Robotic orthosis for bilateral rehabilitation of left hand for patients with hemiplegia.

- Órtesis robótica para rehabilitación bilateral de mano izquierda para pacientes con hemiplejia.

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Fecha de Recepción: 2 de Marzo de 2019 / Fecha de Aceptación: 4 de Mayo de 2019

Abstract: This work describes the development of a mecha- tronic system to perform bilateral rehabilitation in stroke survivors with hemiplegia or movement difficulty in the left hand, based on mirror therapy. This kind of rehabilitation provides neurological feedback when the affected hand (left) mimics the unaffected hand (right) flexion/extension motion (biomechanics) of the fingers. This robotic system consists in one device for each hand. The first one identifies the range of motion (ROM) of all right hand fingers by measuring the resistance of flex sensors placed on each finger. The second device, an active orthosis, replicates the motion of all the fingers on the left hand driven by servomotors coupled in a mechanic system. The information of the flex, which establishes a relationship with the ROM of right hand fingers, are processed by an Arduino board and sent, by wireless communication, to another Arduino board that relates the received resistance value with the motion of the servomotors and the ROM of the impaired hand. Tests performed with five healthy subjects showed a movement replication of the fingers with 0.3ms delay and an average relative error of 6.77±5.01% in the ROM of the impaired hand compared with the healthy hand.
Keywords: Robotic orthosis, mirror therapy, bilateral rehabilitation, hemiplegia.

Resumen: Este trabajo describe el desarrollo de un sistema mecatrónico para realizar rehabilitación bilateral en pacientes sobrevivientes a un accidente cerebro vascular o con dificultad de movimiento en la mano izquierda, basado en terapia espejo. Esta rehabilitación entrega retroalimentación neuronal al imitar el movimiento de flexión-extensión (biomecánica) de los dedos de la mano sana en la afectada. Este sistema robótico incluye un dispositivo para cada mano. El primero, identifica el rango de movimiento (RDM) de cada dedo de la mano derecha, midiendo la resistencia de sensores flex ubicados en todos ellos. El segundo dispositivo, una órtesis activa, replica el movimiento de cada dedo en la mano izquierda guiados por servomotores acoplados a un sistema mecánico. La información del flex, que establece una relación con el RDM de los dedos de la mano derecha, es procesada por una placa Arduino y enviada, inalámbricamente, a otra placa Arduino que relaciona el valor de resistencia recibido con el movimiento del motor y el RDM de la mano afectada. Pruebas realizadas a cinco sujetos sanos mostraron la replica del movimiento con retraso de 0.3ms, con error relativo promedio de 6.77±5.01% en el RDM de la mano afectada comparada con la mano sana.
Palabras clave: Órtesis robótica, terapia tipo espejo, rehabilitación bilateral, hemiplejia.

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1. Introduction:

Stroke survivors are affected by significant disability in their limbs, a certain level of hemiparesis that affects the arm and/or leg appears in 50% of patients with chronic stroke [1][2]. The functionality decrease of the upper limb is one of the most marked physical impairments related with this cerebrovascular disease [1][3]. Motor and sensory dysfunction are two of the most common consequences of stroke, presented as lack of mobility, loss of joint coordination, weakness in some muscles and/or loss of sensitivity in individuals with hemiparesis or hemiplegia [4][5]. This causes that stroke survivors have to live with permanent disability due to the difficulty of completely recovering their movement [4]. Patients with upper limb impairment have to deal with limitations in performing daily life activities, hence, the goal of rehabilitation is to improve the upper extremity functionality in order to increase the independence of patients [4][5]. In the last years, the increment of patients with hemiplegia, as consequence of stroke, has generated an increase in demand for rehabilitation techniques that the health service cannot cover [6]. Approximately the 85% of stroke survivors suffer a motor deficiency in the upper extremities, reducing their quality of life [7]. Statistics show that partial paralysis of the arm limits its functionality up to 50% after stroke, 33-66% of patients do not recover the functionality of the arm and, 5-20% get a total recovery six months after the stroke [8].

For stroke survivors, mirror therapy is one of the techniques that best neurological results shows in hemiplegic patients and it is widely used in the rehabilitation of the impaired hand [9]. This rehabilitation technique consists in the use of a mirror that reflects the movement of the unaffected hand and deceives the brain by visual feedback making it think that the affected hand is performing the movement [10][9]. The purpose of this therapy is to generate the activation of the sensory cortex, allowing the brain to recover abilities [11]. However, it must be taken into account that actually the hand does not move, so it does not recover the motor skill [11].

