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Design of Actuators Applied to a Upper Limb Orthosis

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Abstract. *This work aims to develop a system of low volume electromechanical actuators for an upper limb rehabilitation robotic orthosis in post-stroke individuals. Through the selection of high torque and low volume motors and the design of mechanisms to simulate the user's hand and elbow physiological movements, transmissions systems and a control system using a microcontroller combined with a sensor, was possible developed them. Using artificial tendons system and artificial phalanges for the hand actuator and a four-bar mechanism for the elbow actuator coupled with powers screws transmission, a microcontroller STM32F103, encoder KY-040 and stop sensors for safety, it was possible developed actuators for two modulus, hand and elbow, performing the hand opening on 2.51s with 0.8Nm of torque and the elbow flexion and extension on 4.43s with 12Nm of torque, with angle control of both movements, in that way promote the user's rehabilitation.*

Keywords: *Machine Design, Upper limb Orthosis, Assistive Technology*

1. INTRODUCTION

The World Health Organization (WHO) defines stroke as a sudden interruption of blood flow to the brain tissue due to ischemia or hemorrhage, resulting in the death of brain cells and, consequently, partial loss of neurological function (WHO, 2012). The stroke is the second largest cause of death in the world, accounting for 6.7 million deaths in 2012

(WHO, 2014). In Brazil, among the death main causes, cerebrovascular diseases are in the first place, followed by acute myocardial infarction. The WHO estimates up until 2030, stroke remains the world's second-leading death cause, accounting for 12.2% of deaths predicted for the year (WHO, 2013).

According to the location, extent and lesion severity, the stroke carries a variety of motor, sensory and cognitive disabilities (Langhorne *et al.*, 2011). Among these deficiencies, the upper limb motor function commitment are the most common and affect about of 50-70% of patients in the acute phase(Nakayama *et al.* 1994; Persson *et al.* 2012) and 40% in the chronic phase (Broeks *et al.* 1999; Parker *et al.* 1986; Prange *et al.* 2006). Evidence in the literature indicates that 6 months after stroke, about 30 to 66% of patients do not present upper limb function on the affected side, and only 5% to 20%, demonstrate a complete recovery of functional activities (Kwakkel *et al.*, 2008).

Researches have been carried out with the objective of seeking the best interventions for the rehabilitation of these individuals, with a view to functional return, providing greater independence in activities of daily living, greater social participation and quality of life (Prange *et al.* 2006; Nichols-Larsen *et al.* 2005; Araújo 2011; Maciejasz *et al.* 2014). One of the alternatives to assist in the recovery of individuals with partial paralysis in the upper limbs is the use of robotic orthoses that facilitate cortical reorganization resulting in an increase in the patient's motor ability and elevating performance in functional activities (Liepert *et al.*, 2001). According to Maciejasz *et al.* (2014) "rehabilitation robots" are mechatronic devices ranging from artificial limbs to robots that aim to aid in the recovery of patients in rehabilitation therapy or as personal assistants in hospital settings or residences. The most popular devices for the purpose of upper limb movement recovery are MIT-Manus (Krebs *et al.*, 1998), MIME (Lum *et al.*, 2006), ARM-Guide (Kahn *et al.*, 2006), NeReBot (Masieiro *et al.*, 2007), ARMin (Nef *et al.*, 2007) and BI-MANU-TRACK (Hesse *et al.*, 2003). However, these devices present some disadvantages: they are imported equipment making it difficult to buy them in Brazil, they are robust, bulky and heavy devices without portability, interfering in the accomplishment of daily activities.

The Laboratório de Bioengenharia (LabBio) of Universidade Federal de Minas Gerais (UFMG) developed a device to aid in the recovery of patients who suffered from stroke and have partial paralysis of the upper limbs, which represents an advance in relation to commercially available equipment in Brazil and abroad. Competitive differentials relate to: structure, control system and portability. In order to make the device capable of being easily used, it became necessary to design actuators that could make it light and practical. In this work, the development of electromechanical actuators for application in an upper limb orthosis for the rehabilitation of post-stroke individuals is presented.

2. METHODOLOGY

The orthosis presents a modular and adjustable structure (hand module and elbow module) performing hand opening movements (from fingers II to V) and flexion and extension of the elbow. For the operation of the device, actuators were designed containing motor, actuation mechanism, transmission system and control system. As the device had to have a reduced weight and high portability, the motor was the first item to be analyzed, taking into account its weight and torque, so that the equipment performed all the desired movements and defined all the used mechanisms and parameters. The second project item was the mechanisms that perform the movements. With them, the transmission system was designed to ensure the necessary force for the execution of the activities arrives in the effectors. Finally, a system that controls the correct position of the user limb safely was selected, as close to the physiological as possible.

