis. It is, mostly, obtained by discrete wavelet transform (DWT) where common wavelets are used (Kumar et al., 2004; Vukova et al., 2008).

In this context, we introduce in section 2 a new electro stimulator with EMG feedback and a software which work in real time. Many fatigue treatments were implemented, some from literature and a new one, based on continuous wavelet transform (CWT), which is detailed in section 3. Tests have been made on synthetic and experimental EMG, which are presented in section 4 while in section 5, the influence of noise is also investigated because EMGs are very little signals easily corrupted by the noise. Finally section 6 discusses the presented results on real experimental data and section 7 concludes this article.

2 MATERIAL

We introduce a new electro stimulator allowing the electrical stimulation of a muscle and the fatigue analysis applied to the EMGs feedback in real-time. The device is composed of a hardware part dedicated to deliver stimulations and EMGs amplifications. A software part allows the control of the stimulation and computes the fatigue index. A NIDaq module connects these two parts making the system processing in real-time. Hardware is composed of two parts. The first one is a stimulation board whose circuit is represented on Figure 1. In order to have the same stimulation for all muscles, we decided to use controled injection currents. The circuit is inspired by the work of Han-Chang Wu & al (Wu et al., 2002). The board works symmetrically, the top part is for positive phases and the bottom part for negative phases. The software generates stimulation pulses from $-10\,V$ to $10\,V$. The OPAs copy the voltage V_{in} onto V_{opa} with a null input current. Then, pulse voltages are converted in pulse currents thanks to $R1$ and $Q1$ in order to obtain Ic such as $Ic = \frac{V_{opa}}{R_1} = \frac{V_{in}}{R_1}$. This current can be maintained thanks to the high tension on VDD and $-VDD$. Ic is then copied into the stimulation electrodes by the Wilson current mirror (Q_2, Q_3, Q_4, R_2 and R_3).

Figure 2 shows the EMG board circuit which is the second hardware part. We use surface electrodes because it is a non invasive and painless equipment, although the electrodes positions are crucial (Rutkove et al., 2005). Indeed, EMG signals vary according to their positions on the skin (Rutkove et al., 2005). Two electrodes are on the muscle (E_1 and E_2) and another laid on a bony point (E_{ref}) acting as a reference voltage. This board makes the difference between two voltages of the muscle with a large amplification and reference removal. The two instrumentation amplifiers (INA) U_1 and U_2 are used to erase the reference voltage of the body for E_1 and E_2.
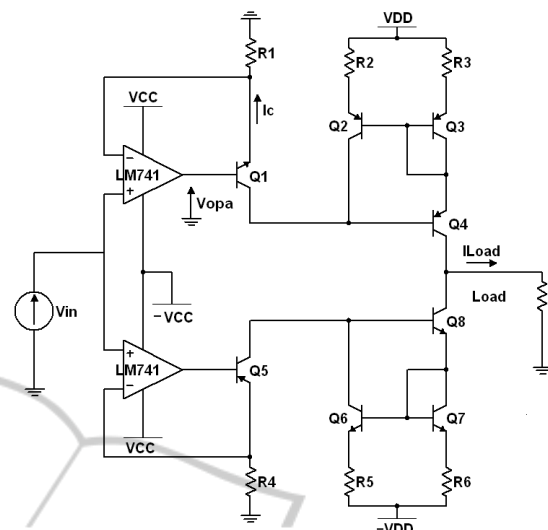

Figure 1: Stimulation diagram.

$$V_{Ei} = G_i \cdot (E_i - E_{ref}), \quad with \quad G_i = \frac{50}{RP_i}, \quad (1)$$

where $i = \{1,2\}$ indicates which electrode is concerned and RP_i is in $K\Omega$. In many EMG amplifiers, just one INA is used to obtain the difference between the two muscular electrodes (Mesin et al., 2009). In our case, we have access to the muscular activity of each electrode. Then, the difference between them is obtained by the same method (eq. 1), consequently $V_{EMG} = G_3 \cdot (V_{E1} - V_{E2})$. Note that V_{EMG} can be filtered with a pass band filter.

