International Journal on Advanced Science Engineering Information Technology

Vol.10 (2020) No. 3
ISSN: 2088-5334

Design of a Hand Orthosis for People with Deficiency of the Medial, Radial, and Ulnar Nerves

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***Abstract*—The reduced mobility in hand is a problem that prevents daily activities such as feeding, bathing, brushing, dressing, grabbing objects, and losing autonomy in everyday situations. The hand disability is mainly due to the deficiency of the ulnar, medial, and radial nerves, which prevents adequate hand movements. In consequence, various assistive technologies are proposed to assist mobility, communication, self-help, and domestic activities. An alternative is the use of active orthosis, which by this proof of concept, the person can perform adequate hand movements. This paper aims to introduce a 3D active orthosis of PLA Plus designed by the Creative Lab in the Universidad Santiago de Cali, which includes an actuator and a low-cost myoelectric signal acquisition system, with two input channels. Finger flexion/extension movements and resting-state were performed. The user's intention is decoded processing rectified and integrated myoelectric signals. An on-off control algorithm was implemented to generate commands that control orthosis movements. The system is controlled by a person who has a disability due to a C5 and C6 spinal trauma that generated muscular atrophy in the distal level of the hand. Results showed the controlled flexion and extension of the fingers with a good performance. This system assists people with disabilities in the ulnar, medial, and radial nerves to make proper hand movements. The design of the above-mentioned orthosis allows individuals to carry out daily living activities to improve their quality of life.**

***Keywords*—electromyography; active orthosis; assistance; decreased mobility; hand orthosis.**

I. INTRODUCTION

Disability worldwide increases significantly, either by accident or illness. According to the World Health Organization (WHO) [1] that between 250,000 and 500,000 people worldwide suffered spinal injuries every year. Many of them are preventable causes such as traffic accidents, falls, or acts of violence. WHO estimates that between 20% and 30% of people with spinal injuries have clinically significant signs of depression and may even hurt the personal functioning and general health status of those affected [1]. As can be evidenced, this situation directly damages the execution of daily and professional activities, becoming a health problem that affects the autonomy, ability, and emotional state of people who have suffered the disability condition.

In Colombia, 1,062,917 people were included in the register of location and characterization of people with disabilities [2]. According to this record, 534,213 people have limitations of movement of the body, hands, arms, and legs, corresponding to 52.3% of the population with a physical disability. This percentage will continue to increase [1]. One of the priority conditions of a disabled person is the restoration of hand function because it is one of the most important parts to provide independence and quality of life for a person. Hand disability prevents a person from performing daily activities such as feeding, brushing, dressing, grabbing objects, among others. Then, different assistive technologies, such as orthosis and prosthesis, are needed to facilitate mobility, communication, and self-help.

The active orthosis can be controlled by myoelectric signals (MES, also termed electromyography, sEMG) through a hierarchical structure of high- and low-level controls [3]. In the high-level control, surface MES are recorded as non-invasive information of the muscle contraction related to the user's intention. Surface MES is the summation of the muscle fiber action potentials, originated by the depolarization of the muscular membrane during its contraction. The amplitude of the signal is proportional to muscular strength. During the processing of the signal, the set of features extraction is performed to preserve relevant information, followed by a classification stage for the recognition of patterns associated with different movements [4]–[7]. The output classification is used as a command to control the orthosis mechanical actuators in a low-level hierarchy.

Several studies proposed different approaches of the orthosis as solutions to improve the functionality of the hand beyond the rehabilitation [8]–[11]. Hand and Hope (HOH) is a device that combines robotics and neuroscience. This artifact gets adapted to the hand and fingers helping to recover movement and functionality [12]. The Department of Mechanical Engineering from the University of Washington created a 3D orthosis that allows holding the fingers with the movement of the wrist [13].

On the order hand, the Department of Innovation in Mechanics and Management of the University of Padua, Italy, made a device for hand rehabilitation. This device actively assists coordinated distal and proximal mobilization for training in the early days after stroke [14]. The force-controlled trajectories of the fingers are performed by elastic actuators, providing a highly compliant interaction with the patient.

