Design of a Robotic Exoskeleton Force Multiplier for Upper Limb

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***Abstract*— This researching is based on the design and implementation of a force multiplier exoskeleton for upper limb with two degrees of freedom. This study focuses on a type of current exoskeleton that improves the motor functions of the human body by increasing the strength, speed and physical resistance of the user. The exoskeleton is based on the anthropometry of the Ecuadorian population and human biomechanics for the modeling of the exoskeleton that was based on the mathematical model of its kinematics; in addition, the design was validated with CAE software in which mechanical simulations and analysis were performed of finite element stresses to determine the safety of the system. In the same way, when using inverse kinematic analysis, the non-linear relationship between the position and orientation of the end of the exoskeleton with respect to a reference coordinate system is determined. These parameters were applied in the design of the control system which uses sensors to determine their position and orientation to execute the required movements by means of a joystick. The intention of the exoskeletal device is to be implemented in an industrial work environment, since it can lift and transport loads of up to 120 Newton.**

***Index Terms*— Exoskeleton, upper limb, strength industry**

I. Introduction

Humans present complex and specialized natural control algorithms that give them the ability to perform complicated tasks in a wide range of conditions and with fast response times. In contrast, robots can perform tasks that require large forces or torques, which depend on the nature of their structure and the power of their actuators [1]. It is evident that, by combining these two entities, the human and the robot, in a single integrated system, interesting solutions can be reached that would benefit from the advantages provided by each subsystem [2].

There are different studies on exoskeletons for example design of a mechatronic arm exoskeleton based on screws and parallel robots that consists of the division of two fundamental components [3]; on the one hand, the mechanical development, formed by a biomechanical analysis of the march and human anthropometry, and by the design of the mechanism of action. On the other hand, the control system, made up of the signal acquisition and processing system, and by the algorithms and control and monitoring software [4][5], the prostheses can also be classified in a general way into 2 groups, according to their principle of operation: passive and active [6][7][8].

There are also several methods of rehabilitation for example Kabat method. This method is used to specifically demand physiological responses from the neuromuscular system. It aims to promote or accelerate the response of the neuromuscular mechanism, through the stimulation of proprioceptors. [9] [10] [11].

There is also an exoskeleton that will be aimed at the rehabilitation of upper limb in those ones who have suffered a stroke. The mechanism activation will be got by brain signals obtained by a non-invasive brain-computer interface. In this way, when the user thinks about performing a movement with the arm (associated with an activity of daily life), the actuators will be activated, and a predetermined movement will be executed within a safe work volume as well. The movement will contribute to rehabilitation in the same way that it is done with human assistance, but adding that the patient always participates actively, which is a motivating factor that can stimulate the patient to make aware the movement and stimulate the brain plasticity for the recovery of his disability. [12][13][14].

So, there are several designs which exhibit a new proposal for the patients' rehabilitation with mobility problems at the upper limb. Where the proposed equipment allows the rehabilitation of the upper limb supported in 4 degrees of freedom (three degrees of freedom in the shoulder and one in the elbow), which is suitable for active and passive therapies [15][16][17].

II. Development

In this study, a force multiplier exoskeleton was created for the upper limb. The device was based on the anthropometry of the Ecuadorian population and its biomechanics, which has two main movements: flexion-extension in the shoulder joint and flexion-extension in the elbow. For these, a three-dimensional model was designed in CAE software. The model of the established anthropometric measurements and the attachment points of the different components for proper operation: battery motors, sensors, control cards, fastening elements, etc.

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III. ANTHROPOMETRY AND BIOMECHANICS

The needs of the Ecuadorian population were considered in this study. An exoskeleton is considered a garment, so user comfort is a design challenge. Through biomechanics it was determined that the flexion-extension movements in the two main joints, shoulder and elbow, will act on the exoskeleton. For the shoulder, the flexion-extension movement has a range of 0 to 100 °, and the flexion-extension movement for the elbow ranges from 0 to 120 ° [18], see Fig. 1. In the anthropometric part, it will be taken the 5th percentile [19] measurements of the Ecuadorian population. It is considered that the design will be for a person of an average mass of 60 kilograms. In addition, in the ergonomic part it will be considered that the exoskeleton must be lightweight, comfortable, safe and portable, allow easy mobility and transportation, as well as easy placement for the user., So in the manufacture of the exoskeleton Aluminum 7021 will be used. Then, the initial parameters with which we worked, shown in Table I, were defined.

