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Exoskeleton Design Controlled by Surface Electromyographic Signals from Upper Limbs

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Abstract

This document describes the processes for acquisition of signals emitted by the biopotentials in the upper limbs of the user of an exoskeleton, its use to control the movements through motors which make the displacements, according to the orders given by the changes in the muscular potential of the operator. For this, it was necessary to achieve 4 phases: In the first phase, the signal is acquired through the use of surface electrodes; in phases 2 and 3 the signal is filtered and conditioned respectively using digital techniques for processing; in the final phase a power interface is used, which activate the motors that manipulate the joints involved in the displacement of the upper extremities of the exoskeleton. Surface electromyography is used to acquire the signals, because it is not an invasive technique and offers the possibility of adapting to any individual who operates the exoskeleton. During the design tests, the response of the control signal was evaluated for different individuals, making multiple movements, seeking to verify the performance of the signal processing, being successful for the control of the exoskeleton.

Keywords: Surface electromyography, Signal filtering, Exoskeleton.

INTRODUCTION

The mechanical exoskeletons are robots coupled to the limbs of the human body focused on increasing their strength, speed and performance mainly. The main applications are in the military, in industry and in medicine. The exoskeleton can be used for limb rehabilitation when there is reduced or no muscle activity due to an accident or illness [1].

Electromyography (EMG) is the recording of muscle electrical activity by means of a needle, sometimes also performed by surface electrodes. The muscular fibers, when contracting, produce potentials which are picked up by these electrodes, represented in patterns indicative of the neuromuscular system. These potentials occur when the cells (fibers) of the skeletal muscles are activated by nerve fibers originating in the spinal cord. Both fibers are “connected” in the neuromuscular junction zone [2].

The signals of electromyography can be recorded visually on a screen, in sound form through a speaker, and a record can also be made on a permanent support, such as on a paper, as it is usually done [3].

The integration of electromyography and an exoskeleton, allows the total interaction between these, where the first captures the small signals of the muscles and the second can transform them into movement endowed with greater force than the operator's own muscles [4].

Among the advantages of using exoskeletons for processes such as rehabilitation, there are: taking advantage of the precision that a robot has to gradually increase the speed in the repetitions of a sequence, the extension of the joint position, the resistance or opposing force of a strength increase exercise, etc. In some exercises, the resistance that opposes, e.g. in a physiotherapy exercise, should be increased gradually to obtain an improvement in the patient, however, without the presence of sensors that estimate precise data of the signals, it leaves a misconception of force at the mercy of human perception, which could delay the patient's rehabilitation process [1].

That is why it is necessary to perform a treatment and conditioning of the small signals generated by the biopotentials of the muscles of the arm and forearm of the operator of the exoskeleton, in order to avoid involuntary movements or out of control, caused by spurious signals that hinder the process of control of the different movements of the exoskeleton. [5]

The main objective of this article is to present the process of designing the control system for the upper extremities of an exoskeleton, in order to efficiently achieve the mobility of each of its degrees of freedom, contributing to the improvement of the kinematics of these devices, represented in coordinated and continuous movements. Thus, section II presents the methods and materials used, section III the development and results obtained and finally the conclusions reached.

MATERIALS AND METHODS

For the initial design, it is necessary to analyze the kinematics of the upper extremities of an exoskeleton, taking into account its morphology and modeling in investigations addressed to different degrees of freedom [5]. The good design of an exoskeleton must take into account the system with which it will interact. In nature, biological systems have their own actuators and control systems, generally more complex than those of the robots themselves, and because of this complexity, it is necessary to make simplifications in several aspects, conserving the general characteristics of the system, this process of copying designs of nature is called bioimitation [6].

In the human body, the upper limb is comprised between the shoulder and the tip of the fingers, this member is divided into three segments: arm, forearm and hand. The complete limb is linked to the body through the clavicle and the scapula, kinematically studied as a unit. For the morphological modeling, the three segments were characterized, which are specified in Table I, the distance of the segments is considered constant, and depends on the height of the individual through a numerical relationship, these values were specified by Pons [6].

