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Prosthetic Control using EMG signals

Braulio Ríos

Monograph related to the conference presented by Lic. Germán Pequera about biological signals: "**Procesamiento de señales biológicas: ¿Es posible evaluar la coordinación de los movimientos explosivos a través de EMG?**"on June 09, 2015.

brauliorioisf@gmail.com

Review. An introduction to Electromyography [EMG] signals is presented. The different types of electrodes that can be used with this purpose are described. Advantages of each type of electrode are mentioned. Examples of use of different electrodes are shown. Different approaches of signal processing for EMG signals are briefly described, comparing results using time-domain, frequency-domain or time-frequency domain techniques. Devices that have been recently introduced to market, and that make use of the techniques described, are introduced.

1. Introduction

Electromyography (EMG) is a technique to detect the electrical activity of muscles, generated by the cells electric potential that is produced when they are neurologically activated.

The analysis of these signals is relevant in a wide range of uses, with different purposes like detection of abnormalities (neuromuscular diseases), detection of muscle activation, and the study of biomechanics of human or animal movement.

Signal sensing requires at least a pair of electrodes for differential measurement of the voltage across the group of muscles in the area of interest.

There are two different approaches for sensing: intramuscular and surface. The latter only requires the placement of electrodes above the skin surface (eventually with a conductive paste), so it is practically non invasive but can only be used for exterior muscles, while the intramuscular EMG provides better accuracy and may be placed to sense a specific muscle or small groups. The use of each method is determined by the requirements of the application.

In the case of prosthesis control, the signals are used to predict the intention of the patient to execute a certain action, so in this case the interest of the signal processing is to detect the activation of certain muscles, in particular those that would be activated by a person without amputation executing the same action. Although the idea is quite simple, it is not easy to find a good solution which provides reliable results, as is required for this application, since the aim of the robotic prosthesis is to ease the patient's daily life, without bothering with unexpected movements.

Although the electric activity of muscles has been widely studied since it was discovered a long time ago (the first recording of electrical activity was achieved by Marley in 1890, and the technique improved steadily from the 1930s through the 1950s, with the development of more accurate electrodes [6]), the processing algorithms to detect precise patterns with such reliability is still being studied, and the capability to execute this processing in a portable device that can be carried comfortably by the patient is only possible with state-of-the-art technology. In fact, to the date of this paper, the FDA has approved marketing for the first prosthetic arm that translates EMG signals to perform complex tasks [7]. A quick search to the topic in the internet, shows a very large number of built devices with successful demonstrations, but the FDA approval means that the device is ready for commercialization and has been widely tested and proved to work efficiently. That means that the use of robotic prosthetic that makes use of EMG signals to be controlled, is just beginning.

2. Electrodes

Sensing of EMG signals requires at least a pair of electrodes, because the electric signal is produced along the muscles, so differential sensing is needed.

Pre-amplifiers located near the electrodes are very often used, to avoid a noise level comparable to the signal during transmission through the wire, considering that the voltage differential signals in the muscle have levels from 50µV and up to 20mV to 30mV, depending on the muscle under observation [6], and its frequency bandwidth ranges from 6Hz to 500Hz [4].

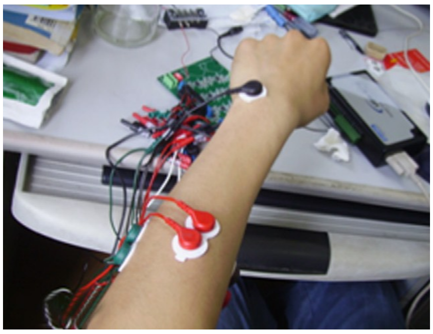

Figure 1: EMG electrodes placed on the skin surface [4]

It has been already mentioned that there are two different types of electrodes to be used for sensing EMG signals. The most commonly used are the surface electrodes (Fig. 1), since they don't require much effort to place and are non invasive. They are usually complemented by a conductive paste, and it is preferred to place them in a waxed area of the skin surface, to minimize resistance between the electrode and the muscle to be observed. Of course the fact that the electrodes are in permanent contact with the body, the devices connected to the electrodes must be designed to avoid electrical currents that may damage biological tissues. This is achieved adding some kind of decoupling stage between the sensing components and the electronics that may drive higher currents.