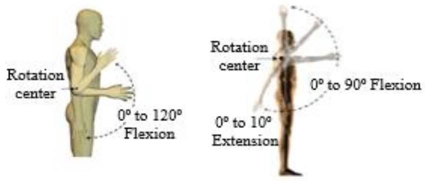

Figure 1. Range of movement - biomechanics

TABLE I. TABLE OF PARAMETERS

Arm link length	L_{eb}	264 mm
Forearm link length	L_{ea}	270 mm
Arm structure mass	M_{eb}	0,4 kg
Forearm structure mass	M_{ea}	0,18 kg
Arm body mass	M_{cb}	1,56 kg
Forearm body mass	M_{ca}	0,96 kg

IV. CINEMATIC ANALYSIS

The kinematics allows determining the final position of a chain of links, from the coordinates of each link with respect to a reference system. For the kinematic model of the upper limb exoskeleton, there are two links (upper arm and forearm) that move in two degrees of freedom, see Fig. 2, based on the two degrees of freedom, Denavit Hartenberg matrix notation (D-H), with which the mathematical equation (1) is obtained. By applying the transformation matrix T and using mathematical software, the workspace (striped areas of Fig. 3) in which the exoskeleton moves without collisions is determined.

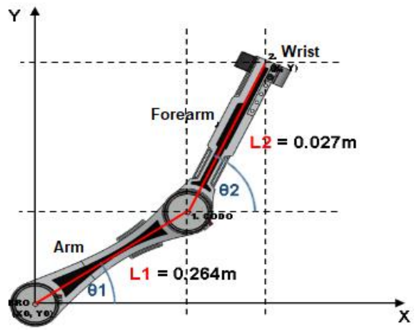

Figure 2. Parameters of the exoskeleton for D-H

$$T = \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} 0{,}264 * \cos(\theta_1) + 0{,}27 * \cos(\theta_1 + \theta_2) \\ 0{,}264 * \sin(\theta_1) + 0{,}27 * \sin(\theta_1 + \theta_2) \\ 0 \\ 1 \end{bmatrix} \quad (1)$$

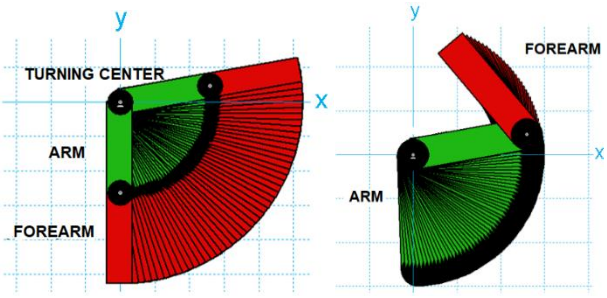

Figure 3. Work space

V. MECHANICAL DESIGN

As initial parameters in the design, the exoskeleton will be able to lift a net load of 12 kilograms, in addition to the weight of the arm, by means of its actuators, it will have 2 degrees of freedom, which will be flexion-extension movements in the elbow and flexion. extension in the shoulder.

Because the movements of the exoskeleton are limited by its links and the structure that forms them, these ranges of motion will have a lifting time of approximately 1.5 seconds for the elbow and 2.5 seconds for the shoulder. In addition, the exoskeleton will allow the movement of adduction (non-motorized) from 0 °to 60 °.

A. Load Analysis

To obtain the total value of the masses M_{tb} and M_{ta} in the links are added the body mass and the structural mass (2), both for the arm and the forearm. Considering the acceleration of gravity g of 9.81 $\mathrm{m/s^2}$, the value of the weights W_1 and W_3 (3) is obtained.

$$M_{tb} = M_{cb} + M_{eb} = 1{,}96\ Kg$$

$$M_{ta} = M_{ca} + M_{ea} = 1{,}14\ Kg \quad (2)$$

$$W_1 = g * M_{ta} = 11{,}18\ N$$

$$W_3 = g * M_{tb} = 19{,}23\ N \quad (3)$$

1) Forearm (elbow-hand link)

For a safe and reliable design, it must be verified that the links of the structure are sufficiently rigid and bear all the loads to which they are going to be subjected, as shown in Fig. 4 where F is the weight to be lifted (117.6 N), for this the most critical conditions of each section must be taken into account and thus determine the maximum torque (4) to which it will be subjected, resulting in 33.22 Nm. According to the diagram of shear forces, the diagram of bending moments is obtained in which the maximum bending moment acting on the forearm is determined.

