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A Mixed FES/EMG System for Real Time Analysis of Muscular Fatigue

M. Yochum, S. Binczak, T. Bakir, S. Jacquir and R. Lepers

Abstract—In this article, we present a functional electrical stimulator allowing the extraction in real time of M-wave characteristics from resulting EMG recordings in order to quantify muscle fatigue. This system is composed of three parts. A Labview software managing the stimulation output and electromyogram (EMG) input signal, a hardware part amplifying the output and input signal and a link between the two previous parts which is made up from input/output module (NIDAQ USB 6251). In order to characterize the fatigue level, the Continuous Wavelet Transform is applied yielding a local maxima detection. The fatigue is represented on a scale from 0 for a fine shaped muscle to 100 for a very tired muscle. Preliminary results are given.

I. INTRODUCTION

Since the discover of the phenomena of electro stimulation in the 18th century [1], techniques and methods of stimulation have not cease improving. Nowadays, stimulators are more complex and responses of muscular electrical activity can be analyzed. During the last thirty years, lot of research had been past with the intention of find indicators which estimate the level of muscle fatigue [2]. The detection of fatigue can be useful in several applications notably for people who cannot feel the muscular fatigue (paraplegic or hemiplegic) or the rehabilitation of injured limbs [3]. Most usual assessments are performed with EMG signals and M-waves recorded by needle or surface electrodes. M-waves are particular electrical activities which follow stimulation pulses (see Fig. 7). Once the signal has been recorded, a dedicated processing can be applied to determine the level of muscular fatigue from M-wave characteristics or global EMG signal, such as the peak to peak (PTP) measures, the total power spectrum, the mean absolute value (MAV), the Root mean square (RMS), the mean (MF) and the median frequency (MDF) [2]. Nevertheless, these are usually post-processing techniques which forbid real time biofeedback control strategies. Therefore, the aim of our study is to realize a functional electrical stimulation (FES) system with an EMG feedback indicator of muscular fatigue in real time. It is based on Wavelet Transform processing. In the last decade, a new kind of indices was indeed obtained using Wavelet Transform[4], [5], [6] characterized by a good accuracy in time-frequency and suitable for real time analysis.

II. MATERIAL AND METHODS

The system, which includes an external hardware part, is PC-controlled though a NIDAQ module [7] by a dedicated

Labview software, enabling, in parallel and in real time, a functional electrical stimulation and a recording of EMG signals. These are acquired even during the stimulation by using surface electrodes yielding a non-invasive and painless process for the patient. Once the EMG signal is obtained, M-waves are extracted and are used to characterize the muscular fatigue.

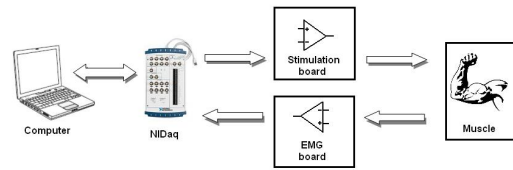


Fig. 1. General diagram of the system

A. Hardware

The computer itself cannot supply the voltage necessary to directly stimulate muscles, so two external hardware boards have been designed for the stimulation. Moreover, the EMG signal must not be send to the computer without modification. Therefore, an external board with instrumental amplifier have been conceived to obtain a usable EMG signal.

1) *Stimulation board*: In order to obtain a functional electrical stimulator, a circuit delivering a constant current output during the stimulation pulse has to be realized with an input voltage control. Actually, two different stimulation boards have been designed, depending on the output current range. The first one (see Fig. 2a) is a simple high tension OPA445, which is set up as a tension to current converter. The output current is defined such as

$$I_{Load} = \frac{V_{in} R_2}{R_5 R_1}, \quad (1)$$

where the tension V_{in} is the stimulation tension computed from the PC and sent as an input through NIDAQ. The supplied current that the OPA can provide is 25 mA at maximum, so this output stage is suitable for little muscles like face or forearm muscles which require a weak current in order to obtain a maximal contraction. For bigger muscles like quadriceps, a second board has been designed, as illustrated in Fig. 2b. In this circuit, two parts operate symmetrically [8] (top for positive phase and bottom for negative phase). Each part is composed of three components. One operational amplifier (OPA) is set as a buffer, leading to obtain a zero input current. The OPA is followed by a transistor Q_1 and a

this current is copied into I_{load2} by the Wilson current mirror (transistor Q_2 , Q_3 and Q_4). The high tension V_{CC} (± 150 V) which supplies the Wilson mirror yields a constant current for a wide range of corporal impedance.