Meanwhile, another approach proposed a prototype with a single actuator that helps to move separated four-finger modules [15]. The modules had a total mass of only 150 g, whereas the valve manifold added another 250 g. The prototype showed a good performance for full flexion/extension cycles up to 2 Hz; however, it showed hysteretic losses between 37–81% of the total input energy.

Similarly, to improve the hand function, electromyography (EMG)-controlled powered hand orthosis for training hand extension in stroke patients with the paretic hand was proposed [16]. The orthosis is composed of a glove-like device developed from two mechanical and electrical sections.

Besides, there are different studies where active devices have been proposed for rehabilitation [17]–[19], combining passive and active assistance applying sEMG-based control strategies for exoskeletons and orthosis for the hand. Moreover, there are also studies where they perform signal processing and control of prostheses based on electromyographic signals as the design and implementation of prosthetic hand control using myoelectric signals [20].

In that sense, this study is aimed to develops the design of an external hand orthosis for active assistance, seeking to restore some limb movements and its functionality for flexion and extension of the fingers. Decoding of the user's movement intention is accomplished through the use of surface MES recording from electrodes located in the residual muscles of the injured hand. The study involves a stage of acquisition of the surface MES, a stage of ergonomic design of the orthosis on cad software, and the design of the actuators. Finally, a test of the orthosis is validated on a disabled hand.

II. Materials and Methods

The research approach of the current work is experimental and applied. It is aimed to improve the motor functionality in subjects with reduced hand mobility for the flexion and extension of the fingers, to improve the quality of life of people with spinal injuries. The design of the hand orthosis was divided into some phases detailed below.

A. Subjects

The study was conducted in a male volunteer from the city of Cali. He is 25 years old age, and he has a partial disability as a sequel to a C5-C6 spinal trauma grade. He has muscular atrophy at the distal level of the hand. The tests were carried out with all safety conditions such as signal power supply isolation and safe mechanical movements with the priority of protecting the physical and emotional integrity of the person. The study conformed to the Declaration of Helsinki and was approved by the Ethics Committee of the Universidad Santiago de Cali, No. 013, Session 003.

B. Acquisition System

The myoelectric signals were obtained from the processed output signal (SIG) from the MyoWare™ Muscle Sensor (AT-04-001), which provides a rectified and integrated signal [21]. The signal was digitalized and processed on a Beagle bone black platform with a sampling frequency of 300 Hz. The power supply of the system was of +5.0 V. Covidien H124SG disposable surface electrodes with a diameter of 23.9 mm, a weight of 0.6 g, non-irritating gel, and latex-free foam surface was used on two locations simultaneously.

A protocol established in [22] to the identification of electrode locations and the muscles with stronger muscle activity was followed. The skin was prepared by hair removal, skin cleansing, and abrasion. Two electrodes were located on the forearm, on flexor digitorum profundus and extensor digitorum communis muscles.

During the test, a comfortable posture was recommended, with the arms resting on a table to maintain an elbow joint angle of 90 degrees. The subject voluntarily contracted the muscles to perform the extension and flexion movement of the fingers following the procedure described in [22]. This approach provides a surface MES dataset consisting of three motions associated with finger flexion/extension movements and the resting state. Every 10 seconds the subject performed a contraction for both movements, during one minute. The surface MES activation from the residual muscles was analyzed through the integrated signal provided by the acquisition system. Finally, the user's intention was decoded to perform a movement.

C. Design of the Orthosis

The design of the active orthosis was made in a cad program. The pieces are manufactured according to the needs of the disabled person. The measurements and the shape can be modified, considering symmetry restrictions.

1) Phalanx Width: the width is taken at the most proximal joint; it is taken at the joint between the distal and medial phalanx.

2) High of the Phalanx: The measurement is taken from the fingertips to the top and the measurement of the finger width at the joint between the medial and distal phalanx.

3) Phalanx Length: The length of the phalanx is taken from the most distal part of the phalanx to the joint.