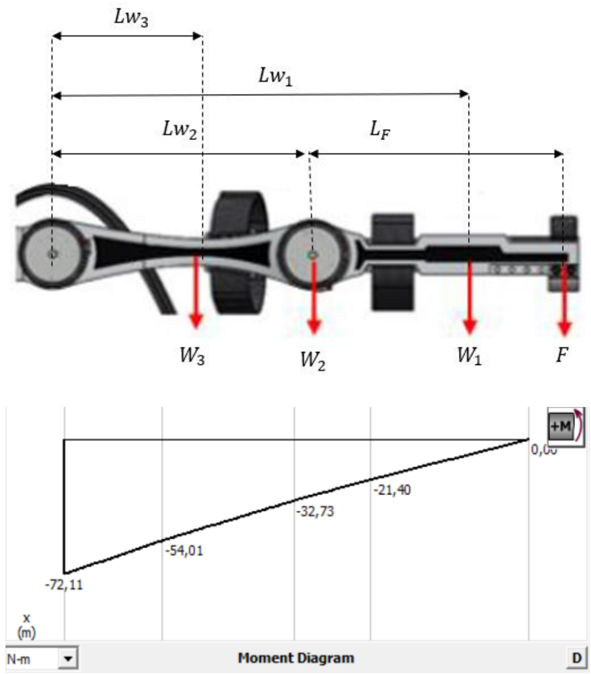

Figure 4. Moment and Force diagram of the shoulder-hand segment

$$T_{codo} = F * L_{ea} + W_1 * L_{w1} = 33{,}22\ N \quad (4)$$

2) Arm (Shoulder-hand link)

For the analysis of the shoulder-hand segment, the same procedure as the previous calculation is followed. As shown in Fig. 4, W_2 is the weight of the elbow motor (12.15 N). By **(5)** the maximum torque to which it will be subjected is calculated.

$$T_{hombro} = F * L_T + W_1 * L_{w1} + W_2 * L_{w2} + W_3 * L_{w3}$$

$$T_{hombro} = 73\ Nm \quad (5)$$

B. Selection of Gear Motors

1) Elbow

To be able to select the appropriate gearmotors, the power of the elbow motor P_{mc} (6) required is calculated. According to the torque, speed and power data that the gear motor must have at the output and considering that there will be performance losses, considering that there will be performance losses was selected as the most suitable for the application, the Maxon EC60 flat Brushless motor.

$$P_{mc} = 33{,}22\ Nm * \frac{120°}{1{,}5\ sec} * \frac{2\pi\ rad}{360°} = 46.38\ W \quad (6)$$

Brushless motor was selected motor complies with the necessary power parameter, but not with the required speed and torque, which is why it is necessary to use a reduction gearbox planetary reduction gear 156:1 to generate the torque and speed required at the output.

2) Shoulder

In the same way, the power that the shoulder motor P_{mh} must have **(7)** is calculated. The same elbow motor was selected as it also meets the specifications that are required. A 353: 1 reduction planetary gearbox is attached to the motor.

$$P_{mh} = 73\ Nm * \frac{100°}{2{,}5\ sec} * \frac{2\pi\ rad}{360\ °} = 50.96\ W \quad (7)$$

C. Stress

1) Forearm

The analysis of stresses in the forearm, shown in Fig. 5, is carried out using CAE software, obtaining a maximum value of 67.53 MPa, which is lower than the yield limit of Aluminum 7021, which is 325 MPa.

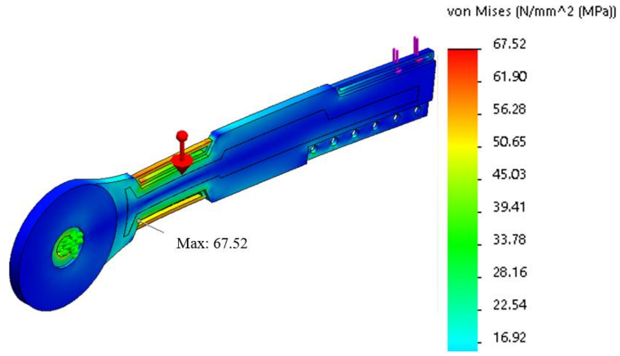

Figure 5. Von Mises stress for the forearm.