Table I. Length of segments

Length of segments		
Segment	**Bone**	**Distance (cm)**
Arm (S1)	Humerus	0.186 * H
Forearm (S2)	Radius	0.146*H
Hand (S3)	Phalanges	0.108H

H = Body height in centimeters

Once defined the segments of the extremities of the exoskeleton, it is important to take into account the following specifications:

- The mechanical behavior of the arm is independent of the rest of the body.
- All the components of each segment, including the bones and soft parts, are part of the same rigid body.
- The deformations of the soft parts (muscles, skin, etc.) do not significantly affect the mechanical properties of the entire segment [7].

As stipulated by [8], the movements of each board in Table II are described.

Table II. Movements performed by the top limb joints

Joint	Movement	Definition	Ranges
Shoulder	Flexion - Extension	To move the biceps forward or backward.	130º -180º 30º - 80º
	Abduction - Adduction	To move the arm to or outside the midline of the body.	180° 50°
	Circumduction	Movement made around the humerus.	60º - 90º 90º
Elbow	Flexion - Extension	Movement around the transverse axis that allows the palm of the hand to approach or move away from the arm.	140º
	Pronation - Supination	Pronation: movement that takes the palm of the hand to under the thumbs. Supination: Move the hand out.	80º 80º
Wrist	Flexion - Extension	Movement around the transverse axis that allows the palm of the hand to approach or move away from the forearm.	90º
	Abduction - Adduction	Movement around the anteroposterior axis that moves the hand to the ulna.	30º- 40º 15º

In Fig. 1, the movements of each of the joints of the upper limb of the human body are illustrated. In each one of them there will be an electrode to measure the activity of the muscles with electromyography.

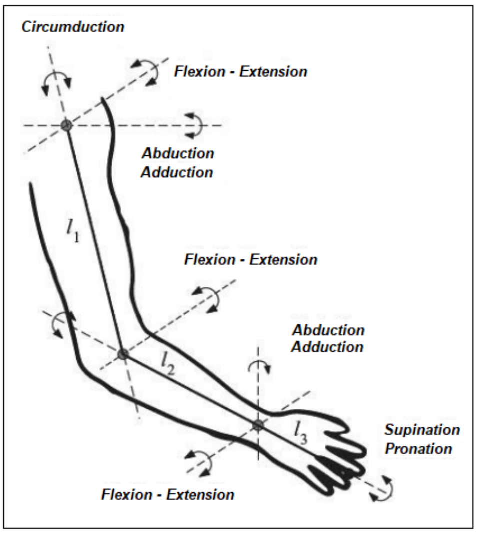

Figure 1. Graphic description of arm movements

(Source: Wearable Robots: Biomechatronic Exoskeletons. J.L. Pons 2005)

For the study of the electromyography signals [2], which generate small voltage stimuli, they were amplified and filtered through circuits and digital devices, in order to improve the quality of the information provided by the electromyographic impulses [9]. Subsequently, it was proceeded to integrate the results in an interface that allowed analyzing the results of different subroutines implemented with electric motors and electro-pneumatic circuits, to later establish which parts of the exoskeleton should have one or another source of stimulus for each of the segments that comprise it.

WORK DEVELOPMENT

The design begins with the determination of the position of the segments of each of the upper extremities of the exoskeleton as a function of the rotations of their degrees of freedom, the analysis of the movements presented in section II is integrated, through the method of the matrices of homogeneous transformations [10]. The parametric equations used, the modeling of the limb, the reading of the electromyographic signals and their processing are presented below.

