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Tesis

Design a hand orthosis to aid post-stroke patients with hemiplegia

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Design a Hand Orthosis to Aid Post-Stroke Patients With Hemiplegia

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***Abstract*—Stroke is the third cause of all disabilities for people over 25 years old. Indeed, the percentage of people who suffer from hemiplegia after stroke is higher than 75%. Patients with hemiplegia have considerable difficulty performing activities of daily living, such as feeding or grasping objects. Assistive devices for stroke patients have been developing since a very long time ago; however, some of them are not well accepted by patients because they are not comfortable, wearable, portable, lightweight and useful. This research presents the first version of the design of dynamic orthosis to aid post-stroke patients with hemiplegia to grasp cylindrical and spherical objects. The proposed orthosis was designed by using a cyclic design methodology called Iterative Design which is used for continuous product improvement; moreover, this paper presents a detailed description of the control algorithm and the electromechanical design in which a flexible power transmission element was introduced to perform the opening and closing of the hand. Then, a motion study was performed to determine the range of motion (ROM) of the orthosis. Results show that the orthosis is able to cover 88.8% of the ROM of the metacarpophalangeal (MCP) joint and 72.7% of the ROM of the proximal interphalangeal (PIP) joint. These results indicate that the hand orthosis can assist patients in performing grasping tasks. In addition, the main feature of this orthosis is ergonomic because it was designed using anthropometric measurements of the hand. Other features of the orthosis are lightweight (230 g), portable and easy to use.**

***Index Terms*—stroke, hemiplegia, assistive device, hand orthosis, dynamic orthoses, static orthoses.**

I. Introduction

Stroke or cerebrovascular accident has become a global health problem [1] because it is the second leading cause of death all over the world [2], the third cause of all disabilities for the adult population [3] and the second cause of dementia [4]. Moreover, as life expectancy increases, the tendency to have a stroke increases [5].

The annual incidence of stroke is estimated from 189 to 218 cases for every 100,000 people in the world [6], in Central America, the incidence ranges from 90 to 120 cases for every 100,000 people and from 121 to 150 cases for every 100,000 people in South America [2]. Besides, by the year 2030, 12 million people worldwide will have died from a stroke, 70 million people will have overcome this disease and more than 200 million disability-adjusted life years will have been lost because of stroke [7].

There is not a specific age to have a stroke, so everybody might have a stroke, for example, one in every four people over age 25 is more likely to have a stroke in their lives [6]. Hemiplegia is a common disorder in people who suffer from a stroke [8]; consequently, patients with hemiplegia lack the independence to carry out their daily activities, which reduces their quality of life [9]. Furthermore, over 75% of all stroke survivors suffer from hemiplegia [10].

Forty-five percent of all patients who have suffered a stroke lose motor function in their upper limbs [11], so it is usual for this group of patients to experience difficulties in doing their daily activities, such as feeding, cleaning or grabbing and holding an object [12]. Indeed, since stroke survivors are expected to increase over the next several years, more research is needed to enhance survivors' quality of life and they can be integrated into society [13].

In recent years, rehabilitation engineering has had a remarkable boom due to the variety of upper limb devices that have been developed to improve survivors' quality of life [14]–[17]. Among these devices, there is a hand orthosis to assist patients with hand paresis in performing daily activities [18], there is another assistive device that assists patients' left hand while they are eating, writing and typing [19]. Also, some devices are used in rehabilitation, such as a dynamic orthosis which was developed to improve children's hand function at home [20] and there is a custom-made orthosis that assists stroke patients in hand function rehabilitation [21].

As a result, this work aims to design a hand orthosis to aid post-stroke patients with hemiplegia to grasp cylindrical and spherical objects. This assistive device is designed for stroke patients who are between 16 to 70 years old, can close their left hand, but can not open their left hand, and patients also have hand weakness. Thus, improvements in wearability, lightweight, portability, adaptability and ease of use are needed for orthoses [22], so this research presents a dynamic orthosis which is designed to comply with these requirements.

This work is organized as follows: Section II describes the design methodology. It also presents the electromechanical design in Section III which is divided into three subsections: mechanical design, synchronous belt drives selection and electronic design. Section IV introduces the control algorithm. Section V reports the simulation and testing which are used

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to characterize the assistive device. The results are reported in Section VI. Finally, conclusion and future work are given in Section VII.