The ease of use of the surface electrodes also implies that they can not be targeted to a very specific group of muscles, in fact they can only measure significant signals from the superficial muscles or near the skin surface. That means that the signals from all the nearby muscles are mixed, and the processing will require additional filtering to get more distinguishable shapes from the original signals.

Intramuscular electrodes require surgery to be placed correctly, and that is why they are reserved to very specialized uses, where better accuracy is needed, or where the muscles to be sensed must be very specific. In the case of prosthesis control, it is not desirable the need of intramuscular electrodes, due to the difficulties to remove the prosthesis without surgery. However, it is very difficult to handle a device with more than one degree of freedom, using only surface EMG, and in [3] a comparison is made and it is shown a better performance and promising results using intramuscular electrodes specifically for control with several degrees of freedom, focused in an ergonomic robotic arm that could reach specific targets efficiently, analyzing the problem from the Fitt's law approach (relation between time and distance to reach a specific target).

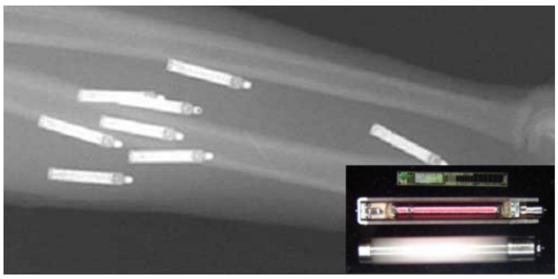

Figure 2: Intra muscular electrodes with wireless capability for data and power transmission [5] and [19]

A very interesting approach that allows a prosthetic device based on intramuscular sensors to be removable, is shown in [5], where a robotic arm with several degrees of freedom is demonstrated to work properly and very softly, using wireless intramuscular electrodes (Fig. 2). In this case, each electrode is an independent device with capability for RF communication, and can also be recharged using inductive wireless power transmission [9]. The sensed signals are transmitted to the prosthetic arm without the need to be connected to it, so it is possible for the patient to remove the prosthesis when needed, without the need of surgery. The result is a very complex system (in hardware and installation effort), but it seems to work surprisingly well, due to the high fidelity signals and specific muscles that can be used to control the robotic arm. This system is not yet available commercially, but could have a very promising future if the surface EMG controlled devices cannot achieve similar results, although great effort in the signal processing field is being done, to allow reliable control of devices without the need of such a complex system.

3. Signal Processing

The acquired EMG signals, specially in the case of surface electrodes (which are the most widely used), are mixed with signals generated by various muscles and contain much noise. The recognition of limb motions from EMG signals is difficult, and in order to design a well performed EMG recognition system, the selection of the signal features plays a very important role [4]. The simplest features to extract with computations, are the time-domain based, such as mean absolute value (MAV), root mean square (RMS), waveform length (WL), zero-crossing rate (ZC), and autoregressive coefficient. Due to the non-stationary characteristics of the signals in dynamic movements, the variation of these features deteriorates the accuracy of the recognition. Frequency-domain features, such as mean or median frequency, are more reliable than time-domain features, but they require more calculation efforts and also rely on methods designed for analyzing stationary signals. Time-frequency analysis methods, such as short-time Fourier transform (STFT), wavelet transform (WT) and wavelet packet transform (WPT) provide information of both time domain and frequency, which is desirable for non-stationary signals [4]. A method based in WT is proposed in [4], which is said to give good resolution in terms of time and frequency.