To validate the analysis, the maximum stress produced at the forearm pivot point is calculated from the maximum torque (32,735 Nm) and the maximum shear force (128,77 N). Then the rectangular section module (8) is calculated, where b, h is 0,01 m and 0,039 m respective, resulting in $2{,}535 * 10^{-6} m^3$. The normal stress (9) is the quotient between the maximum moment and the section modulus, giving the value of 12.913 MPa. With the help of (10), where (128,77 N) is the maximum force and A is the area of the cross section($0{,}78 * 10^{-3} m^2$), obtaining 0,4952 MPa. Finally, with the von Mises theory (11), an equivalent effort of 12,941 MPa is obtained [20]. With the values of the calculations made, the data obtained by software is compared and checked and the validity of this method is demonstrated.

$$S = \frac{b * h^2}{6} \quad (8)$$

$$\sigma = \frac{M}{S} \quad (9)$$

$$\tau = \frac{3V}{2A} \quad (10)$$

$$\sigma_{eq} = \frac{1}{\sqrt{2}}\left[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}{}^2 + \tau_{yz}{}^2 + \tau_{zx}{}^2)\right]^{1/2} \quad (11)$$

2) Arm

In Fig. 6 the maximum von Mises value is 114.73 MPa. When using this theory, it is obtained that this value is less than the yield stress Sy of the material, with which the link does not suffer failures.

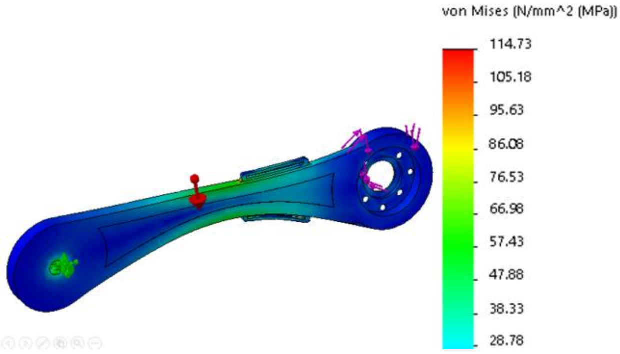

Figure 6. Von Mises strain for the arm.

3) Shoulder

Figure 7 shows 106.60 MPa as the maximum value of von Mises value that is less than Sy of Aluminum 7021, complying with the Von Mises theory, so that the link does not fail.

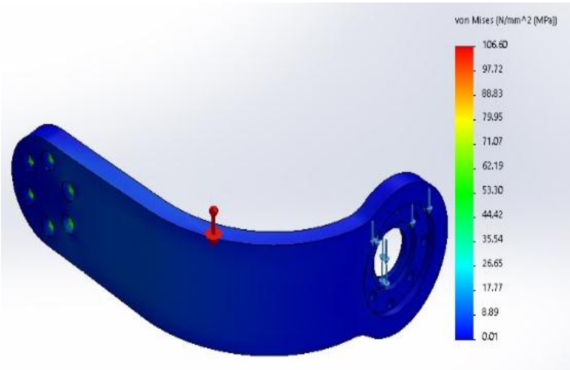

Figure 7. Von Mises strain for the shoulder.

4) Back

Figure 8 shows the value 14.75 MPa as the maximum value of von Mises value that is less than 325 MPa, complying with the von Mises theory, so that it does not fail.

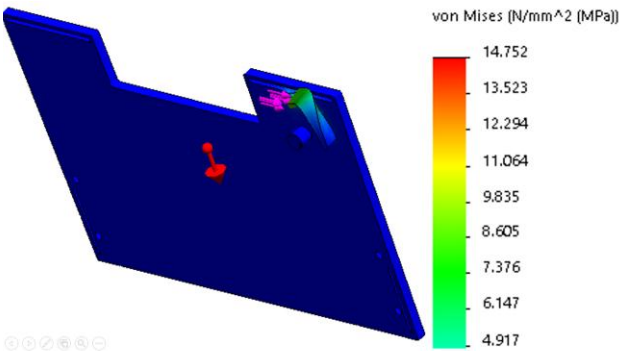

Figure 8. Von Mises stress for the back

VI. Design Control System

The control unit Fig. 9 processes the data received from the sensors and the commands generated by the user of the exoskeleton, and then transmits to the electric actuators the signals needed to carry out the load survey. The control unit consists of three phases: perception of the environment, processing and interpretation of the environment and execution of the action.