$$I_c = \frac{V_{in}}{R_1} \text{ ,} \quad (2)$$

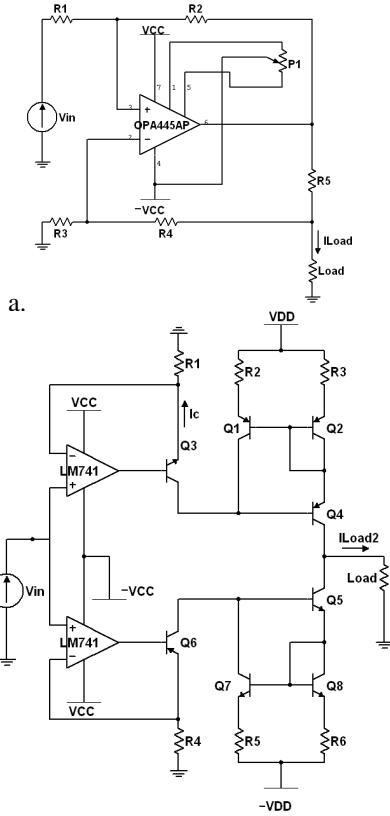


Fig. 2. a. stimulation board with OPA445. b stimulation board with Wilson mirror current.

2) *EMG board*: EMG signals obtained from the two EMG probes are firstly amplified by an instrumental amplifier INA128 [9]. This kind of component supplies high accuracy despite a consequent gain G . Moreover, the Common Mode Rejection Ratio (*CMRR*) for this component is larger than 120 *dB* ensuring a good removal of the common tension at the both input electrodes (see Fig. 3). Gain G of this amplification stage can be set as such as

$$G = \frac{50}{R_1 + R_2} \quad (3)$$

with $R_1 = R_2$ expressed in $K\Omega$ units. Note that a band pass filter following the *INA* can be used in case of a poor Signal to Noise Ratio. Furthermore, a third electrode is added in order to compensate the voltage of the human body.

3) *Interface computer/hardware:* In order to connect the computer to the hardware device, a *NIDAQ USB 6251* module of National instruments is used as a real time interface of the system. It is indeed able to send control signals toward the stimulation board and to receive the EMG board signal

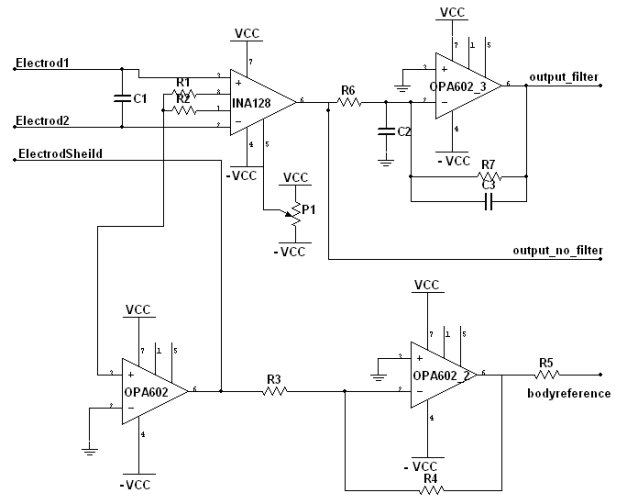


Fig. 3. EMG board

simultaneously. In addition, Labview has a lot of Virtual Instruments (VI) adapted to the NIdaq including real time VIs.

B. Software

The software part is developed using both Matlab and Labview, especially its real time tools. As illustrated in Fig. 4, an interface has been designed enabling to configure the parameters of the stimulation and to display several curves corresponding to the stimulation signals, EMGs, reference M-waves and the continuous indicator of muscular fatigue level. Concerning the configuration of the stimulation signal, the system includes several control parameters according to the stimulation board, such as the amplitude of the output current (from 0 to 25 *mA* or 100 *mA*), the pulse time (from 100 to 600 μs), the period (from 10 to 200 *ms*), the cyclic ratio and even the waveform (see Fig. 5), as suggested in [10]. Besides one can choose to save the received EMG signals.

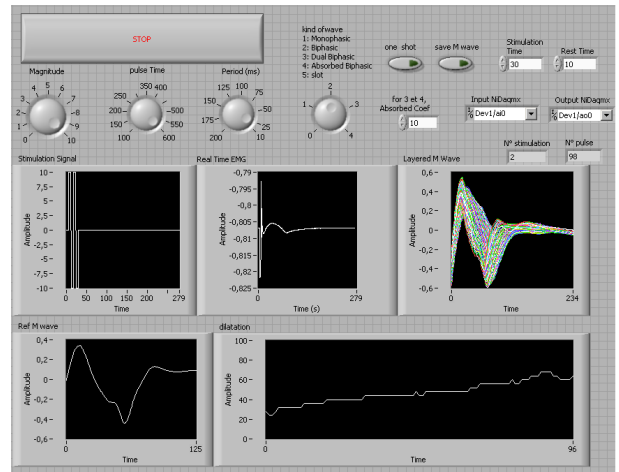


Fig. 4. User Labview interface.