D. Actuators

When selecting the system engine, the torque must be calculated. The engine weight and the system ergonomics also have to be considered. Eq. (1) calculated the torque required to perform the movement of the fingers.

$$\tau = Fdsen(\phi) \qquad (1)$$

where F is the Force, d is the distance and ϕ is the angle between Force and distance vector [23].

III. RESULTS AND DISCUSSIONS

A. Acquisition System

The myoelectric signals recorded on the muscles showed differences in the signal amplitude of both muscles for the considered movements. The difference of amplitude peaks of the integrated myoelectric signals during the movement was processed in real-time in the micro controlled platform. This difference allows the identification of finger flexion/extension performed by the subject. The resting state related to non-movement of the orthosis was defined when no amplitude peaks were found. Figure 1 shows the amplitude of the signals when the finger extension task was performed. Fig. 1.a corresponds to the extensor digitorum communis muscle and Fig. 1.b presents the flexor digitorum profundus muscle.

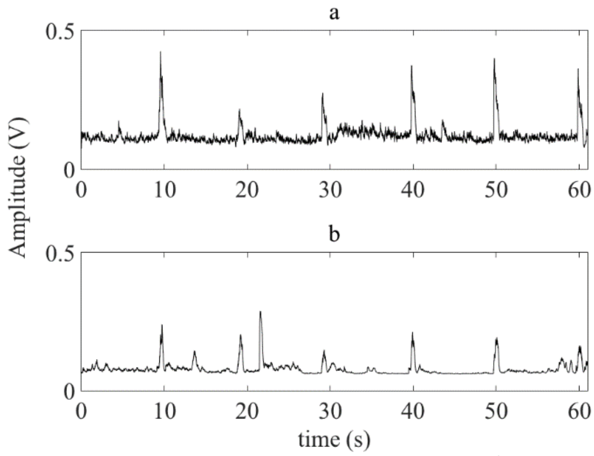

Fig. 1. Finger Extension (a) extensor muscle, and (b) flexor muscle

Fig. 2 shows a comparison of both signals simultaneously during the finger extension. It could be noted a higher activity of the movement-related muscle compared to the antagonist muscle activation, with an amplitude peaks above 0.40 V for the movement executed every 10 seconds. However, the flexor digitorum profundus muscle showed amplitude peaks lower than those achieved by the agonist's muscle. As can be seen in Fig. 2, flexor muscle does not exceed 60% of the amplitude of extensor muscle.

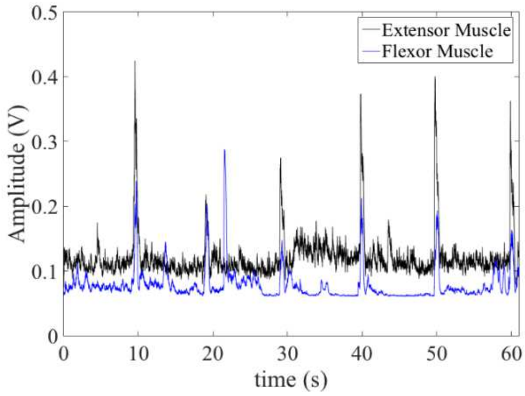

Fig. 2. Myoelectric signals of the muscles (finger extension movement)

Fig. 3 shows the signals corresponding to the finger flexion Fig. 3.a corresponds to the extensor digitorum communis muscle and Fig. 3.b presents the flexor digitorum profundus muscle.

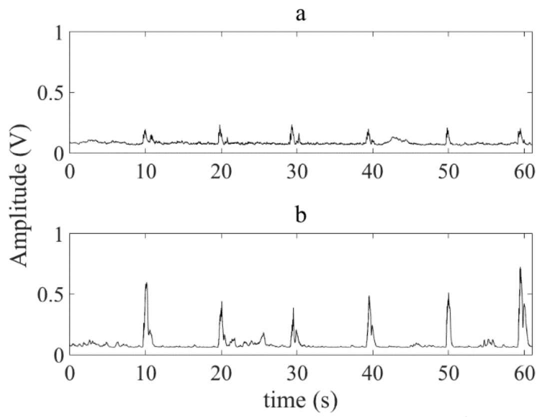

Fig. 3. Finger Extension (a) extensor muscle, and (b) flexor muscle

Fig. 4 presents both signals in the same plot. In this case, it was observed amplitude peaks higher than 0.50 V in the flexor muscle during its activation, while the extensor muscle reaches amplitude peaks of up to 0.25 V. That is a muscle activation approximately 50% less than the amplitude of the agonist's muscle.

