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ON/OFF sEMG Switch for FES Activation

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***Abstract*—Surface electromyography (sEMG) is the electrical representation of muscle activity. In the case of patients with central nervous system damage, sEMG signals can be used as a control signal to start therapies at patient demand. This is achieved by means of processing such signals using different families of wavelets to clear the signal from baseline sifts and noise, and to find muscle activity/no-activity regions. A one channel ON/OFF switch control is designed, where a threshold is calculated automatically based on a training protocol that consists of 3 muscle contractions and 3 rests. With this data, the threshold is set and as long as the contraction amplitude surpasses it, a simulation for functional electrical stimulation (FES) is activated. Each processing window (200 samples) is compared to the previous one before declaring the switch at ON position, to avoid misfires. The proposed algorithm allows any user to voluntarily activate FES therapy on demand, and rest as necessary; possibly assisting in the regeneration of sensorimotor paths due to neuroplasticity if established as rehabilitation therapy.**

Keywords—sEMG control, threshold switch, neuroprosthesis, online activation, wavelet analysis

I. Introduction

Surface electromyography (sEMG) studies muscle function through the analysis of the sum of all muscle unit action potentials (MUAP's) underneath the skin, where surface electrodes are placed [1] to record electrical signals. There are two main types of electrode configurations: monopolar and bipolar, being bipolar configuration the most used one. Acquisition through bipolar configuration uses two electrodes placed on the skin, centered above the belly of the muscle of interest, with a recommended inter-electrode separation of 20 mm from center to center and a reference electrode placed at a dielectric area, where there is a minimal risk of large common mode disturbance or minimal electrical contribution [2]. These acquired signals can range from microvolts (μV) to millivolts (mV), with most of its energy between 10 Hz and 500 Hz [3].

sEMG–based control techniques have been in development by diverse research laboratories around the world due to its rehabilitation potential. These interfaces are based on the fundamental properties of sEMG signals, being arm movements the most commonly found since these protocols are intuitive enough to be operated by users with little or no training [4]. This kind of control can be used to control prostheses [5], exoskeletons [6], neuroprostheses (NP) [7] and videogame-based rehabilitation therapies [8], among others.

This paper focuses in sEMG–based control for functional electrical stimulation (FES) activation. In FES, bursts of short duration charge pulses activate neurons, generating pulsatile voltage between an anode and a cathode both placed on the skin, contacting the sensory-motor systems in the vicinity of the electrodes below the skin. The resulting pulsatile electric field creates a condition for the depolarization and hyperpolarization along the nerve, resulting in an action potential (AP). The AP is generated from the anode to the cathode and via synapses, different neurons trigger motor activity [9]. Apart from conventional physiotherapy and occupational therapy, FES is also commonly used to improve motor function in patients with central nervous system (CNS) damage [10].

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The CNS consists of the brain and the spinal cord. CNS injuries are a consequence of brain damage, such as stroke, or spinal cord injury. These two types of injuries are the most common ones when it comes to rehabilitation through FES therapy. CNS injuries produce spasticity and due to this, people cannot make upper limb movements as easily as they should. FES can gradually reduce spasticity and help its users regain life quality, lost after the CNS damage occurred.

FES uses multichannel stimulation to mimic lifelike sequences of muscle contractions to ease or aid voluntary actions of damaged muscles. The significant impact of FES is that, if integrated properly, it activates both motor and sensory systems, contributing to changes in cortical excitability [9]. FES has big potential when used in upper limb motor NPs because, by activating motor and sensory systems, users have a better possibility of receiving a more efficient therapy, giving them extra motivation and excitement [11].

Raw sEMG signals contain inevitable noise that is caused by different sources, i.e. inherent noise in the equipment, ambient noise from electromagnetic radiation, or motion artifacts, that cause signal variability and contamination [12]. In order to reduce noise, it is important to pre-process the signal before implementing the sEMG–based control.

There are different ways of filtering raw signals, such as digital filters or wavelet transform (WT) –which is a time-scale representation technique. WT uses correlation with translation and dilation of a wavelet function to yield this transformation.