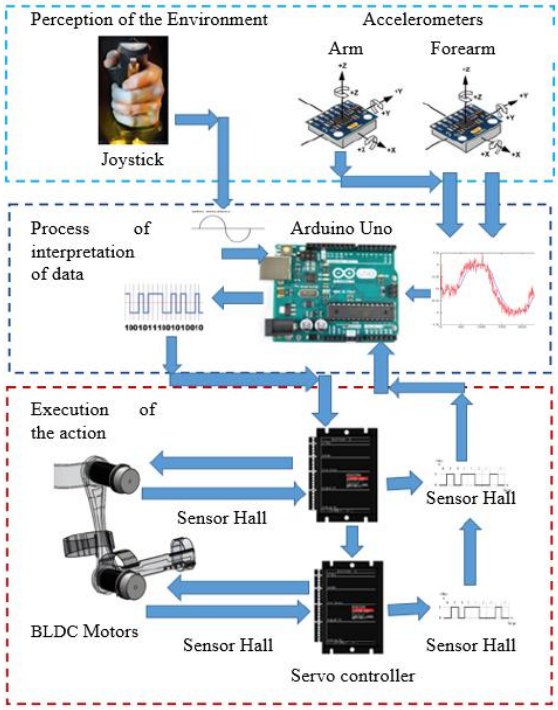

Figure 9. Block diagram of the control unit

A. *Perception Phase of the Exoskeleton Environment*

The exoskeleton has two sensors, one to know its position (accelerometer sensor) and another to know its speed (Hall sensor) at the time of its operation. In addition, it has a joystick to send the control signals. The set of signals generated by the module forms the input data to the system, which generates the orders for the movement of the exoskeleton.

B. *Processing and Interpretation of Data*

This phase consists of an Arduino Uno microprocessor and its software for the treatment of this data. The digital and analog data from the sensors are read and interpreted by the microprocessor, and then activate the corresponding control signals to execute a movement, as shown in Fig.10.

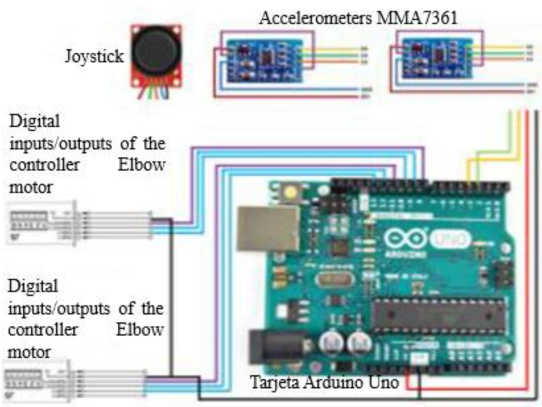

Figure 10. Connections of the phases of perception and data processing.

C. Execution of the Action: Power Stage

This phase of the control unit allows carrying out the actions of execution of the movements of the joints and executed by means of the motor devices, the ESCON 50/5 servo controllers and the Maxon EC 60 FLAT Brushless motors one in the elbow joint and one in the shoulder, as shown in Fig. 11.

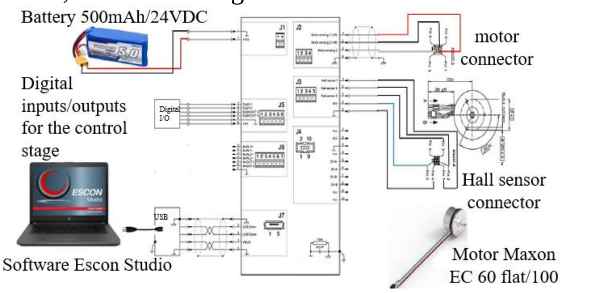

Figure 11. Power stage connections

VII. Implementation

A. Mechanical Components

By machining on a CNC machine, the different elements of the exoskeleton shown in Fig. 12 were manufactured.