II. Methods

The design of the hand orthosis has been carried out using a design methodology called Iterative Design because its cyclic process provides excellent opportunities for designers to develop prototypes in less time. Besides, the prototype improves each completed cycle. The design methodology, which is illustrated in Fig. 1, includes six major stages, but only five stages were used.

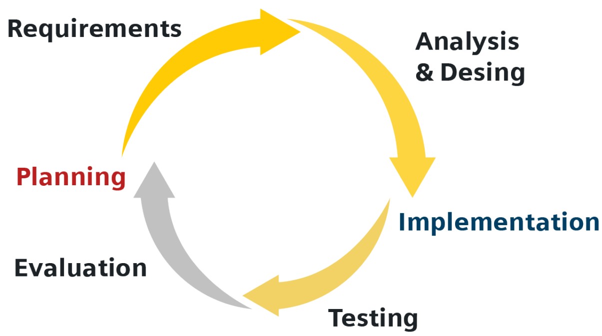

Fig. 1: The six major stages of Iterative Design.

First, in the planning stage, the functional architecture of the hand is studied, such as how the finger joints are distributed [23], [24], what the ROM of the joints of the hand is required to perform daily activities [25], [26] and what anthropometric measurements of the hand are used to design an ergonomic orthosis [27], [28]. Furthermore, if the patient's wrist extension musculature is not strong enough, the patient must use a hand orthosis that has a support that extends across the forearm to prevent wrist–hand deformities. On account of this, the general design concepts for a wrist–hand orthosis are reviewed and used to develop the first version of the hand orthosis [22].

Second, in the requirements stage, a list of requirements, which is described in Table I, was prepared with the information collected from the first stage. Indeed, technical concepts used in the design of a hand orthosis, such as mass, torque and speed were added to the list of requirements to develop a lightweight and wearable orthosis [18].

TABLE I: DESIGN REQUIREMENTS.

Parameter	Requirement	Refs
Mass	$\leq$ 400 g	[18]
Torque	2 - 3 N-m	[18]
Speed	$\approx$ 90 RPM	[18]
ROM of MCP joint	0° - 90°	[25], [26]
ROM of PIP joint	0° - 110°	[25], [26]

Third, in the analysis and design stage, design concepts used in mechatronics projects and assistive devices were reviewed, such as the kinematics of mechanisms, actuators, transmission, materials, sensors, controls theory and design, and simulation softwares [29], [30]. Next, brainstorming was used to make a list of mechanical elements and electronic components that could be used to develop a new hand orthosis. Then, using the list of the second stage (Table I), each mechanical element and electronic component was analyzed to choose what elements or components will make a lightweight and foolproof device. Finally the design of the orthosis was made by using SolidWorks.

Fourth, in the testing stage, simulation tools were used to examine the performance of the mechanical and electronic design. Finally, in the evaluation stage, the list of the second stage (Table I) was used to validate the design of the orthosis.

III. Electromechanical design

A. Mechanical design

The proposed orthosis consists of three main components: a base, a dynamic part, and a passive part, as shown in Fig. 2. The base was designed to prevent a claw hand deformity. Besides, it is characterized as fixed support for the dynamic part, the passive part, and an actuator. The dynamic part was designed to open and close the hand. The passive part was designed to maintain the thumb in an immovable posture in order to avoid colliding with the dynamic part.

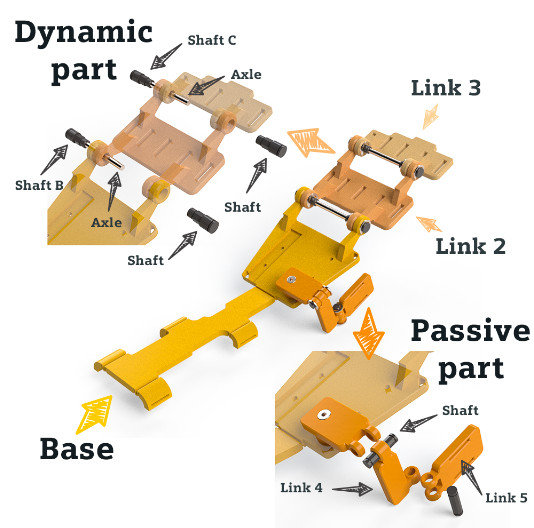

Fig. 2: The three main components of the hand orthosis and its elements.