Aside from the conventional therapies, technological tools, as robotic systems, have been introduced for improving physical rehabilitation in upper and lower limbs. For example, [12] presents the design of an exoskeleton for lower limbs, which aims to be used by patients who suffered partial lower body paralysis (due to stroke or spine injuries). Other works like [13] and [14], present the use of muscular signals as interface between the patient and the robotic system for interpreting the interaction of the limb to be evaluated, based on electromyographic (EMG) signal processing. For upper limbs, there also exist robotic devices, in fact, some works focus their research in assisting specific joints. For example, MIT- Manus, MEDARM and ARMin III are concentrated in shoulder and elbow joints [15][16]; while BRAVO hand exoskeleton is an orthosis that assists the action of grasping by controlling the flexion/extension angle of the fingers [17]. Among these robotic devices, researchers have developed systems that are applied in bilateral rehabilitation for hands, which consists in a system where the unaffected hand of the patient acts as a guide for the movements of the impaired hand based on the concept of self-motion control [17][18]. The work developed in [17] presents a system focused in bilateral rehabilitation, which estimates the movement and force applied by the non-affected hand on EMG signals, and then it is replicated in the affected hand thanks to the assistance of a hand exoskeleton driven by motors. Nintendo has applied their technology in the development of a virtual environment for the implementation of simulated mirror therapy, which increases the interest of patient, feeling attached to each rehabilitation session [19]. Therefore, it can be said that nowadays there are plenty of applications with robotic devices to help people suffering with some type of disability [20], in fact, rehabilitation assisted by robotic systems, in post-stroke individuals, have shown an improvement in the upper limb motor control [15][21][22].

As stated before, the proposed robotic system for hemiplegic patients, is based on mirror therapy, with an additional proposal where the system complements the visual feedback with a motor feedback through the application of bilateral rehabilitation. This work proposes the flexion and extension motion of the fingers of an impaired hand (left hand) which replicates the same movement performed by a healthy hand (right hand). The development of two devices (gloves) is presented, the glove worn by the unaffected hand, which uses sensors that indicates the range of motion (ROM) of the fingers, and the glove for the paretic hand, which is as an active orthosis that uses servomotors to mimic the movement. Moreover, this low-cost robotic system purpose to provide help in physiotherapies.

2. Methodology:

A. Development of the glove for the healthy hand.

Fig. 1. One DOF in metacarpophalangeal joints.

As previously explained, the healthy hand is the one that leads the rehabilitation motion. Thus, it is necessary to develop a system capable of identifying the ROM of the fingers while doing a flex- ion/extension movement. Because a glove fits perfectly in a hand, it is chosen to adapt in it an electronic system able to recognize its motion. In this work, the flex sensors are used to identify the ROM of the fingers in only one degree of freedom (DOF), the flexion/extension of metacarpophalangeal joints (Fig. 1).

This glove uses five flex sensors, coupled one on each of the fingers. Because the length of each finger and thumb is different, also the longitude of all the flex sensors varies, therefore the range of resistance values for each of them is not the same. As the hand closes (flexion), the movement of the fingers forces the flex to bend, making the sensors to increment their resistance value, as explained in [23]. So, it is necessary to establish a relationship between the resistance from the sensors and the angle accomplished by each of the fingers; this is stated in the following equation:

$$\theta = \frac{\alpha_r (R - R_{min})}{R_{max} - R_{min}}$$

Where (zeta) is the angle accomplished by a finger, (alpha) refers to the angular limit of flexion of the metacarpophalangeal joint in the right hand, R is the resistance value corresponding to the angle accomplished by the finger, R_min and R_max are the minimum and maximum resistance value of a flex sensor, respectively. The motion executed by each finger is evaluated independently by each sensor. The Fig. 2 shows the glove worn by the healthy hand (right hand), which is coupled with the flex sensors.

B. Development of the glove for the affected hand.

Fig. 2. Glove for the healthy hand (right hand).

The impaired hand has to mimic the motion of the fingers performed by the unaffected hand (right hand). In this case, the mechanism that controls the left hand is also coupled to a glove. The system for this glove has five servomotors, one for each finger. It implies that all the fingers from the affected hand has one active DOF (flexion/extension of metacarpophalangeal joint); two passive DOF (flexion/ extension of distal and proximal interphalangeal joints) for the pinky, ring, middle and index; and one passive DOF (flexion/extension of distal interphalangeal joint) for the thumb; because of the anatomy of the hand. To make the fingers move, two resistant nylon threads are attached, in one of their extremes, to a pulley system fixed to the axis of the servomotors, and the other end to the fingertip. Each pulley contain two grooves, one for tensing the threads when the servomotor turns in one way (flexion),

Fig. 3. Simulation of the mechanic system for the active orthosis. a) Polleys coupled to the servomotors. b) Polley

and the other grove for tensing the opposite thread when the servomotor turn in reverse (extension). This system, showed in Fig. 3, makes possible the flexion/extension motion of the fingers during the therapy.

A relationship between the ROM of each of the fingers and the movement of the motor, measured in angles, is stated by the next equation:

$$\beta = 2(\alpha_i)$$

Where β is the angle turned by the motor and αl is the angle of flexion of the metacarpophalangeal joint in the left hand.
The Fig. 4 shows the glove worn by the affected hand (left hand), which is coupled with the actuators for all the fingers. The motion achieved by each finger is independent.