The aim of the feature selection, is to find a reliable way to classify the signals. Features with similar results for different kind of muscles are not useful for the recognition of limb motions. Features that produce groups that are easily delimited, depending on which muscles have been activated, allows the development of a classification algorithm to detect the intention. In [4] it is shown that the WT based method developed is successful in the detection of 7 different hand motions, and the processed signals are used to reproduce the hand motions in a PC.

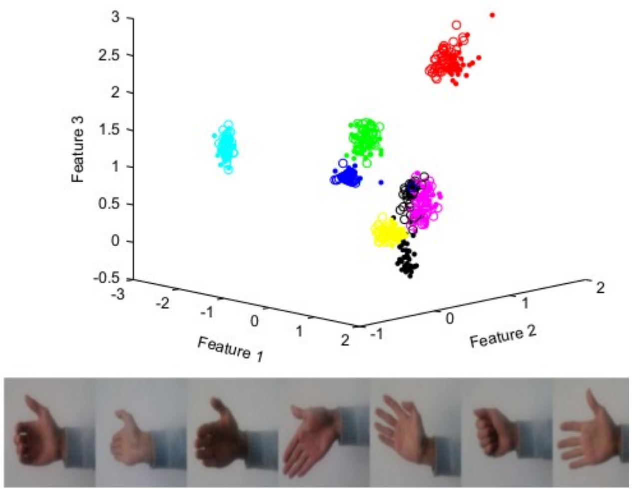

Figure 3: Feature extraction based on WT, from 7 different hand motions [4]

Moreover, some reports show that some features based on time domain analysis can also be successfully used to detect intention with several degrees of freedom, using only two surface EMG sensors. In [8], using features like the MAV, variance (VAR), fourth-order autoregressive (AR) coefficient and sample entropy as the feature set and the linear discriminant analysis (LDA) for classification, it is claimed that a 99.79% accuracy is obtained for eight different hand gestures, and the results are shown in a computer screen simulator. In reference [12] it can be found a very similar approach.

In any of those reports, the signal processing is done in a PC without the processing limitations that could be found in an embedded system. Anyway, there are several successful examples using similar processing algorithms that proved to work in embedded environments.

All the different approaches found, are based in machine learning algorithms, meaning that there is a previous training stage, where the different movements or gestures that are to be detected, must be executed by somebody (it could be the future user or another person), in order to generate some kind of database with the expected value of each feature in each movement. The training methods can have different complexity, being the most used those where the user executes a predefined set of movements or gestures to be recognized, and the obtained features are recorded related to each of them, so that when an input produces a similar array of features, it is detected as one of the movements in the set. This is the approach used in the previously analyzed references [4] and [8].

A novel and very complex approach is presented in [11], aimed to recognize a wider range of gestures. It is based in a 3D electromagnetic positioning system, which records the exact motion of the hand related to the EMG signals obtained, generating a database with an arbitrary number of gestures that can be identified when similar input patterns are detected. But the training method requires that the inputs are executed by a real hand, and it is not proven that the same patterns are produced by an amputee, which is the final user of the system.

There are also methods based in machine learning algorithms to detect muscular diseases, which is a very different application from what is presented in this paper, but it is worth to mention since the field of signal processing with this purpose has been also widely studied (a comparison of methods is presented in [2]), and some results may have common points of interest. For example, it is shown that algorithms based in wavelet transforms (WT) have a good performance for the signal processing with that purpose, in agreement with the results mentioned at the beginning of this section, related to [4].

4. Prosthetic control using EMG

Several projects aimed to the fabrication of robotic prosthetic devices controlled by EMG signals claim to be successful, in different institutions and even in domestic projects. Even an open platform have been published in [1], with the objective of producing a collaborative basis for the development of further embedded devices to control prosthetic arms specifically. This platform requires high performance boards and is based on an operating system, but claims to make it easier for developers to implement their algorithms and evaluate results in a shorter period of time.

Some of the most relevant and proved to work devices produced will be shown in this paper.