The dynamic part is divided into two mechanisms: a customized link 2 and a customized link 3 which are presented in Fig. 2. Link 2 is connected to the base by a customized shaft B and link 2 is connected to link 3 by a customized shaft C. The shaft B is composed of two customized shafts and an axle in the same way the shaft C is composed. When link 2 rotates about shaft B, link 2 performs the flexion movement of the

MCP joint. Meanwhile, link 3 performs the flexion movement of the PIP joint of the hand when link 3 rotates about shaft C.

A closed loop motor and a flexible drive are used to rotate simultaneously the links 2 and 3. Thus, the motions of links 2 and 3 perform the opening and closing of the hand. The datasheet of the closed-loop motor, which is a servo (No. SV-1271SG, Savox, United States), is reported in Table II in which a column of well-used units of measurement was added. For example, the torque was multiplied by 0.007062 to measure torque in newton-meters (N-m) and the angular speed was converted into revolutions per minute (RPM) using (1)

$$\omega = (\frac{60^\circ}{0.08s})(\frac{60s}{1min})(\frac{1rev}{360^\circ}) \tag{1}$$

where ω is the angular speed and the servo's rotational speed is $60^\circ/0.08s$ [31].

TABLE II: CHARACTERISTICS OF THE SERVO.

Parameter	Value	Common value
Angular speed (7.4 V)	0.08 s / 60°	125 RPM
Torque (7.4 V)	347.2 oz-in	2.45 N-m

The flexible drive comprises an input sprocket, three output sprockets, and two synchronous belts, as shown in Fig 3. Synchronous belts were chosen because they do not require lubrication and do not stretch; besides, the angular velocity is constant [32], [33]. The input sprocket rotates about axle A and, through belt 1, rotates sprockets 2 and 3 about axle B. Meanwhile, sprocket 4 is driven through belt 2 from sprocket 3. To perform a simultaneous motion of links 2 and 3, the input sprocket must rotate as fast as the output sprocket, so the input sprocket and the three output sprockets must be of equal diameter.

Fig. 2 shows the passive part which comprises three customized links, each link is joined by a customized shaft that has a decagonal prism shape. The shape of the shaft allows links 4 and 5 to maintain the functional position of the thumb to grasp cylindrical and spherical objects.

Referring to Fig. 3, memory foam, which is 2 mm thick, was placed under the base and the links 2, 3, 4 and 5. Memory foam prevents friction injuries between the links and skin. Besides, hook and loop straps are added to attach the forearm and the fingers to the hand orthosis.

B. Synchronous belt drives selection

A procedure for selecting the sprockets and the synchronous belts has been carried out using a general selection which is reported in [33] and a drive design manual which is reported in [34]. The procedure was divided into five steps.

Step 1: an angular speed of the input sprocket, which is given in RPM, was specified by using the angular speed of the servo; thus, the angular speed of the input sprocket is 125 RPM, then an angular speed of the output sprocket was specified so that the output sprocket turns as fast as the input

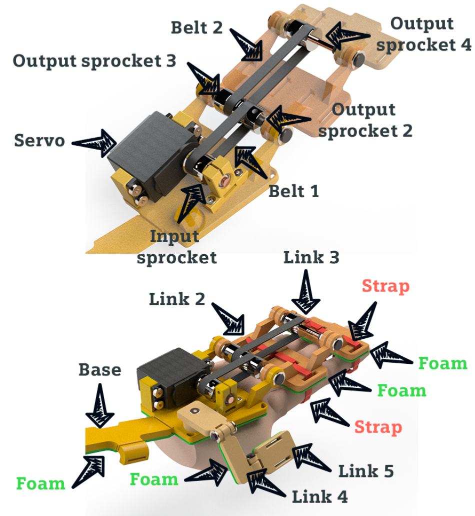

Fig. 3: The flexible power transmission element and the overall design of the hand orthosis.

sprocket. Next, a rated power was specified by using the torque of the servo; thus, the rated power is 2.45 N-m [33].

Step 2: a service factor was determined by using a table which is presented in [33]; thus, the service factor is 1.4 because the hand orthosis is a medical equipment that might work between 8 and 16 hours daily.

Step 3: a design power was evaluated by solving (2)

$$P_{des} = P_{rated}.SF \tag{2}$$

where P_{rated} is the rated power and SF is the service factor [33]. Then, a belt pitch, which is provided in [34], was selected by using the design power and the angular speed of the input sprocket.