A. Definition of parametric equations

In Equations (1) to (3), the rotation movements in the X, Y and Z axis respectively for one of the upper extremities analyzed are described, determining its kinematics.

$$R_{X(\gamma)} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\gamma & -\sin\gamma & 0 \\ 0 & \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$R_{y(\alpha)} = \begin{bmatrix} \cos\alpha & 0 & \sin\alpha & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\alpha & 0 & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$R_{z(\beta)} = \begin{bmatrix} \cos\beta & -\sin\beta & 0 & 0 \\ \sin\beta & \cos\beta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

For which (4) describes the translation movement in any of the 3 axes.

$$T_{(d)} = \begin{bmatrix} 1 & 0 & 0 & d_x \\ 0 & 1 & 0 & d_y \\ 0 & 0 & 1 & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

B. Modeling of limb

In Fig. 2, the ergonomic distribution of each of the segments of the exoskeleton is observed, in each of them there is an engine to print movement to the corresponding segment.

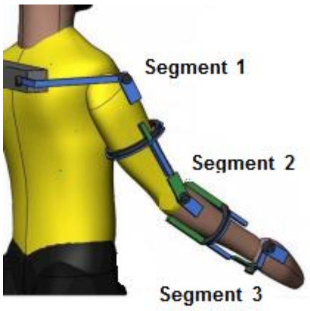

Fig 2. Ergonomic arrangement of the exoskeleton segments

(Source: Diseño de Exoesqueleto con base en Cuatro Casos de Estudio de Rehabilitación de Miembro Superior. Revista Mexicana de Ingeniería Biomédica. 2018)

In Fig. 3, the model in Simscape of the movements of each of the segments is observed, the data was taken with reference to an operator of 1.7 meters in height. This simulation allows to evaluate the exoskeleton design and validate the command of the basic control signals.

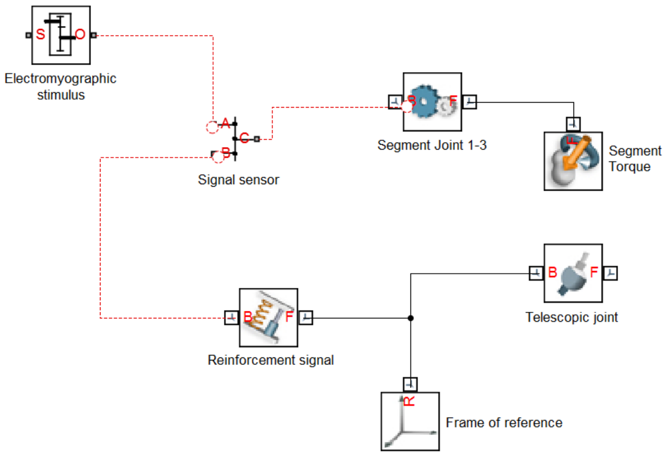

Figure 3. Simulation of movements of the exoskeleton using Simscape

(Source: Authors)

In Fig. 4, the response of each of the segments to the electromyographic stimuli of the muscles of the segments of the right upper extremity of the exoskeleton is observed.

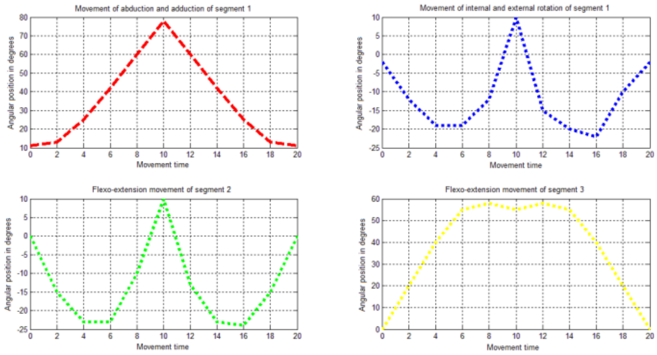

Figure 4. Results of the simulation of movements of the exoskeleton

(Source: Authors)

C. Reading electromyographic signals of the operator

To acquire an electromyography signal, it was necessary to use three electrodes that deliver voltages at a millivolt scale, instrumentation amplifiers and a cardiac signal module with an amplified signal on the 3.3V scale [11]. The procedure can be seen in Fig. 5.