2.1 Motor selection

The motors used in the hand and elbow module were selected considering the benches and clinical test in a robotic orthosis to users with upper limb disabilities in Rocha (2007) and Araújo (2011) works. With this information and after a pilot study in post-stroke patients with limited upper limb function (COEP-ETIC-0439.0.203.000-10) the necessary torque to perform the flexion and extension elbow and extension fingers were defined. Therefore, a 0.8Nm value of torque was set for the hand module and 12Nm for the elbow module. The other point analyzed was the motor weight and dimensions. The actuator must be directly coupled to the structure, to do so, the motor must have the smallest possible weight and length combined with satisfactory torque.

2.2 Mechanisms of the hand and elbow module

Using the Araújo (2011) work as a reference, it was decided to use a cable, artificial tendons, coupled to fingerstalls for the hand opening mechanism, by traction and relaxation of tendons. However, only the artificial tendons were not enough for the full opening of the hand. Artificial phalanges were developed where the artificial tendons are coupled in their interior making the complete opening of the hand. The artificial phalanges limit the movement of each user's phalanges avoiding higher than physiological amplitudes. Thus, in order to perform the opening movement of the hand, the artificial tendon that pulls the distal phalange must be tensioned, making the movement of rotation about the axis of its articulation. The rotation movement occurs until the moment the angle between the intermediate and distal phalanx is 180°, at this point, the artificial phalanges have a limiter that prevents the distal phalanx continuing its movement. With the tendon still being tensioned, the rotation movement is now around the axis of rotation of the intermediate phalange articulation. The rotation movement of the intermediate phalange follows until 180° angle is made with the proximal phalange, at which point the movement limiter again acts ceasing the rotation movement of the intermediate phalange, making the only movement present the is in proximal phalange. To stop the movement is actuated travel limiter present in the transmission box of the hand actuator, limiting the movement of the nut of the transmission system performing the complete opening of the hand, how shown in Fig. 1.

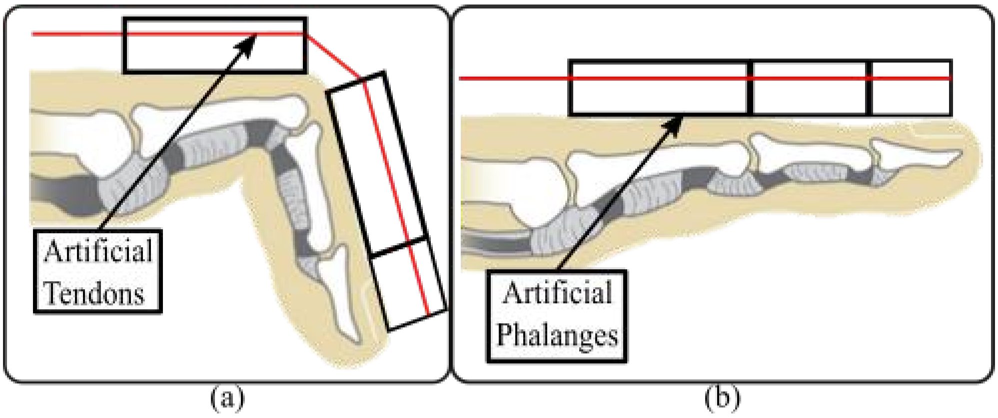

Figure 1. Schematic representation of the mechanism operation: (a)flexion, (b)extension

As for the design of the mechanism elbow module, a system was designed to emulate the flexion and extension of the elbow. After reviewing mechanism projects and considering that the system should be light and compact, it has opted for the design of a rotating rod system, which has its rotation axis concentric to the rotation axis of the elbow joint which is connected to the hand module. For this, a four bars system was used, with three rotating joints and a linear joint, making the system compact. According to Fig. 2 the rotating joints A and D are shafts made by screws for coupling of mechanism to the structure, the linear joint B is the power screw, also used like system of transmission of the motor, generating the force for operation of the mechanism (F) and the rotation joint C is the union between the power screw nut and link 3, which is the arm rotation rod thus making the elbow flexion and extension and represents the output torque (M) of the mechanism. The links 1 and 2 represents the coupling of the motor with the power screw and the motor mount to the structure.