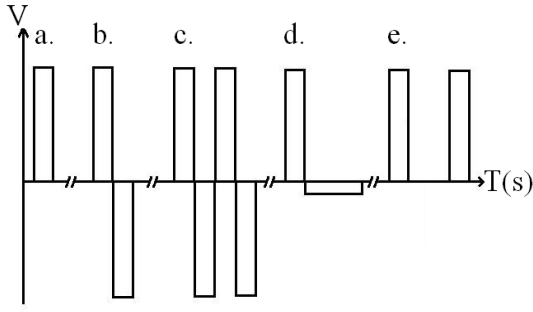


Fig. 5. Waveforms that can be sent to the stimulation board. a. Monophasic. b. Biphasic. c. Dual Biphasic. d. Absorbed Biphasic, the magnitude of negative phase depends on absorbed coefficient percentage. Positive and negative surface are equal. e. doublet Nlet.

C. Signal Processing

During the stimulation, an indicator of fatigue level is performed. This task requires several steps. The first one focus on the detection and suppression of stimulation artifacts and follows a two-stage peak detection algorithm, as proposed in [11]. In fact, the artifact tension is higher than the M-wave tension, so we can detect the artifact by setting two thresholds between its value and the M-wave maxima. The artifact removal is then performed depending on the sign of the gradient of the signal when these threshold values are crossed. The removed artifacts are then counted to check if it corresponds to the number of stimulation pulses. As a result, one can observe in Fig. 6a and b, the EMG signal before and after the artifact removal treatment. Once this process is completed, the M-waves are analyzed in order to characterize the muscular fatigue. This task is based on a process using continuous wavelet transform (CWT). To reduce the influence of interferences and false M-waves, which could be induced by movement of EMG wire or a displacement of the EMG electrodes on the muscle (for instance the moving of the skin with respect to the muscular fiber [12]), a mean on few M-waves is performed. In this way, studied M-waves are more robust and match the real activity of the stimulated muscle. Means are done from one second to a few of seconds. It is not necessary to compute the fatigue indicator for each stimulation pulse because changes in M-waves are rather slow. Moreover, we remove the signal offset to study the M-wave without the body user reference voltage.

The first mean M-wave will be used as a reference signal and the following M-waves mean will be compared to it by performing a CWT. The continuous wavelet transform of a time signal $x(t)$, which is in our case the EMG signal, is defined as

$$T(s, \tau) = \frac{1}{\sqrt{s}} \int_{-\infty}^{+\infty} x(t) \Psi_{s, \tau}^*(t) dt, \quad (4)$$

where $\Psi_{s, \tau}^*(t)$ is the complex conjugate of the analyzing

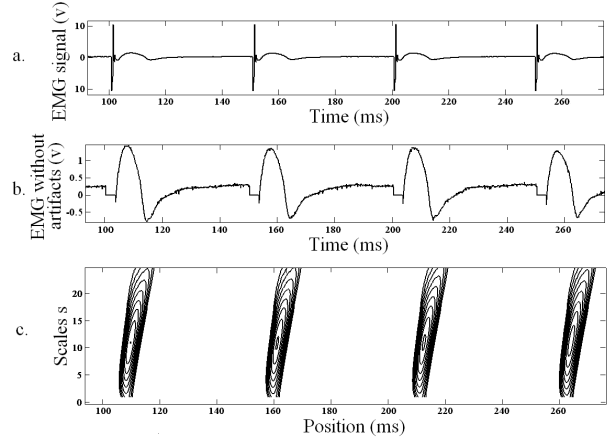


Fig. 6. Example of artifact removal and local maxima detection for 20Hz stimulation with 25 mA on the biceps brachii. a) EMG signal directly from EMG board. b) EMG signal after artifact removal. c) local maxima representation.

wavelet function related to the mother wavelet $\Psi(t)$ as

$$\Psi_{s, \tau}^*(t) = \frac{1}{\sqrt{s}} \Psi\left(\frac{t - \tau}{s}\right) dt, \quad (5)$$