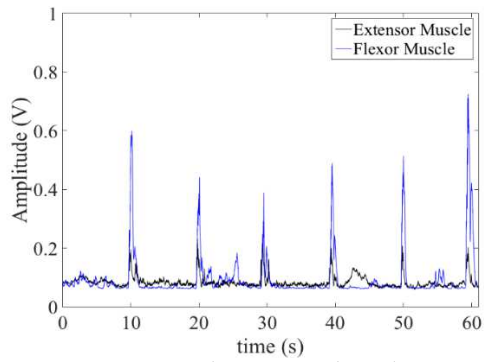

Fig. 4. Myoelectric signals of the muscles (finger flexion movement)

B. Design of the Orthosis

The active orthosis was developed with PLA Plus on 3D print in the creative Lab of University Santiago of Cali; the design is presented in Fig. 5.

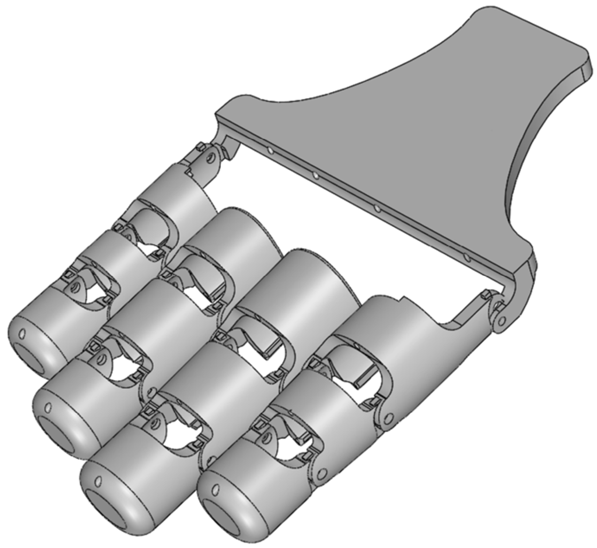

Fig. 5. Myoelectric signals of the muscles (finger flexion movement)

Fig. 6 presents the design of the distal phalanx. Section A refers to the limit point that prevents the backward extension of the orthosis to avoid fractures. Section B is the point where the proximal phalanx gets connected to the medial phalanx. Then, joint movement can occur. Section C is the hole where the thread passes through. It allows finger extension. Finally, section D is the hole where the threads (related to finger flexion) go through. Fig. 7 describes the design of the index finger medial phalanx structure.

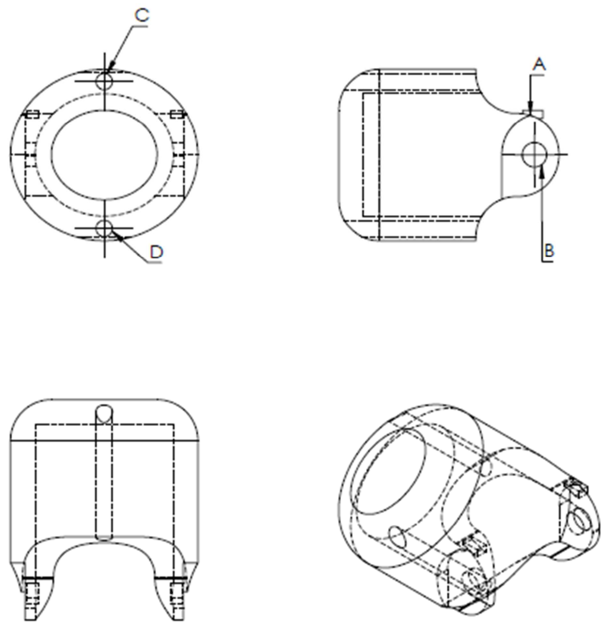

Fig. 6. Distal phalanx of the index finger

Section A is the point that connects the distal phalanx that acts as a joint. Section B is the point that joins the proximal phalanx of the index finger. Section C is the hole where the thread passes through, that allows the finger extension, and section D is the hole where the thread passes through relation to the finger flexion. For the design of the middle, ring, and little fingers at the level of the distal and medial phalanges are the same as shown in Figs. 6 and 7, just with a difference in the dimensions for each of the phalanges.