The software is developed with Labview. It allows to choose many stimulation parameters in order to have different stimulation pulse shapes and sequences. The current amplitude can vary from 0 mA to 100 mA, the duration of pulses can be set from 500 μs to 2000 μs, the frequency of pulse train from 10 Hz to 100 Hz. The shape of pulses have been chosen among the most common ones in the literature (Watanabe et al., 2000; Karu et al., 2002) such as Monophasic ones, Biphasic ones, Dual Biphasic ones, Asymetric Biphasic ones and Doublet Nlet ones. The stimulation and rest duration and the kind of fatigue treatment are also adjustable. Many graphics have been added in order to visualize the electrical activity such as the representation of one period of stimulation pulses, the ongoing EMG signal in real time, the reference M wave and fatigue analysis results.
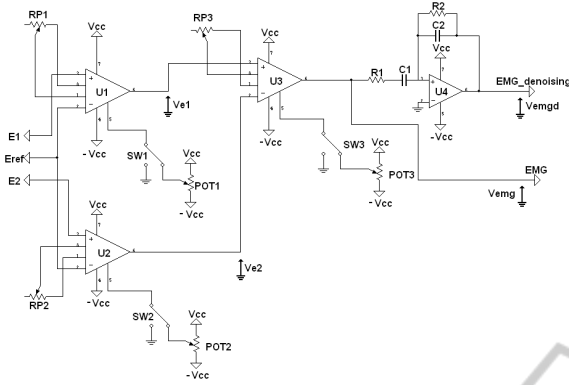
Figure 2: EMG diagram.

3 FATIGUE DETERMINATION

The EMG board leads to obtain the muscular electrical activity but also the stimulation artifacts (Fig 3.a). The elimination of these artifacts are delicate because M waves are in the same ranges of frequency. The method of artifacts removal which has been chosen is a two-stage peak detection algorithm (O'Keeffe et al., 2001). A signal with this artifact removal is given as example in Fig 3.b. The first M wave is used to construct a wavelet pattern from which the dilation of the folowing M waves is deduced by using the continuous wavelet transform (CWT), that is:

$$C_{a,b} = \int_R s(t) \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right) dt, \qquad (2)$$
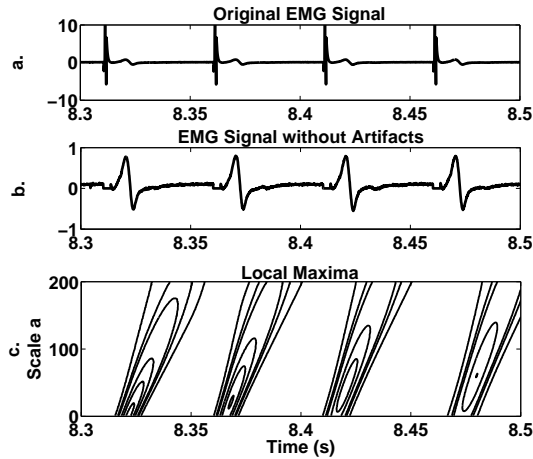

Figure 3: Example of artifact removal. a. EMG signal from EMG board b. EMG without artifacts c. Local maxima circles represent the values of CWT coefficients in top vision like topographical view. Big circles are small values and small circles are high values.

with $s(t)$ the signal, (*i.e.* the EMG signals), ψ the used wavelet (in our case, it is the first M wave) and a the applied scale factor. For each received M wave during the stimulation, a local maxima algorithm is used on the results of CWT, leading to find the best match between the scale factor and the temporal expansion of M waves. Figure 3.c shows some levels of CWT coefficients, the smallest circles corresponding to the highest values. Those indexes represent the expansion undergone by the M wave reference during the stimulation. The scales from local maxima are used as fatigue indexes. The indexes of fatigue from literature move downward zero over time, contrary to CWT indexes which go up from 1. In order to keep this tendency, the inverse of scale parameters have been taken as $I_{CWT} = 1/a$. Resulting curves are displayed in Figure 7. In addition to our fatigue index based on the CWT, other indexes were implemented in the software. Those treatments are directly inspired from literature (Thomas, 1997; Mizmhi, 1997; Chesler and Durfee, 1997; Mizrahi et al., 1997). Two indexes are based on magnitude, Peak To Peak (PTP) and Root Mean Square (RMS) and two others are frequency based, Mean Frequency (F_{mean}) and Median Frequency (F_{med}).