WTs are important because it is difficult to eliminate or attenuate some noise components using conventional filtering, since noise frequency components tangle with the ones of sEMG signals. WTs can be categorized in two types: discrete wavelet transform (DWT) and continuous wavelet transform (CWT). DWT is the most used when denoising signals because for each decomposition the obtained wavelet coefficients are correlated to high-frequency components of the signal (called detail coefficients, D_i), or to the low-frequency ones (called approximation coefficients, A_i), as shown in Fig. 1 [13].

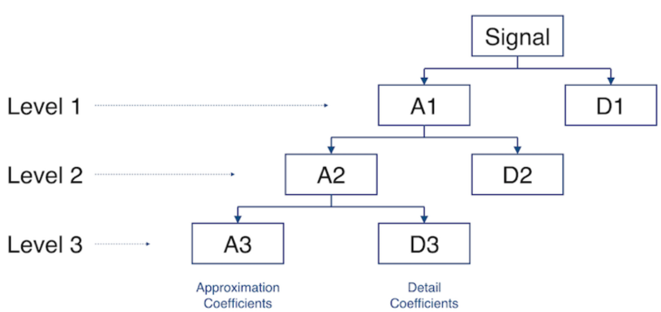

Fig. 1. Discrete Wavelet Transform decomposition tree. Approximation coefficients represent the lower frequencies of the signal. Detail coefficients represent the higher frequencies of the signal. This tree represents 3 decomposition levels, but the signal can be further decomposed depending on the desired frequency to obtain.

The most commonly used filter in signal processing is the Notch Filter and it is used to attenuate the electric power-line interference, which has its main frequency components at 50 Hz in Europe and at 60 Hz in America [14].

The aim of this paper is to show the development of a one channel online ON/OFF sEMG switch control for FES activation and all the necessary steps in order to make the switch functional and efficient, which are: sEMG signal pre-processing, ON/OFF switch control algorithm development and FES activation depending on the resulting output of the switch control. For this application, FES activation is simulated to generate the movement Open Hand; and the switch's goal is to determine if the signal corresponds to sEMG activity or to rest activity. It is important to mention, that even though the switch is being proved using Open Hand, 4 more hand movements (power grasp, fine pinch, supination, and pronation) can be pre-selected manually by the user and be activated by the same muscle or channel. So, a total of 5 hand movements can be activated by FES triggered by the ON/OFF switch control. This is a first approach to sEMG-controlled FES activation.

II. Methodology

Surface electrodes location is very important and their placement must be made following the SENIAM's recomendations [2]. After skin cleaning using an alcohol swab, electrodes are placed on the belly of the brachioradialis muscle, with a 2.5 centimeters separation, the reference is placed in the olecranon, a dielectric area.

Signal recording is performed using the open hardware acquisition system OpenBCI, which has a sampling frequency of 250 Hz, a fixed gain of 24, with a 1–channel bipolar configuration. For signal processing, sEMG is acquired through the OpenViBe open software and processed offline. For the development of the ON/OFF control switch, signals are acquired online through a software called *Control and Configuration Platform for Upper Limb Rehabilitation Neuroprosthesis* (Plataforma de Control y Configuración de una Neuroprótesis para Rehabilitación de Miembro Superior) registered at the national copyright institution of Mexico [15], this platform was previously developed [16] and reported [17].

All signal processing and control algorithms are developed using Matlab®.

A. *sEMG Signal Processing*

The processing of the sEMG signals is of great importance. To perform this procedure, a protocol was designed and followed, Fig. 2.

The processing of the signal has several steps, as seen in Fig. 3. To start, the signal is sent to the processing algorithm in windows of 100, 125, 150 and 200 samples. Then, the signal goes through a Notch filter to attenuate the components that correspond to the power line. The Notch filter that was used is a level two Butterworth IIR filter, with cutoff frequencies of 59 Hz and 61 Hz.

Once the noise has been filtered out, the signal is processed using DWT, as explained ahead.

The baseline shifting is located by decomposing the signal using the 9th wavelet of the Daubechies family (db9) and 5 levels of decomposition, to find the lower frequency components (> 1 Hz) and eliminate them. Then, the baseline shift signal is reconstructed using only approximation coefficients. This signal is subtracted from the filtered sEMG signal in order to eliminate baseline shifts, Fig. 3.