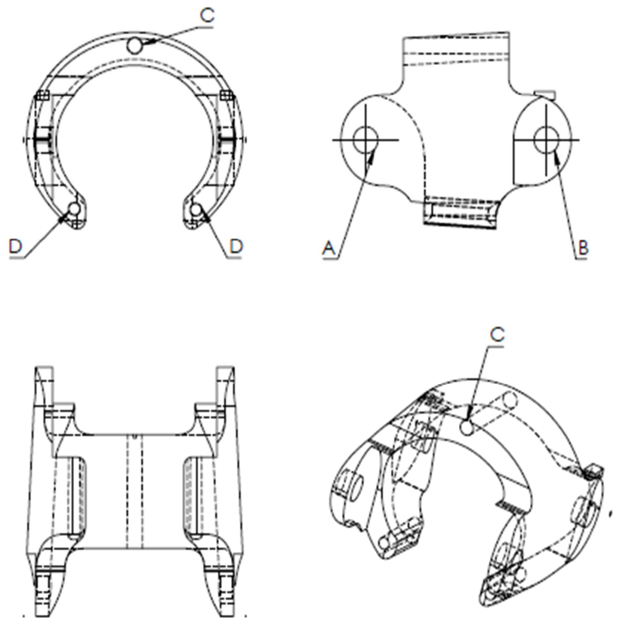

Fig. 7. Medial phalanx of the index finger

Fig. 8 shows the proximal phalanx of the index finger.

Section A is the joint with the distal phalanx. Section B is the point of union with the structure above the hand and supports the orthosis, and section C is the inner part of the finger that coincides with the middle finger.

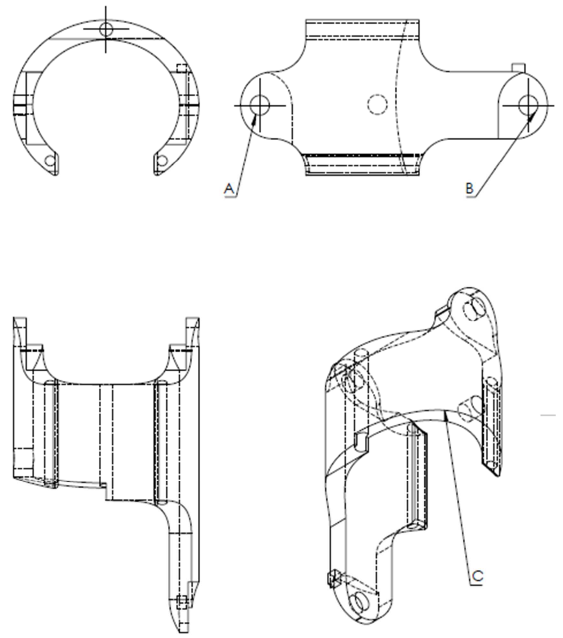

Fig. 8. Proximal phalanx of the index finger

Section A includes two pins to give support between the phalanges. Section B is the point where the middle of the fingers coincides with the knuckles, which connect the medial phalanx through the joint. Section C is the hole where the thread passes through. It allows finger extension. Finally, section D is the hole where the threads (related to finger flexion) go through.