The first determined item was the length of the link responsible for the output torque that would rotate the rod with a minimum torque, the value of 12Nm. Thus, following the diagram is shown in Fig. 2, the output force of the linear joint (F) was related to the output torque link lever arm (L_3) and the angle between the two links (θ), resulting in the mechanism output torque (M). To calculate the input force of the mechanism, the Eq. 1 was used following the Budynas and Nisbett (2011) methodology for the power screw design, where T is the maximum torque of the motor, d_m is the mean diameter of the thread, f)the coefficient of friction between the bolt and the nut and l the height of the thread.

Another analyzed point was the angular movement of the arm rotation rod, resulting in the linear joint length and links 1 and 2, for the flexion and the extension of the elbow, an angular movement of 110° is required. To determine the length of links 1 and 2, a schematic diagram is developed using SolidWorks® emulating all operating positions of the mechanism.

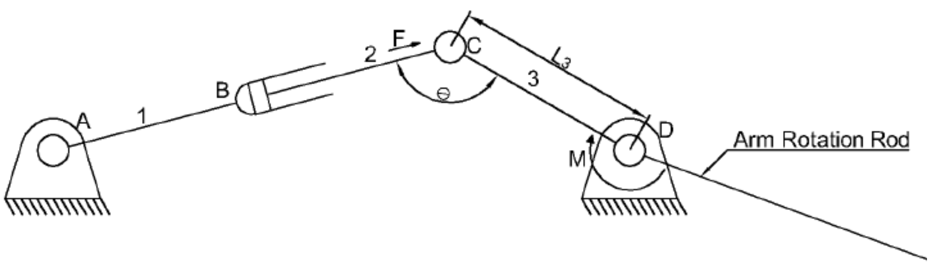

Figure 2. Schematic diagram of the elbow module

$$F = \frac{2T}{d_m} \cdot \left(\frac{\pi d_m - fl}{l + \pi f d_m} \right) \tag{1}$$

2.3 Transmission of the hand and elbow module

For traction and relaxation of the artificial tendons and for the linear joint of the elbow module mechanism, the power screw transmission system was used because of it has a low volume compared to the other systems, allowing its use coupled directly to the body of the orthosis. For the power screws design, it was first defined the length and action time, with the hand opening maximum time set as 3 seconds and elbow flexion or extension time set as 5 seconds defining the pitch and number of threads.

With the design methodology explained by Budynas and Nisbett (2011), it was possible to calculate the minimum dimensions for the transmission system. Following Fig. 3, the stress can be determined on all planes and axis as shown by Eqs. 2 where n_t is the number of engaged threads d_r the root diameter of the thread and p the screw pitch.

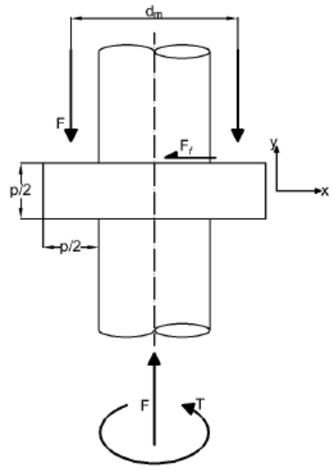

Figure 3. Distribution of screw loads.(Adapted Budynas and Nisbett (2011))

$$\begin{aligned} \sigma_x &= \frac{6F}{\pi d_r n_t p} & \tau_{xy} &= 0 \\ \sigma_y &= -\frac{4F}{\pi {d_r}^2} & \tau_{yz} &= \frac{16T}{\pi {d_r}^3} \\ \sigma_z &= 0 & \tau_{zx} &= 0 \end{aligned} \quad (2)$$

After calculating all the tensions, it was possible to determine vonMises stress through Eq. 3 to ensure that the component didn't fail because of stresses.

$$\sigma' = \frac{1}{\sqrt{2}} \left[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6 \left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2 \right) \right]^{\frac{1}{2}} \quad (3)$$

An Excel® routine was developed with all of these equations to determine the bolt and the nut dimensions of the transmission system. This method was chosen due to the practicality of recalculating all system variables with any combination of pitch, diameter and material without requiring a complex programming language, turning the project more dynamic.

2.4 Control system design

To perform all the orthosis movements, an electronic system was developed to control the actuators. The first item to be analyzed were the sensors to measure the user's hand and elbow position and stop sensors to stop the movement in the physiological limiting positions. Communication between the user and the orthosis was also necessary to determine the position, speed and opening time the user wants to perform the movements. Finally, to manage all the information of the sensors, user commands and to control the operation of the actuators, it becomes necessary for a microcontroller to be able to perform all these tasks.