C. Interface between the gloves

An Arduino board is used in each device. In the glove for the healthy hand, the Arduino receives the analog values from the flex sensors and then it converts them to digital values. This new digital signal is sent to the impaired hand glove by wireless communication (NFR24L01 module), and it is used for controlling the servomotors. The controller, which is in the glove for the affected hand, collects the resistance information from the five flex sensors as the inputs the glove for the affected hand, collects the resistance information from the five flex sensors as the inputs of the system. Throughout the Arduino, it relates the inputs with the movement of the actuators and make them turn according to the required flexion/extension of metacarpophalangeal joints of the fingers from the impaired hand.

3. Results:

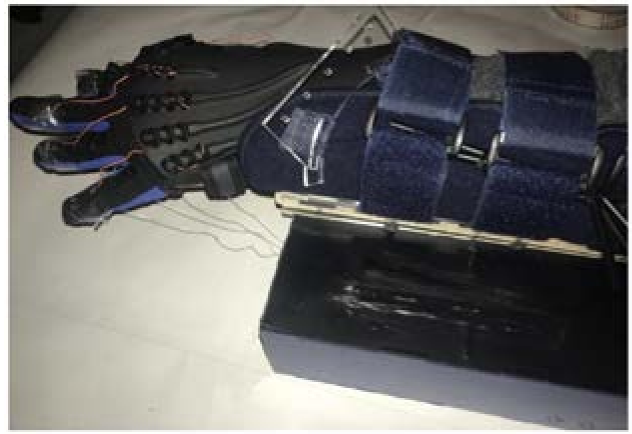

Fig. 4. Glove for the impaired hand (left hand)

Based on the Equation 1 for the glove used by the unaffected hand, a relationship between the resistance and the ROM of the healthy hand is established. Taken into account that the flex sensors have different length for all the fingers, the Table I shows the range of resistance of the sensor (R_min to R_max) and the resistance value (R_inc) that the flex increments for each angle of flexion, all for each finger.

Tabla I Relationship Resistance-Rom

	R_{min} (KΩ)	R_{max} (KΩ)	R_{inc} (KΩ)
Thumb	39.5	98.69	0.65
Index	27.87	54.1	0.29
Middle	13.8	27.31	0.15
Ring	29.37	50.24	0.23
Pinky	23.55	42.63	0.21

When the robotic system is working, a delay of 300ms introduced by the communication protocol was found. Despite this delay, a comparison between the ROM of the healthy hand and the affected hand was made. In order to obtain an accurate measurement, a goniometer was used to measure the angle achieved for each finger. Five healthy subjects, with a mean age of 19.4 0.55 years old, collaborated for assessing this robotic system. The methodology followed for testing it, consisted in flexing arbitrarily each finger of the unaffected hand and then measure simultaneously the ROM of each finger in both hands, five times. This simultaneous measurement allowed to obtain a mean angular error from the ROM proposed by the right hand (*ROMr*) and the ROM obtained by the left hand (*ROMl*) given by the equation 4, and also an average relative error between the ROM of both hands, given by the equation

$$angular\ error = |ROM_r - ROM_l|$$

$$relative\ error = \frac{ROM_r - ROM_l}{ROM_r}$$

The Table II shows the ROM error measured in each finger and their relative error. An overall mean angular error obtained by the robotic system is 3.62±2.5°, and the average relative error is 6.77±5.01%.

Tabla II Relationship Resistance - Rom

	Angular error (°)	Relative error (%)
Thumb	5.96 ±3.18	10.79 ±6.18
Index	2.6 ±1.47	4.93 ±3.15
Middle	3.4 ±2.19	6.17 ±4.28
Ring	3.16 ±2.13	5.86 ±4.14
Pinky	2.96 ±1.76	6.10 ±4.90

Fig. 6 Robotic system for bilateral rehabilitation of the left hand

4. Conclusions:

A robotic system that reflects the flexion/extension motion of the right hand, in the left hand, was developed. This device proposes a technological alternative for conventional mirror therapy applied in left hand rehabilitation to people suffering hemiplegia. The sensors used for identifying the range of motion of the healthy hand offered a wide variation range, which allowed detecting the resistance information without overlapping between different angles. The communication system could be improved with another communication protocol in order to avoid the 300ms delay obtained in the present work.

The motion achieved by the impaired hand simulates a natural movement guided by the healthy hand with an average relative error less than 10%, which is an encouraging result for performing a bilateral rehabilitation. The use of this orthosis provides a visual feedback, which is basically what the mirror rehabilitation tries to achieve, but also provides motor feedback which can help the brain to relearn a motor function that was lost. The results obtained open the possibility to replicate this system for the other hand and for implementing in other joints of upper and lower limbs.

As future work, EMG signal acquisition from both hands is going to be included, in order to recognize movement patterns from the healthy hand and replicate them in the impaired one. EMG analysis in the affected hand will be required as well, to evaluate the improvement of the functionality during the rehabilitation.

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