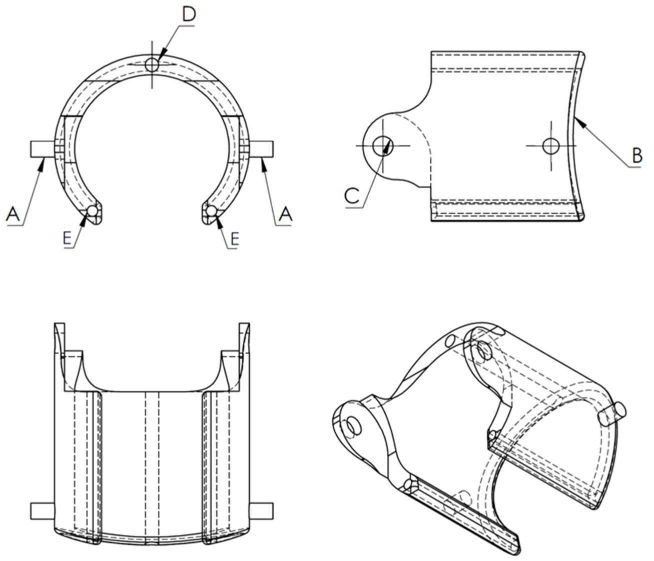

Fig. 9. Proximal phalanx of the middle finger

Fig. 10 presents the design of the proximal phalanx of the ring finger. Section A shows a hole that receives the pin of the proximal phalanx from the middle and little finger.

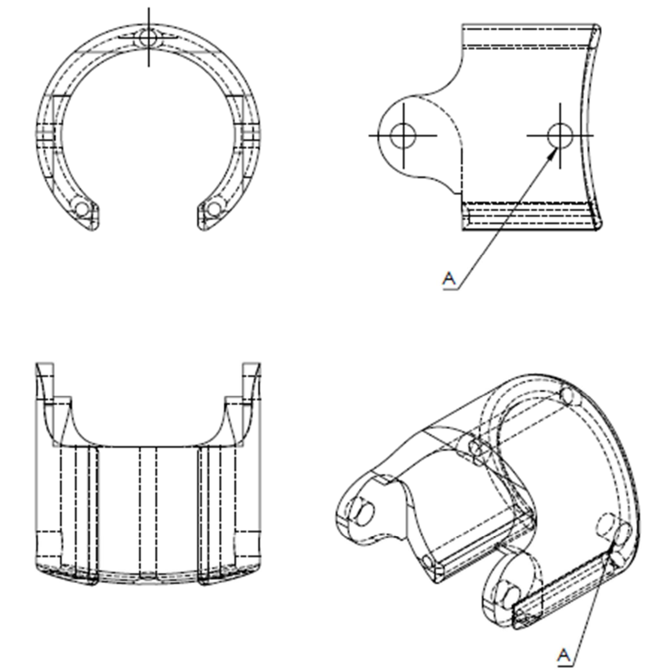

Fig. 10. Proximal phalanx design of the ring finger

Fig. 11 presents the design of the little finger. Section A is the pin that allows to couple the proximal phalanx of the ring finger, and section B is the tab that allows the union and fixation of the fingers to the structure that guide the threads. A hollow cylinder of the finger was made with a 1 mm of the additional radius that allows adjustment. The design is 3 mm thick, which depends on the material and its resistance. The holes through which pass the threads have a radius of 1.2 mm. The holes for the rivets have a radius of 1.5 mm. These holes allow the phalanges of the design to be coupled.

In the medial and proximal phalanx, at the anterior part, a space of 12 mm long is created to allow the placement of the phalanx. This size varies depending on the width of the finger. The proximal phalanx of the index and little fingers has a tab that allows them to be fixed with the structure of the hand where the extension threads are conducted.