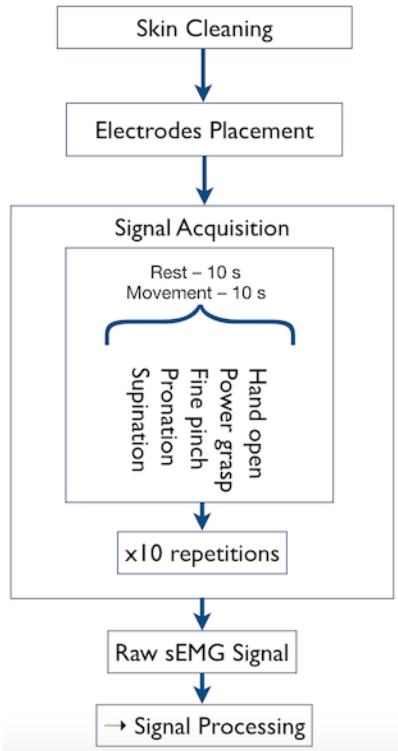

Fig. 2. Signal acquisition protocol to acquire sEMG signals for offline post-processing.

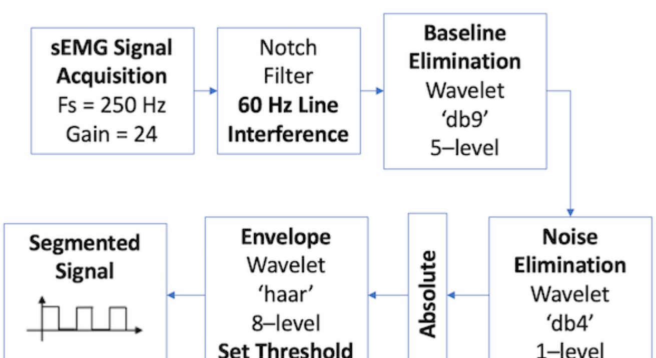

Fig. 3. Signal processing algorithm to segment sEMG signal movement activation versus no movement or rest.

The second DWT uses the 4th wavelet of Daubechies family (db4) with 1 level of decomposition, for general noise elimination. After decomposing the processed signal, the detail coefficients are used for the reconstruction. With this transformation, we obtain as a result a signal with less noise that will be more contrasting, this will help improve the ON/OFF switch behavior.

From this cleaned processed signal, the absolute value is calculated. The resulting signal is decomposed using a Haar wavelet with a decomposition level of 8. In this transformation, the signal is reconstructed with the approximation coefficients, resulting in the envelope of the sEMG processed signal.

B. ON/OFF Switch Control

For the ON/OFF switch control, the first step is to calculate the average value of the envelope signal for each processing window. It is necessary to concatenate the number of windows that correspond to a period of three muscle activations and rest periods (which has the same duration as the contraction) and determine their maximum value, to determine the threshold that activates the switch the half of the maximum value is used.

After the threshold is calculated, the online acquired signals will have to surpass this threshold to result in a positive switch output ON=1. If the incoming processed signals do not surpass the threshold, the output is negative or OFF=0. This approach allows the application to operate online after the first three muscle activations and their respective rest periods, which acts as a calibration prior to an effective use of the switch.

It is important to have as little delay as possible, which is why windows of less than one second are recommended for online processing, taking into consideration that the envelope signal must maintain the necessary characteristics mentioned above to operate efficiently with the switch.

Therefore, the procedure described above was tested with windows of 100, 125, 150 and 200 samples, which are windows of 0.4, 0.5, 0.6 and 0.8 seconds according to the established sampling rate used for this application.

C. FES Activation

The switch output is designed to be a trigger signal to activate FES stimulation, using the Rehamove2® electrical stimulator [18]. Both, sEMG and FES control are performed through the NP software platform mentioned above [15], whose online graphical user interface is shown in Fig. 4. To exemplify the trials of this paper, we used a FES simulation, even though an actual stimulation it has been proved.

If the switch is ON, a signal is sent to activate FES and the simulation is generated. On the contrary, if the switch remains OFF the simulation signal is not generated –this means that either there is no movement or sEMG envelope signals do not have the necessary amplitude to surpass the threshold–.