4 TEST WITH SYNTHETIC SIGNALS

Synthetic EMG signals have been realized to check the CWT fatigue algorithm by using a M wave reference recorded experimentally. Then, thanks to those reference M waves, synthetic EMGs are created. Figure 4 illustrates the method for the experimental M wave (Fig 4.a). The M wave reference is temporally increasingly dilated by a factor from 1 to 3 (Fig 4.b). Then, each resulting M wave is juxtaposed (Fig 4.c) and weighted by a decreasing exponential envelope to give a synthetic realistic EMG (Fig 4.d).

The CWT algorithm is applied on the synthetic EMGs. Figure 5 shows the results for experimental based EMG signal. To check the efficiency of this algorithm, a mean-square error measure is performed. This error is computed as:

$$ER_{mean} = \frac{1}{n} \sum_{i=1}^{n} \frac{|FR_i - IR_i|}{IR_i} \times 100, \qquad (3)$$

where ER is means of error ratio, FR are found results and IR are ideal results. n represents the number of analysed M wave. Table 1 at the line "without noise" displays this error ratio, which is equal to 1.04% for the synthetic EMG based on an experimental M wave.

The error rate indicates that the CWT based index applies quite well to experimental M waves.

5 NOISE SENSITIVITY

EMGs are very little signals that can engender a significant noise to signal ratio (NSR). Therefore, it may be useful to study the influence of noise on the process. A standard uniform noise distribution on the open interval (-1,1) is used. Then it is multiplied by a factor defined on a certain percentage of maximum voltage of EMG and the EMG signal and noise are added. Figure 6 shows the CWT fatigue indexes on a experimental based EMG signal under noise (the magnitude of noise was 10 % of the V_{EMG} maxima). The dot line corresponds to the ideal case, the dashed line to a noisy EMG signal and the continuous line to a pure EMG one. Obviously, the results with noisy EMG are worse than pure EMG.

With the intention of reducing the noise impact on the CWT based index, five filters have been implemented. Those filters can be separated into two groups; the filters of the first group are applied to EMG signals. In this case, the filtering which is applied before the fatigue extraction can be a simple low pass 1D Butterworth one or a 1D wavelet one which uses the discrete stationary wavelet transform (SWT). The second group corresponds to some filtering applied to the CWT coefficients. Then, filtering is made during the fatigue algorithm computing. Three cases have been investigated; the first one is an imagery filtering issue, the second one is a 1D Butterworth filter applied to each line of the 2D matrix $C_{a,b}$ and the last one is a 2D wavelet filtering based on SWT. Filters are
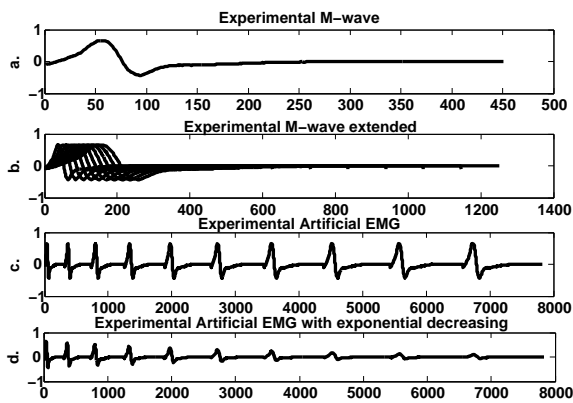

Figure 4: a. M wave from experiment b. M wave extended in time with a factor from 1 to 3 c. artificial EMG signal created with experimental extended M waves by juxtaposition d. loss in amplitude by an decreasing exponential to give final artificial EMG signal.
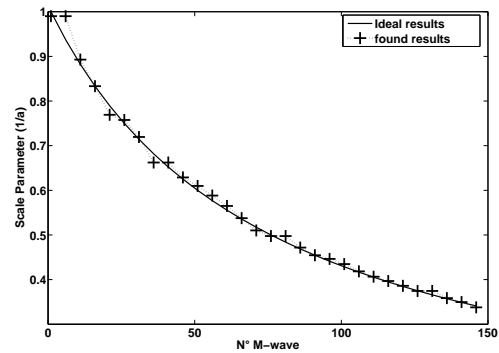

Figure 5: Results of fatigue detection by CWT with synthetic EMG (gray + line) and ideal result (black line).
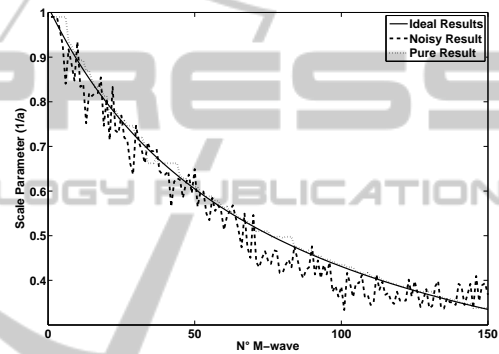