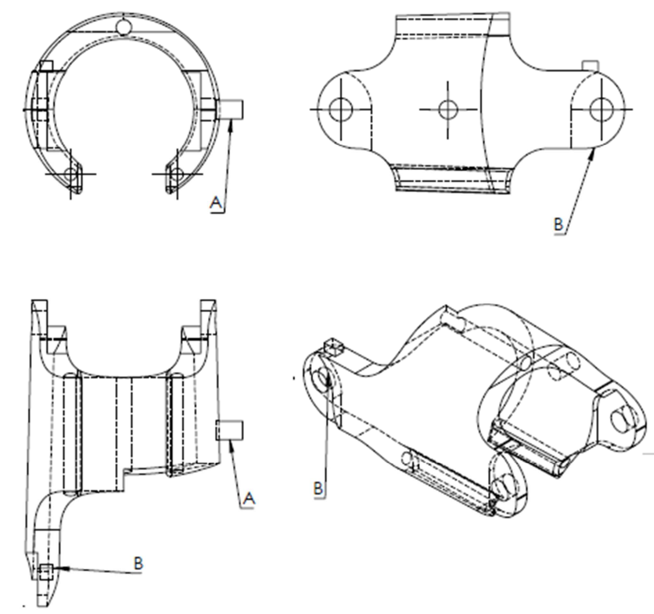

Fig. 11. Proximal phalanx of the little finger

Fig. 12 shows the design of the thread structure for the orthosis. The location of this structure is the dorsal side of the hand. Section A is the holes of a radius of 1 mm that allow joining the structure to the glove of the orthosis. Section B is the canal of a radius of 1.5 mm through which pass the threads of the fingers structure towards the actuator.

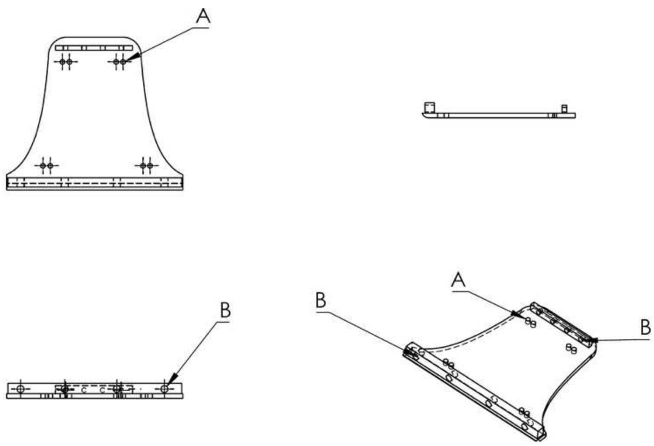

Fig. 12. Thread structure

C. Actuators

The flexion and extension of the fingers were executed through a servo motor. The servo motor performs the functions of the tendons on the orthosis by threads, doing or completing the movements that the impaired person cannot do by itself.

The force for this application should be enough to overcome the weight, being the mass of the object multiplied by gravity. Now, considering that the mass of the select individual is 80 kg, the mass of his fingers is 0.28 kg. The distance between the application point and the axis of rotation is the length of the middle finger (maximum length) with a dimension of 9 cm. The angle between the force and the distance vector is 90 degrees. When the fingers are in the same direction of gravity, an angle of 90 degrees is formed in the point where the maximum torque is presented. For a F = 9.8 m/s^2 x 0.28 kg = 2.75 N, the torque is obtained by Eq. (1).

$$\tau = 2.75N \cdot 9cm \cdot sen\left(90\right) = 0.2475Nm \qquad (1)$$

The torque required is 0.2475 Nm, and it is necessary a security factor of 1.5. The final torque is 0.37 Nm.

D. Actuator response

Considering two signals, an on-off control algorithm was implemented to control the actuator and the movement of the orthosis. Fig. 13 presents the signals to the extensor and the flexor muscles, the activation of the actuator clockwise to achieve movement of finger flexion, and the activation of the actuator counter-clockwise to give the movement of finger extension movement.