FES electrodes are placed at the insertion of the muscles. Depending on the desired movement to be stimulated, there are several positions that can be used. In this case, for hand open, the negative electrode is placed at the medial portion of the forearm, and the positive over the superior extensors of the tendons, at the forearm too.

Fig. 4. NP control platform – online window.

FES operates with different parameters, depending on the movement wanted and the user that will receive the stimulation, as well as different stimulation electrodes placed strategically according to the location of the muscles of interest for the desired movement (there is one channel for each movement). Due to these application interests, five FES channels must be used to functionally stimulate the five hand movements (open hand, power grasp, fine pinch, pronation and supination) [17].

The FES activation parameters have the following values:

- Frequency of the stimulation pulses. The stimulation signal frequency is 30 Hz.
- Intensity of the stimulation pulses. The stimulation signal intensity used for FES ranges between 1 mA and 20 mA.
- Ramp time of the stimulation pulses. The standard time used for FES is of 1 second each, both ramp up and ramp down.
- Pulse width. The standard value is of 300 µs for hand open, power grasp and lumbrical grip; and 400 µs for pronation and supination.
- The stimulation to rest ratio is 40 %, 4 s active and 6 s rest.

III. Results

A. sEMG Signal Processing

After a successful electrode placement, 10 sEMG signals recordings were acquired for offline processing.

The Notch filter eliminates the 59–61 Hz band frequency and the baseline shift removal processing allows to better visualize the sEMG contractions versus the no movement sections. The noise elimination segment removed undesired frequencies from the signal; later, the absolute value of the sEMG signal is calculated. These steps left us with a signal that can be used to find the envelope, which is the last phase of the processing algorithm. The Haar wavelet decomposition finds the envelope of the signal without modifying its amplitude or phase. This envelope signal is used later for the ON/OFF Switch Control. The sequence in which the sEMG signal is processed is illustrated in Fig. 5.

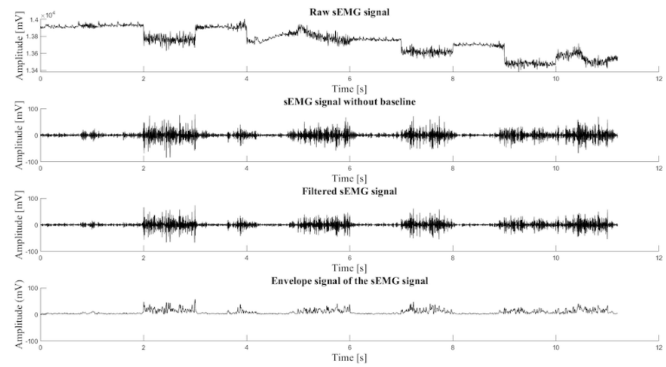

Fig. 5. sEMG signal processing sequence. From top to bottom: Raw sEMG signal, sEMG signal after the Notch filter and without baseline drifts, sEMG signal without ambient noise, and resulting envelope from the processed sEMG signal.

B. ON/OFF Switch Control

The ON/OFF Switch control is used as a command signal for activation of FES when the threshold is surpassed by the envelope of the sEMG signal correctly.

In order to have a useful threshold, it is necessary to have an established acquisition protocol that is congruent with the time had for threshold calculation at the sEMG signal processing algorithm, to avoid delays.

The best results for switch activation were obtained using the 200 samples window, that correspond to 0.8 seconds of signal processed; yielding the best equilibrium between time-delays and misclassification error, which is zero for this case. Worst case scenario, for windows of 100 samples (0.4 seconds), 6 out of 500 windows (that return a record of 200 seconds) do not turn ON the switch. This means we have an error of 1.2 %.

Fig. 6. ON/OFF Switch Control example. Threshold establishment and switch activation.

Smaller windows take longer to process and generate time delays.

When the threshold is properly triggered, the switch control sends a FES activation command. It evaluates if 2 continuous windows of the envelope signal are above the set threshold; the algorithm always compares the current and last window to avoid false-intended activations. Likewise, when 2 continuous windows of the envelope of the clean sEMG signal does not surpass the set threshold there is no request sent to the Rehamove2® device.