The scale $s \in \mathbb{R}^{+*}$ corresponds to the width of the wavelet function $\Psi_{s, \tau}(t)$ and $\tau \in \mathbb{R}$ is the translation of wavelet along the time axis. The wavelet coefficients in the CWT represent the degree of correlation between a wavelet mother function and the EMG signal. Therefore, the choice of the wavelet basis is crucial for the accurate representation of the EMG signal in the wavelet space. Using a pattern defined from the first mean M-wave experimental signal, an admissible wavelet for CWT is designed by approximating it using least squares optimization under constraints leading to an admissible wavelet (it is obtained by a fitting process using a projection on the space of functions orthogonal to constants). Our goal is to find the level of temporal dilatation between the M-wave reference fatherly and the current M-wave which is given straight forwardly by the value of the scale s corresponding to the M-wave CWT analysis. This level is normalized on a scale from 0 to 100% where zero percent represents a muscle without fatigue (or a least as tired as it was at the beginning of the stimulation). An increase of this level up to 100 % corresponds to an increase of the muscular fatigue which is expressed by a doubling duration of the M-wave ($s = 2$). The temporal dilatation determination is performed by using a local maxima detection. The results of this local maxima computation are shown in Fig. 6c, in which several circles corresponding to level set of local maxima amplitudes can be observed (large circles correspond to the smaller amplitudes). Once this step passed over, one can associate the level dilatation of the CWT to the temporal dilatation of M-wave reference. This dilatation represents a fatigue indicator. Indeed, more tired the muscle is more M-waves are flattened and broadened [13] (see the example shown in Fig. 7). We find the maximum of correlation of the CWT and thus find the corresponding dilatation coefficient.

This result is set on scale before being displayed on the software interface.

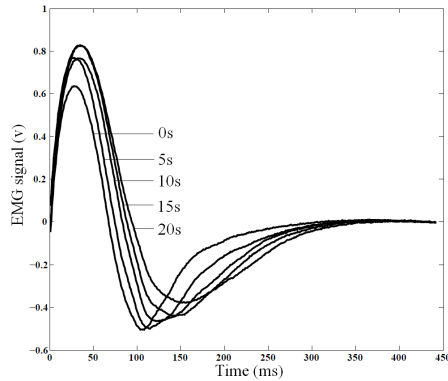


Fig. 7. Layered M-wave for 20s stimulation. One can observe that the M-waves become increasingly long.

III. RESULTS

In this part, the results of our system are presented in the case where the muscle under investigation is the right biceps brachii. The arm and the forearm are placed so that they form a 90° angle and the contraction is done in an isometric way. We laid two stimulation electrodes at both ends of the muscle and two EMG electrodes are put on the muscle belly. The EMG reference electrode is applied on a bony point of the left arm (like humerus distal extremity). The first step is the M-wave reference recording which is done during a first stimulation of 5 s, followed by a 10 s pause. Next, the muscle is stimulated during 60 s with CWT and local maxima processing. Figures 8a and b show the evolution of the calculated indicator of muscular fatigue. The fatigue is represented on a scale from 0 to 100 % where 0 % indicates this initial condition of the muscle at the beginning of the stimulation. We can see that the peak to peak duration of the M-wave increases during the stimulation. These two examples show a drift from 40 to 60 percents. We notice that the dilatation follows a quasi-linear drift which implies that the fatigue grows in a constant way. M-wave dilatations symbolize a good indicator of fatigue because one can observe extensions from more than 60 %. Fatigue value is not always in the zero neighborhood at the beginning of the stimulation (Fig. 8 top). This phenomenon may be due to the length of the acquisition of the reference M-wave in which the muscle is already beginning to be tired when the stimulation is applied again.

IV. CONCLUSION

This work presents a system of functional electrical stimulation which is able to indicate the intensity of the muscular fatigue during an exercise. This device has three parts, an external hardware board, a Labview-Matlab software and a *NIDAQ* link module. We can see the interest of Continuous Wavelet Transforms and local maxima in order to find a fatigue indicator. The reading is easy thanks to a representation on a scale from 0 to 100 % and gives

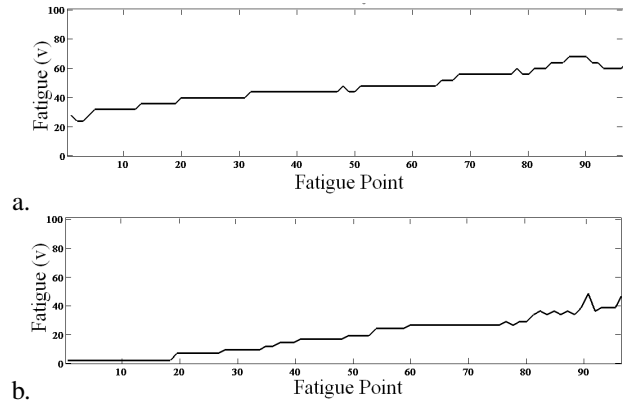


Fig. 8. Evolution of the fatigue parameter during stimulation.

the state of the muscular fatigue during the stimulation. As an possible application, this kind of indicator could be useful in rehabilitation medicine and medicine of paralyzed limb. Indeed, it may be difficult for paraplegic or hemiplegic persons to give a feedback about their fatigue feeling during FES rehabilitation. So, this kind of system could allow these persons to do functional electrical stimulation rehabilitation without taking the risk to over-stimulate a muscle.

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