Step 4: a velocity ratio, which is 1, was calculated dividing the angular speed of the input sprocket by the angular speed of the output sprocket [33]. Then, the input sprocket and the output sprocket were selected by using a table which is presented in [33]; as a result, the input sprocket and the output sprocket designation is 2MR-20S-06 where 2MR represents the belt pitch, 20S represents the number of teeth and 06 represents the belt width.

Step 5: using the characteristics of the selected sprockets, the input and output sprockets were designed in SolidWorks because there is a toolbox, called Belt/Chain, that can create belts and calculate the length of the belt. Therefore, the belt 1 designation is 2MR-122 and the belt 2 designation is 2MR-168 where 2MR represents the belt pitch and 122 represents the belt length [34].

C. Electronic design

The actuator operating voltage is between 6 V and 7.4 V, so the battery operating voltage must be higher than the actuator operating voltage [31]. On account of this, a rechargeable battery (No. PTK-5501, ProTek RC, United States), which delivers 7.6 V, was selected to power the system because its specifications are made for servos whose operating voltage is between 6 V and 7.4 V. Nevertheless, the battery voltage is usually higher than 7.6 V after charging; as a result, a voltage regulator (No. 8A UBEC, HENGE, China) was chosen to decrease the voltage and power only the actuator [31].

The other electronic components are made up of a microcontroller (No. ATMEGA328P-PU, Microchip, United States) and a force-sensitive resistor (FSR) sensor (No. FlexiForce A401, Tekscan, United States). When the FSR sensor detects physical pressure, it changes its resistive value, so there is a conversion from newtons to voltage. The microcontroller takes the voltage as an analog signal, then the analog signal is scaled to control the actuator by a series of pulses which are transformed into angles.

Fig. 4 illustrates a box where an emergency stop button and a push-button switch were installed to turn the system on or off. Inside the box, the voltage regulator was housed and there is a custom printed circuit board in which the microcontroller and four wire-to-board connectors are affixed. The battery must not be exposed to sunlight for too long because it might burst; on account of this, the battery is put in a special bag (No. PTK-8120, ProTek RC, United States) which was fabricated for charging, storing, and transporting. In addition, Fig. 4 shows the FSR sensor which is housed in a flexible structure. Besides, a flat Delrin disc was placed between the FSR sensor and the flexible structure to have a distributed load when the FSR sensor detects physical pressure.

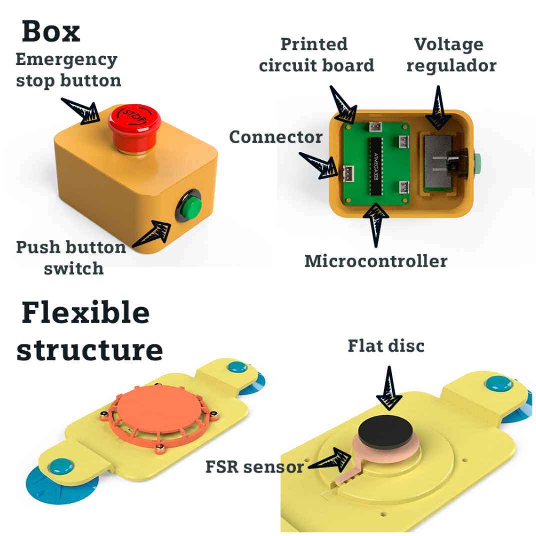

Fig. 4: The electronic box and the flexible structure of the FSR sensor.

IV. Control Algorithm

There is just one method to control the orthosis because an intuitive device was proposed in this paper. Before the patient can use the orthosis, the patient must calibrate the ROM of the orthosis and set the links 2 and 3 as shown in Fig. 3. A manual control, which was written in C language, is as follows: When the patient applies pressure to the FSR sensor with his right foot, the FSR sensor generates analog signals between 0 and 1023 which are read by the microcontroller. Next, depending on how much the patient pressed, the microcontroller sets an angle to rotate the servo shaft, which means links 2 and 3 perform a clockwise motion to close the hand. If the patient stops pressuring to the FSR sensor, the servo angle will be zero, which means links 2 and 3 perform a counterclockwise motion to come back to their initial position.