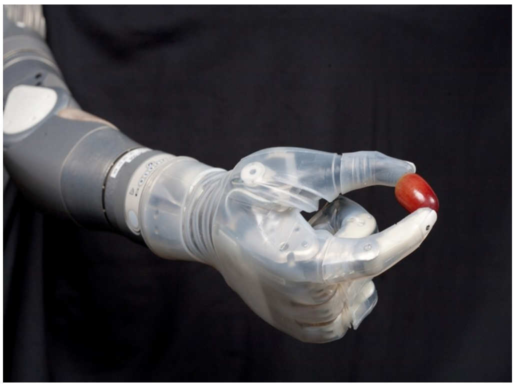

Figure 4: DEKA Arm System: the first FDA approved bionic arm, allows to perform complex operations on amputees, using non invasive EMG sensors [13].

Until the date of this publication, the FDA have recently approved (May, 2014) marketing for the first EMG controlled robotic arm [7], named DEKA Arm. This project, which received funds (U$s 40 million) from DARPA (Defense Advanced Research Projects Agency of the USA) and was developed by DEKA R&D Corp., is intended to restore functionality for individuals with upper extremity amputations [13], and is currently working in partnership with the United States Department of Veterans Affairs (VA), implanting the system in amputees, and showing very positive results until now. The funds received and the VA partnership allowed for a study with 36 participants, who were fitted with the DEKA Arm and tried to perform common routine tasks such as using keys, preparing food, feeding themselves, and combing their hair. According to the FDA, the study showed that about 90 percent of participants were able to perform complex tasks with the bionic arm [14].

Even most recently, in June 2015, the first user received the BeBionic hand, a device that has just come to market in the UK, and is now commercially available by the company Stepper Group [15]. It also uses surface EMG to control the device, being capable of recognizing 14 different gestures from the processed signals [16], claiming to be "the world's most lifelike bionic hand". The company is still working in new models of the hand, with smaller sizes and custom designed options.

Figure 5: BeBionic hand: the device has been just released and is now commercially available. It claims to be "the world's most lifelike bionic hand". [15]

The company TouchBionics have been providing bionic hand solutions since a long time ago, and in May, 2014, introduced new control methods [17], allowing for the user to program a wide range of "grips" (gestures), from surface EMG signals processing. A wide range of products is available from this company, being highlighted their most recent models of I-Limb, for patients with upper limb loss at the wrist or more proximal, which allows the selection of a customizable set of grips "providing wearers with the flexibility to perform a wide range of daily activities with improved control, accuracy, and ease-of-use" [18].

Figure 6: I-Limb ultra, from the company Touch Bionics, is capable of being programmed with a wide range of gestures. Other similar models are also available. [18]

5. Conclusions

The companies behind the commercial devices, do not facilitate publicly much of the information related to the exact algorithmics and signal processing behind the control strategies used for gesture recognition, due to the growing market competition, and the fact that proprietary technologies involved requires important R&D investments (as is publicly known in the case of the DEKA Arm). However, it is clear that the technology transfer from the investigations developed in the previous years, allowed critical improvements in the devices that are starting to be available nowadays.

The most valuable results from the latests investigations, refer to the field of signal processing and machine learning techniques, which allowed the development of control strategies using only surface EMG signals, which is way more comfortable, simpler and cheaper than approaches based on intramuscular electrodes.

Even so, the devices available are quite expensive to the massive public, ranging from USD 11.000 for the BeBionic hand [20], and USD 25.000 to USD 80.000 for the I-Limb Ultra, depending on how far up the arm it needs to extend [19]. Expectations are that those prices will decrease as long as new devices appear in the market and the investigation and development cost is amortized.

Right now we are in a critical moment, since years of academic research are beginning to allow real improvement on the quality of life of many people who could not perform ordinary tasks by themselves, providing reliable devices, that are not merely aesthetic and passive prosthesis, but rather a useful limb substitution that avoids the amputation to be such a traumatic experience.

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