The sensors were chosen by analyzing their dimensions, weight and compatibility with the mechanical system. to measure the hand and elbow's position, an angular position sensor was selected and as brake sensors, tactile sensors were chosen, which stop the movement as soon as it is touched.

For communication between the user and the control system, a wireless connection was used to promote practicality in use portability.

The last design item was the microcontroller. For this selection, it was necessary to know what types of electrical signals the sensors send, the type control communication used by the user and the electrical signals the motor needs to work. The microcontroller needs to have input and output ports compatible with all these signals and to compare and manipulate them to control the actuator.

3. RESULTS

3.1 Motors

The motors selected were Maxon Motors™ model EC16® with a GP16A® coupled reduction, which has a reduction of 157: 1, resulting in output torque of 0.797Nm with a nominal output speed of 180 rpm. This choice is justified by the low weight of the reduction motor assembly (61g) and its reduced dimensions (16mm diameter and 78mm length), making it possible to attach directly to the body of the orthosis. The motor works with 12V of voltage and consumes a nominal current of 1.71A, this facilitates its coupling with the microcontroller electric system that operates the low voltage

Following the motor, Maxon Motors™ offers the Escon 50/4 EC-S Module® which is a programmable servo controller and allows to change the engine characteristics as acceleration and deceleration ramp, safety brake and allows various input signals to manage the operation of the motor. These features were fundamental in the development of the mechanical and electrical systems, because of the variability of motor control options and characteristics made it possible to test numerous configurations of the mechanisms used and controls to make the best choice of them using the same motor due to their flexible settings.

Despite the lower torque than desired for the elbow module system, its use is feasible due to the coupling on the mechanism shown in Fig. 2, thus multiplying the generated torque, reaching the output torque of 12Nm.

3.2 Mechanism

For the hand module, artificial tendons were used, which are cables that relaxing and stressing the fingers. For this, their material is DuPont™ Kevlar® aramid fiber, because it makes them lightweight and resistant to the loads applied by the motor assembly with the transmission system. Three artificial phalanges at each finger were used, made by the 3D printer using PLA. The hand module actuator is shown in Fig. 4.

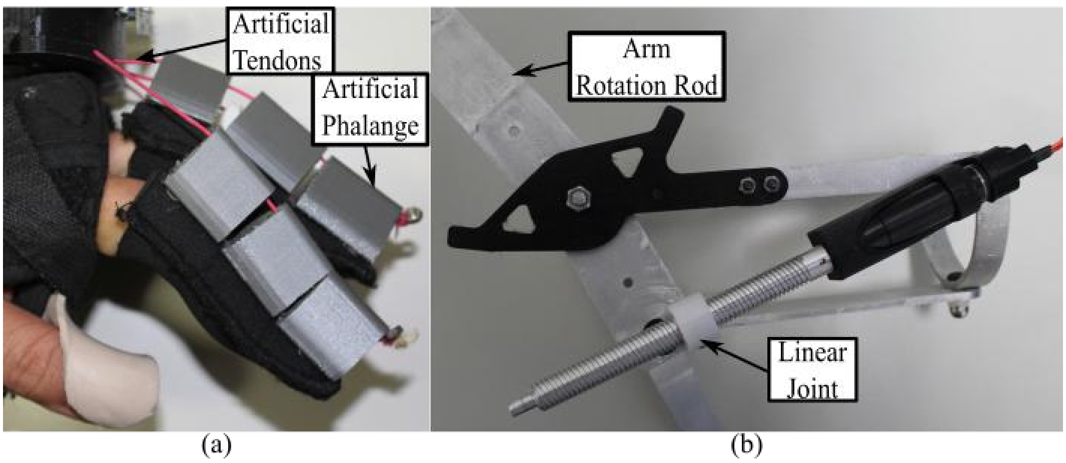

Figure 4. (a)Hand and (b)elbow modulus mechanism.

As the orthosis is for post-stroke patients, the extension movement is active and the flexion is passive because this movement easier to the user, thus the artificial tendons are tensioned for the hand opening movement up to 180° and through a progressive tendons relaxation, reducing the force generated by the transmission system is done the hand closing movement.

For the 4-bar mechanism of the elbow module, the first design item determined was the lever arm of the arm rotation rod (L_3) to obtain a minimum torque of 12 Nm, as shown in Fig. 2. Using the Eq. 1 considering the maximum torque of the motor it was possible to calculate the input force on the link 3 and the angle between the links 2 and 3 a lever arm minimum length of 65mm was determined. Another point of the mechanism is the length of the linear joint to rotate the arm at an angle of 10° to 120°, making a 106mm linear joint length required. The hand and elbow mechanisms module is shown in Fig. 6.