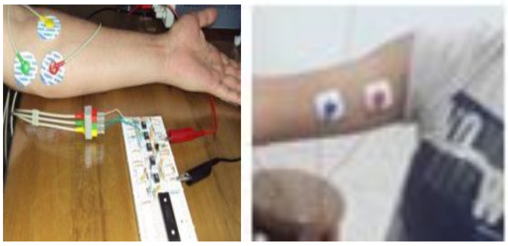

Figure 5. Muscle activity reading with surface electrodes

(Source: Authors)

The recording of the EMG signal of the arm can be seen in Fig. 6, it shows the presence of noise which should be suppressed at its lowest expression with some type of filter, as evidenced in the next section. [12]

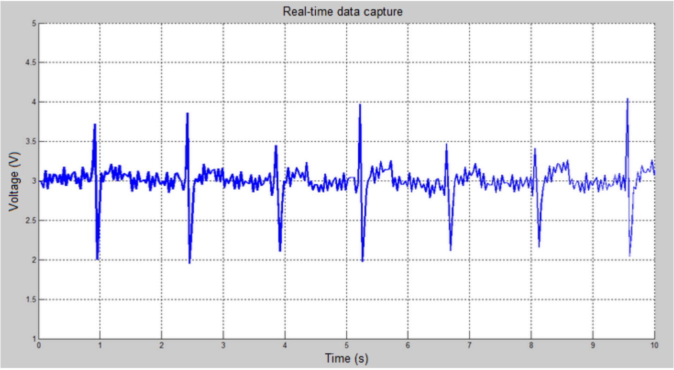

Figure 6. EMG signal of the right arm

(Source: Authors)

D. *Filtering the electromyographic signal*

In signal processing, a finite impulse response (FIR) filter is a filter whose impulse response is of finite duration, since it is set to zero in finite time [11]. The filter architecture used is shown in Fig. 7.

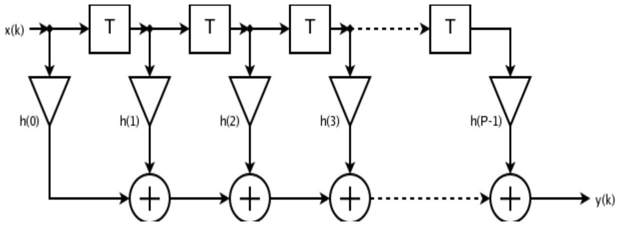

Figure 7. Schematic of the digital filter

(Source: Authors)

Due to the noise present, it is necessary to transform the overshoots (Fig. 4) to logical signals (I / O), for which a FIR digital filter of order 12 is used, the logical component of the filter was developed on an MBED card, with the aim of rejecting the noise generated by the 60 Hz electrical network. It was possible to suppress the noise of the signal of 60 Hz of the electrical network, the signal resulting from the action of the filter can be observed in Fig. 8.

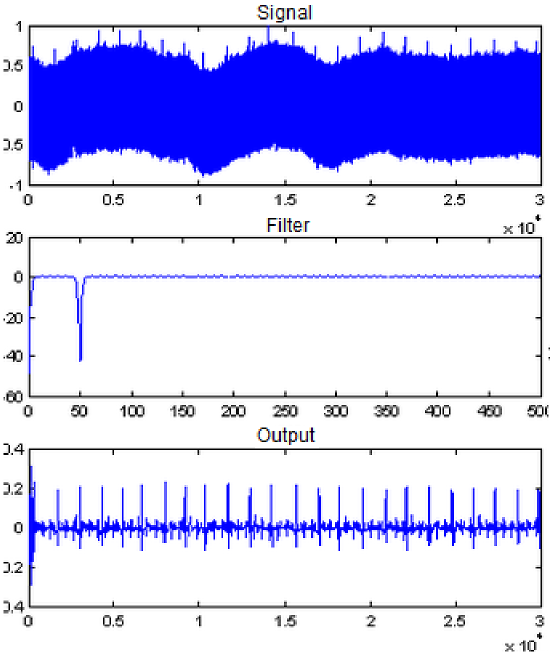

Figure 8. Response of the FIR digital filter
(Fuente: Autores)

E. *Conditioning of the signal*

To condition the signal, the output of the digital filter was taken as input to the Arduino Atmega 2560 card, the product of the logical processing of each of the three segments of an extremity of the exoskeleton was used to construct a stereo signal which constitutes the intelligent signal that will control the movements of the exoskeleton [13]. Fig. 9 shows the architecture of the signal conditioning circuit.