V. Simulation and Testing

A motion study was used to determine the ROM of the orthosis. The first step was to configure the elements that move links 2 and 3. The servo was configured as a rotary motor because SolidWorks has a toolbar to specify an angle of rotation, then the input sprocket was configured to drive the sprockets 2 and 3 and the sprocket 3 was configured to rotate the sprocket 4. The motion study consists of using the toolbar of the rotary motor to set an angle between 0° and 110°. In addition, the mass of the orthosis was evaluated by using the mass properties dialog box which is an application of SolidWorks.

VI. Results

Fig. 5, which illustrates the result of the motion study, showed that the ROM of links 2 and 3 is between 0° and 80° because there is a collision between links 2 and 3 when the servo rotates through 90 degrees. As a result, the motion study showed that the orthosis is capable of opening and closing of the hand because link 2 covers 88.8% of the ROM of the MCP joint, and link 3 covers 72.7% of the ROM of the PIP joint.

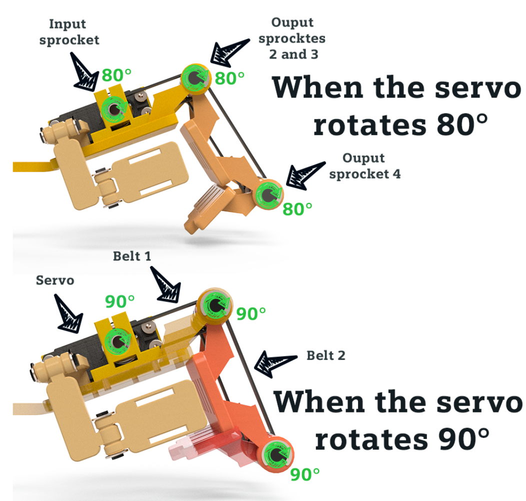

Fig. 5: The results of the motion study.

When Polylactic Acid (PLA) is used as a material to manufacture most elements of the orthosis, the orthosis has a mass of 230 g. Accordingly, this shows that a lightweight orthosis was designed because the mass of the orthosis must be less than or equal to 400g. Regarding the datasheet of the

TABLE III: CHARACTERISTICS OF THE STATE OF THE ART.

Device	Function	Force transmission	Actuators	Torque	Mass	Velocity
Gasser et al. [18]	Assistance	Cable	DC motor	2.9 N-m	229 g	300 RPM
This paper	Assistance	Synchronous belt	Servo	2.45 N-m	230 g	125 RPM

servo and the velocity ratio of the driven system, the hand orthosis can exert a rotational force of 2.45 N-m on the finger joints, with a constant angular speed of 125 RPM (60° /0.08s). On account of this, these characteristics seem to be really interesting because the MCP joint requires approximately 2 to 3 N-m of torque to rotate and the joint's rotational speed is approximately 45° /0.083s (90 RPM) in activities of daily living.

Finally, a comparison of the proposed hand orthosis with a constructed dynamic orthosis, which is presented in Table III, was made in order to validate the main features of the proposed orthosis. Table III reports the proposed orthosis has considerable potential to assist patients in performing grasping tasks, but human clinical studies are still lacking to validate the effectiveness of the proposed orthosis.

VII. Conclusion and future work

In this work, the electromechanical design and an essential motion study of a hand orthosis with a flexible power transmission element and one actuator are presented. Anthropometric measurements of the hand have been taken into account in the design process; as a result, the hand orthosis can be used exclusively by post-stroke patients with hemiplegia who are between 16 to 70 years old. Thanks to the design software and the motion study, the orthosis was able to be characterized as a lightweight (230 g), portable and wearable device. Besides, the motion study showed that the ROM of the orthosis varies from 0° to 80° which is good to perform grasping tasks with cylindrical and spherical objects because the average ROM for the finger joints is about 90°. In sum, this article presents an ergonomic hand orthosis to aid post-stroke patients who can not open their left hand or have hand weakness because the hand orthosis can exert a rotational force of 2.45 N-m on the finger joints, with a constant angular speed of 125 RPM.

Future works will concern the manufacture of the orthosis and an experimental validation on a healthy person will be conducted in order to evaluate the ROM of the hand orthosis. Then, with the help of a 3D optical scanner, the shape of the base, and the links 2, 3, 4 and 5 will change to improve the ergonomics of the orthosis. Next, with the help of physiotherapists, a series of experiments on patients with hemiplegia will be carried out to evaluate the functionality of the hand orthosis in grasping objects.

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