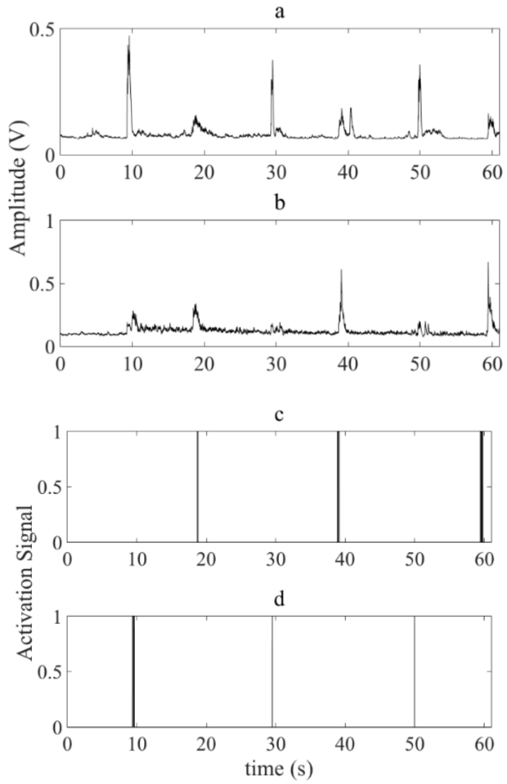

Fig. 13. Myoelectric Signals (a) flexor muscle, (b) extensor muscle, and activation of the engine (c) counterclockwise, and (d) clockwise

Three conditions for the activation of the actuator were considered:

- If the extensor digitorum communis muscle signal is greater than the flexor muscle in 0.20 V, the actuator is activated clockwise.
- If the flexor digitorum profundus muscle signal is greater than the extensor muscle signal in 0.20 V, the actuator is activated counter-clockwise, and
- If the difference between the two signals does not exceed a threshold of 0.20 V, the actuator remains in the last position.

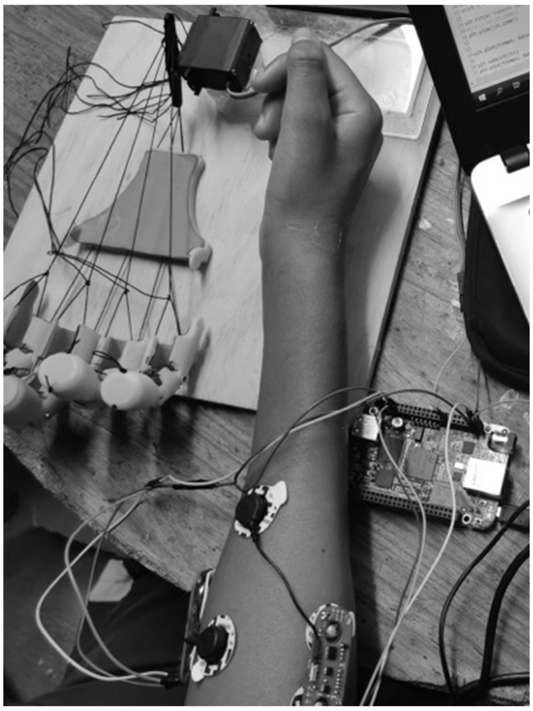

Fig. 14. The active orthosis of the hand

Fig. 14 shows the model printed in 3D with PLA plus material. This is the first functional sample of the orthosis. The orthosis movements were made with a device attached to an external base. This procedure was performed to evaluate the operating conditions.

IV. CONCLUSION

This paper presents the design of an orthosis proposed for a person with a disability in the ulnar, medial, and radial nerves. The aim was that he could carry out daily activities by himself, establishing a better quality of life. The operation of a myoelectric signal acquisition system by using a Myoware sensor and a Beaglebone Black platform leads to obtain excellent and differentiable signs of the common flexor and common extensor muscles of the volunteer fingers. This is an important process when performing specific movements. The amplitude of the signals was different because they depend on the movement performed and the impairment of the person.

Besides, a servo motor test was performed for the independent movement of the four-finger joints. Finally, an initial ergonomic design of the orthosis of the fingers was presented, to join both mechanical and electrical systems. It should be noted that the presented design allows the flexion and extension of the fingers without any problem, but it is subject to modifications since it seeks to improve its functionality.

NOMENCLATURE

d	Distance	cm
ϕ	angle	grades
F	Force	Newton (N)
τ	Moment (torque)	Nm

ACKNOWLEDGMENTS

The authors are grateful to the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) - Brazil, Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES) - Finance Code 001, and Departamento General de Investigación (DGI) - Universidad Santiago de Cali, Colombia, project No. 819- 621119-487.

DISCLOSURE STATEMENT

The authors reported that no potential conflict of interest.

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