Fig. 6 shows a real-time example of the functioning Switch Control for ON and OFF cases, when the threshold is surpassed, and when it is not and how the result is shown at the control platform.

C. *FES Activation*

When the ON/OFF Switch Control is activated posterior to a muscle contraction recorded as an sEMG signal, FES activation is simulated. This activation corresponds to 1 of 5 hand movements (open hand, power grasp, fine pinch, pronation or supination) as selected previously. For each movement, a different set of parameters is pre-defined at the control platform [17]. FES activation can be simulated too; Fig. 7 shows an example when threshold is surpassed by the sEMG signal, that simulates the activation of FES for the open hand movement.

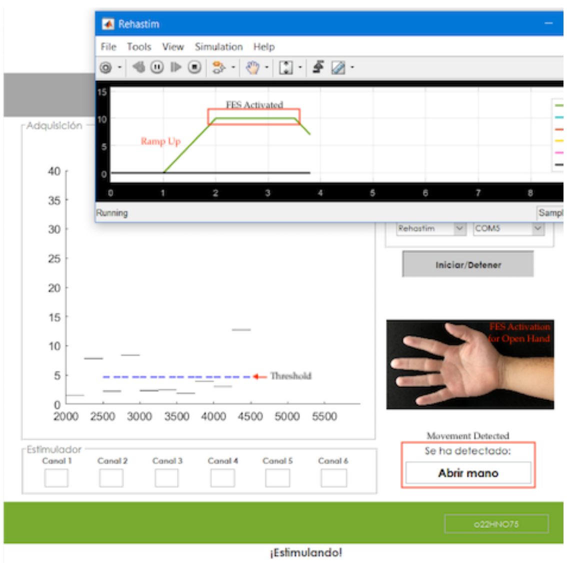

Fig. 7. Open hand movement FES activation simulation for the ON/OFF Switch Control.

IV. Discussion and Conclusion

An ON/OFF sEMG Switch Control is an effective alternative to achieve FES activation using sEMG signals, because this process involves a comparison between two data sets. There is no need to develop a more complex solution, as it is very important to keep each stage of the process simple in order to have an easy overall solution for solving a complex problem. It is important to seek for simple solutions when developing online applications, as simple ways to solve a problem will compute faster than the more complex ones.

In this application, using sEMG signals to control FES activation provide biofeedback to users. Biofeedback is extremely valuable for rehabilitation as it assists in the regeneration of sensorimotor paths due to neuroplasticity, as well as in providing the user a strong motivation and a feeling of independence due to the possibility of activating FES using their own hand movements.

When processing signals to obtain the best possible results in the switch, it is necessary to do so being careful not to take away elements of the signal itself; meaning that, at the moment that the signals are filtered we must ensure that the necessary characteristics to activate the switch are still there. It is also important to establish a training or calibration protocol for the proper functioning of the switch and to minimize the number of errors.

The time the muscle should be activated and the time for rests must be equal. If not, the threshold value will be altered and that will lead to bad outcomes.

The use of algorithms like the Switch Control could be a useful aid in upper limb rehabilitation and may help to regenerate neuroplasticity, which make them a great option of control. It is an algorithm that does not take a long time to be processed and is effective thanks to the help of wavelet transforms.

Wavelet transforms are a great option to process sEMG signals since the combination of different families along the algorithm allowed us to identify different signal parameters, as movement contraction and no movement regions. They have the potential to be used as an intention detector, since wavelets are very good for identifying fast changes in the signal.

Also, wavelets let us know the frequency components during all the muscle activity. Muscle activation is formed by 3 types of fibers: fast, slow and intermediate. Wavelet analysis can let us know the contribution of each fiber group during muscle activation. For medical rehabilitation, this is very important as the specialist can indicate the right strength therapies depending on patient needs. These algorithms can also be used for assessment of rehabilitation therapy for those who have suffered a stroke or a spinal cord injury.

Repetitive muscle activity leads to the interaction of several muscle fibers to achieve movement functionality. If such activity is replicated constantly, at some points the muscle will get fatigued. This is especially true for FES therapies, since they recruit all muscle fibers. Further wavelet analysis of sEMG signals in time and frequency will be able to let us see how the patient's fatigue process is developing during an activity and tell when to stop.

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