3.3 Transmission System

Power screws were designed for the transmission system of the hand and elbow actuators. The selected materials were the 6063 Aluminum for the bolts and the Nylon for the nuts. They were chosen according to their low coefficient of friction, weight, strength and of the self-lubricating characteristics of nylon.

Using Eqs. 2 and 3, the dimensions of the hand actuator bolt with: 12mm diameter; 2mm pitch and triple thread, of the elbow actuator bolt with: 12mm diameter; 2mm pitch and quadruple thread, and the length of 15mm for the nuts were defined. The maximum stress of Von Mises was 4MPa to the hand module and 11MPa to the elbow module, these values were below than yield stress of the material.

Was necessary a useful length of 45mm for the hand screw and 106mm for the elbow, it was possible to perform the total opening of the hand in 2.51 seconds and the flexion or extension of the elbow in 4.43 seconds, meeting the design requirements. The transmission systems are represented in Fig. 5.

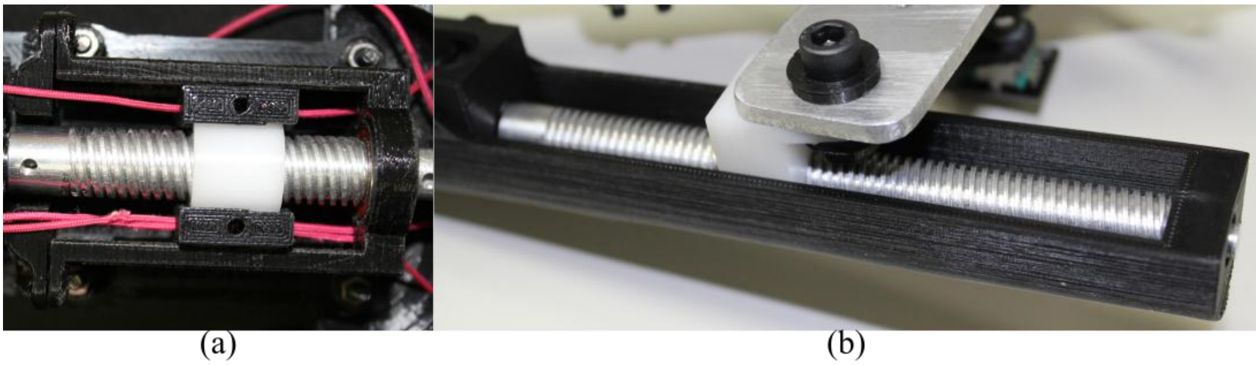

Figure 5. Transmission system of the (a)hand and (b)elbow module.

3.4 Control System

For the control system, a snap action switch was selected as the stop sensor, while to determine the position of the arm and the amount of hand aperture the KY-040 encoder. Four brake sensors were used, each located at the ends of the screw and nut brackets. The encoder was used to measure the elbow modulus rod position and the amount of revolutions of the hand module screw, determining the flexion or extension angle of the elbow and the opening of the hand. To manage the system, the microcontroller STM32F103 was used, which determines the direction and the speed that each motor needs to be, according to the responses of the sensor. The position sensor can be seen in Fig. 6 in which the circled area determines the position of the stop sensor. The position of each sensor is shown in Fig. 6.