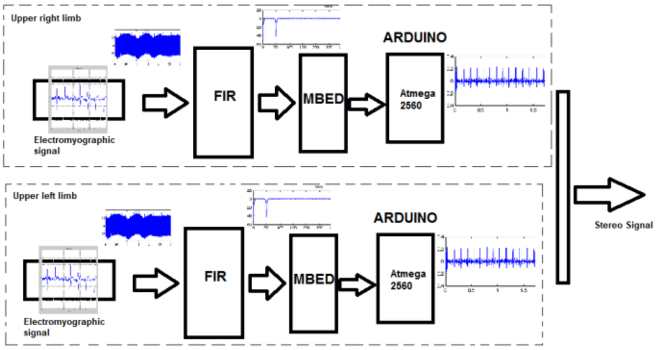

Figure 9. Exoskeleton controller architecture.

(Source: Authors)

Once the signal is obtained, the threshold is set so that it executes the logical states, representative for each one of the movements of the segments, as it is related in Table III.

Table III. Logical states for exoskeleton segments

SEGMENT	MOVEMENT	LOGICAL STATUS
1	Flexion	00000001
	Extension	00000010
	Abduction	00000011
	Adduction	00000100
	Circumduction	00001001
2	Flexion	00000001
	Extension	00000010
	Pronation	00000011
	Supination	00000100
3	Flexion	10000000
	Extension	01000000
	Abduction	11000000
	Adduction	00100000

Fig. 10 shows the manner in which the two limbs are worked after demultiplexing the stereo signal from the filtering and conditioning stage. [14]

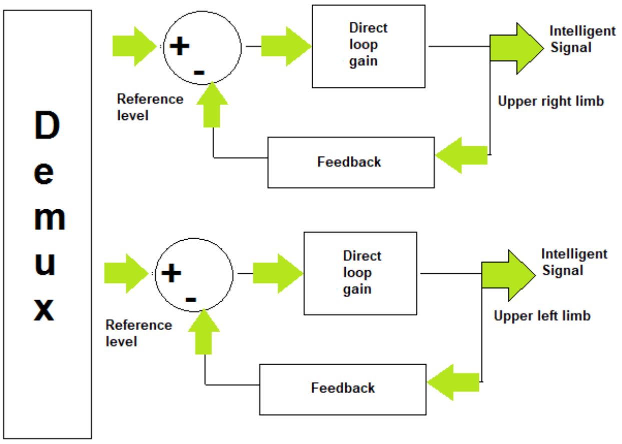

Figure 10. Main circuit

(Source: Authors)

CONCLUSIONS

The muscular membrane provides signals on the scale of millivolts, for this reason it requires a previous amplification, in order to make a better treatment of the signals, necessary for the actuators of the exoskeleton.

The EMG Intramuscular method can be considered too invasive or unnecessary in most cases, the surface electrodes avoid the discomfort of the needles and give a signal of good quality for further treatment, which is evidenced in the proper control of the actuators.

For a better obtaining of the information coming from an EMG, filtering the noise with digital means is the best alternative to avoid involuntary movements of the end effectors of an exoskeleton.

The use of surface electromyography in exoskeletons offers the great alternative of being able to change the user in exoskeleton with great ease and speed, since it is not an invasive technique, which makes it ideal for rehabilitation actions.

The results presented here are susceptible to improvements if they are integrated into a light metal structure and micro motors with irreversible torque using mechanical brake techniques that allow them to withstand heavy weights. An analysis by numerical methods could show improvement compared to various materials and/or alloys.

The sensitivity of the electrodes is a determining factor during the reading process of the myographic activity, it is recommended the use of commercial brands for sports activity, which evidenced a better performance of the control circuit.

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