Figure 6: Application of the CWT fatigue index on an experimental based EMG signal. Dot line are the ideal results, dash line are the results for the noisy EMG (the magnitude of noise was 10 % of the V_{EMG} maxima) and continuous line for the EMG signal.

applied to the synthetic EMG signals. In order to have a clear representation of filters efficiency, averages of errors have been made by using eq. 3. Those errors are listed in Table 1. For both Butterworth filters, the errors are identical all the time, but the execution duration is really longer for the 2D filtering because it is applied to the CWT coefficients. Therefore, the number of point that need to be treated is much more important. The best filter for the synthetic EMG signals is the imagery inspired one (a circular averaging filter) with a decrease from 6.69% of error for the noisy signal to 2.48%.

The same test on the influence of noise has also been performed for the others fatigue indexes from the literature. As 2D filtering cannot be applied to those signals because no CWT has been made, only two filters have been performed; the 1D Butterworth and the 1D SWT filter. The errors between the ideal results and three signals (noisy synthetic EMG, filtered with Butterworth and SWT) have been made and those errors are shown in Table 2. The differ-

ence of error between the results of a unfiltered signal and a filtered signal is very significative. The error is more significative for the SWT filtering. It is therefore necessary to choose a SWT filter rather than a classic one because wavelet filter are more efficient on a noisy EMG.

Tables 1 and 2 show that CWT fatigue indexes are less noise dependant than the literature indexes with or without denoising.

Table 1: Square-Mean Error for the CWT fatigue index (%).

Kind Filtre	Experimental Based Error
Without Noise	1.0395
With Noise	6.6945
Filter 1D Butterworth	2.6042
Filter 1D SWT	2.8618
Filter 2D Image	2.4826
Filter 2D Butterworth	2.6042
Filter 2D SWT	7.8229

Table 2: Square-Mean Error for Indices in Literature(%),PTP: peak to peak, RMS: root mean square, Fmean: mean frequency and Fmed: median frequency.

Experimental Based EMG Signal			
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

6 VALIDATION

The CWT fatigue processing has been applied to EMG signals obtained under experimental exercice which has been made on the right biceps. The stimulation pulses were biphasic and symetric and the pulses duration was 1000 μs. The pulse train was 50 Hz and the injected current was 60 mA. The artifacts have been removed and the first M wave found has been used as a reference M wave. The results of CWT treatment are shown in Figure 7 for two distinct subjects. The indexes go toward more and more weak values. The dilation of M waves becomes increasingly important over the stimulation. As the expansion of the M waves is an indicator of fatigue, this curve shows that the muscular fatigue increases during ES. The fatigue indexes based on CWT are indeed an indicator of fatigue usable on EMG signals during ES. On the bottom result (Fig 7), the fatigue
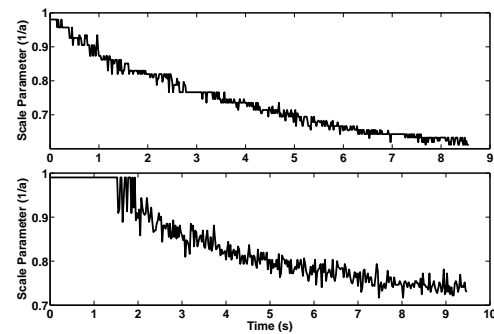

Figure 7: Results of the fatigue detection thanks to our CWT treatment for two distinct subject. On the bottom plot, we can see a plateau time at the beginning of the stimulation.

indexes rest to its maximum level during beginning of the stimulation, corresponding to a plateau state.

7 CONCLUSIONS

A presentation of a ES device with the analyze of fatigue thanks to an EMG feedback and a CWT treatment has been given. It has been shown that wavelets can provide a reliable fatigue index by using the drift of M wave elongation during a ES. A study of noise sensitivity was made and showed that imaging filters (a circular averaging filter) apply rather well to CWT fatigue indexes. It would be interesting to confirmed these primilary results on an increased number of subjects and muscles. Subjects may be healthy or with a disease in order to compare the variation of indexes between them.

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