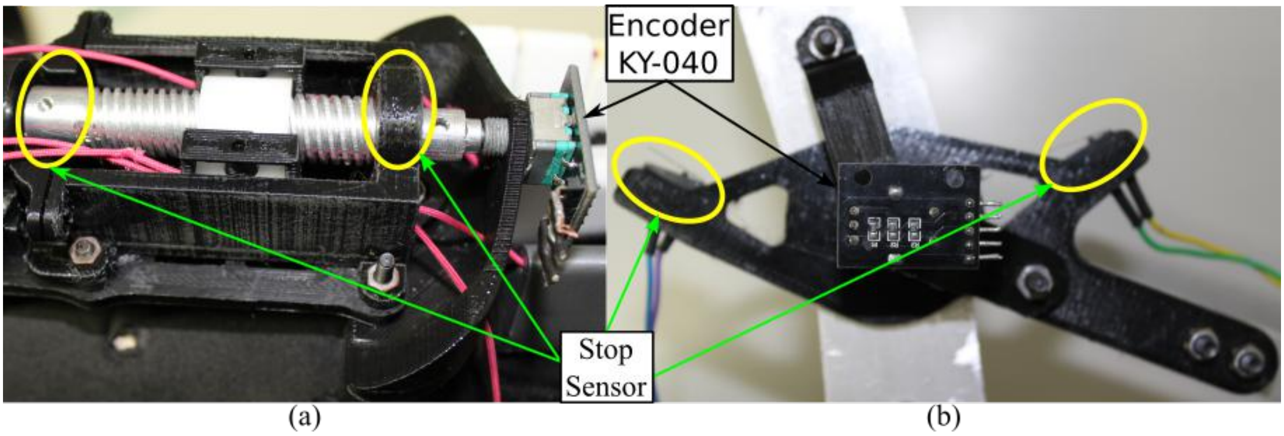

Figure 6. Sensors position of hand module(a) and elbow module(b)

The control of each actuator is represented by a control diagram shown in Fig. 7. The user sends the microcontroller the desired position for the hand or the elbow, the microcontroller receives the command and compares the current position of the member and sends the sense and direction of operation to the actuator. The current position values are updated during every operation until the desired position is reached or one of the brake sensors is activated. The stop sensor acts as a safety sensor because it limits the maximum and minimum position of each limb segment, and if one of them is activated the actuator will not operate.

To the user communicate with the control system was used a Bluetooth HC-05 module, that permits direct communication with cellphones and computers using applications to make a user's interface with the orthosis.

4. CONCLUSION

For the robotic orthosis actuator development used in upper limb rehabilitation in post-stroke individuals, it was necessary to select the motors and design the mechanism and the transmission and control system. The motors chosen

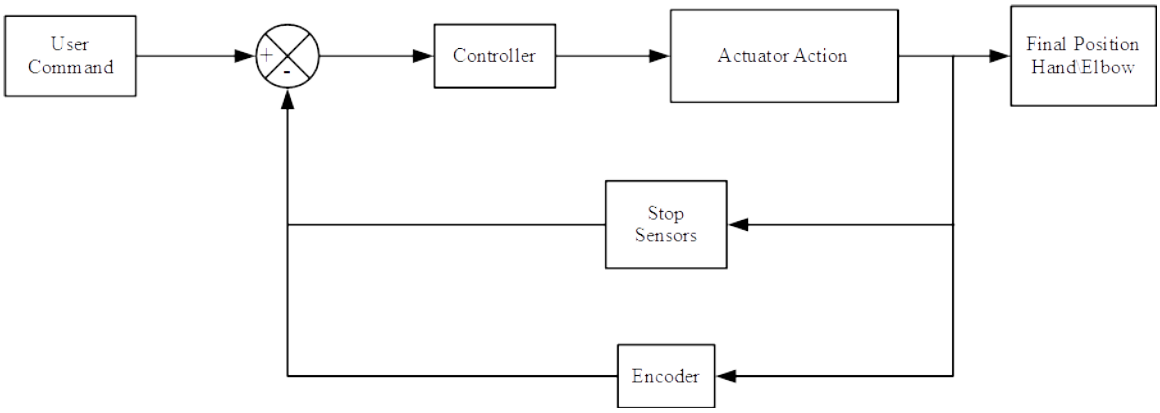

Figure 7. Mechanisms of hand module(a) and elbow module(b)

have 0.797Nm of nominal torque made by Maxon Motors™ and they have a programmable control system.

To the hand module actuator, a mechanism was developed with artificial tendons made by Kevlar® cable assembled to artificial phalanges made in PLA, it performed the extension and flexion the users hand fingers. In the elbow module actuator, a four-bar mechanism was developed with two rotation joint and a linear joint to performed the elbow extension and flexion and multiply the motor torque to 12Nm.

Coupled with the mechanisms a transmissions system was developed using power screws. For the hand module the bolt has 45mm of length, 2mm of pitch and triple thread, and in the elbow module 106mm of length, 2mm of pitch and quadruple thread.

Finally, the control system was designed. Using STM32F103 as a microcontroller, an encoder KY-040, to measure the elbow positions and the hand opening, and a snap action switch as a stop sensor to ensure user safety. With Bluetooth HC-05 module the communication between user and actuator was made and the orthosis made de desire movements. With this coupled components, the orthosis was able to perform the hand opening in 2.51 seconds and elbow flexion or extension in 4.43 seconds and reaching all project requirements.

5. ACKNOWLEDGEMENTS

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