B. Control System

For the acquisition of exoskeleton control signals, a joystick is implemented which generates the orders to perform the movements of the exoskeleton. The position and orientation of the exoskeleton is obtained from the accelerometers placed on the links. However, for this case, the characterization of them must be carried out in order to obtain an ideal equation (12) of their behavior, where $y_{[n]}$ represents the current filtered acceleration value, $X_{[n]}$ is the current raw sample taken from the accelerometer, and $y[n-1]$ is the sample filtered at the immediately preceding instant. The programming in Arduino allows acquiring the positioning signals of the accelerometer and filtering them to eliminate noise, then the characterization of the sensor is performed and the transformed data is obtained in degrees, immediately the state in which the links of the exoskeleton are found through the position signal and thus execute the displacement actions within the ranges established in the biomechanics, the movements can be done by the acquisition of signals from the control that has in turn digital outputs, see Fig. 13.

$$y_{[n]} = (1-\propto)X_{[n]}+\propto y[n-1] \tag{12}$$

Figure 12. Mechanical parts

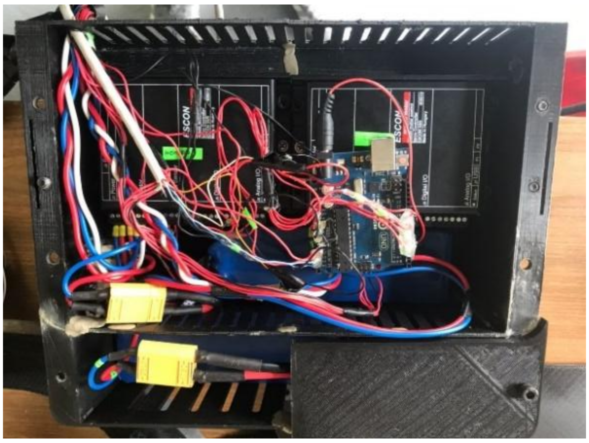

Figure 13. Accelerometer data acquisition

The Escon 50/5 power card. that allows the movements of the flat brushless EC60 motors of the elbow and the shoulder to be carried out, the acquisition of the hall sensor signal from the motors allows to determine the speed and position of the motors with which there is a feedback in the control, as shown in Fig. 13.

C. Final Exoskeleton

Fig. 14 shows the exoskeleton completely implemented the mechanical part and the control system that is located inside the backpack on the back.

Figure 14. Final assembly

VIII. Tests and Results

To prove the proper functioning of the exoskeleton and verify that it meets the design requirements, the following tests will be carried out.

A. Time of Each Cycle

To determine the time in which the exoskeleton performs each movement. It was not considered that the engines do not reach their rated speed until after a starting time, and do not stop the movement until a deceleration time, this increases the movement time by an average of 0.77 sec.

B. Range of Movement

In the movement range tests, the previously established angles are used Fig. 15, in which the flexion movement of the elbow will be from 0 to 120 ° and from the shoulder from 0 to 100 °. Elbow extension movements are from 120 °to 0 °and the shoulder from 100 °to 0 °.

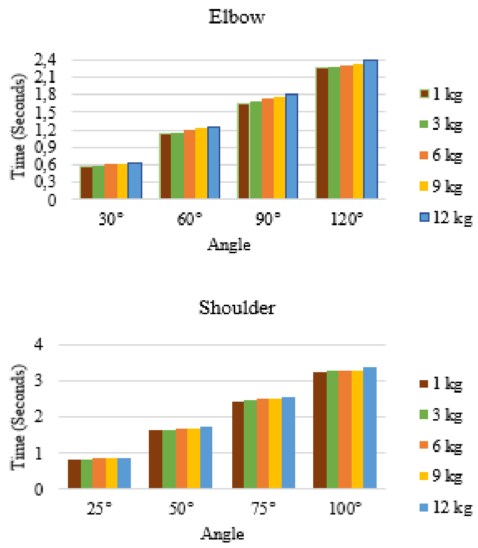

Figure 15. Time of each cycle

For the elbow joint, the average time it takes for a 30 ° angle is 0.59 seconds, for 60 ° is 1.19 s, for 90 ° is 1.72 s and for 120 ° is 2.31 s. Similarly, in shoulder joint, the average time it takes for a 25 ° angle is 0.84 seconds, for 50 ° is 1.66 s, for 75 ° is 2.49 s and for 100 ° is 3.3 s.

According to data obtained the Table II for the movement of flexion of the elbow the average displacement angle is 119.84 °, the angle that must reach is 120 ° so the error is 0.13%. For the movement of flexion of the shoulder has an average angle of 99.694 °, the angle that must reach is 100 ° with which there is an error of 0.306%. Based on the data in Table II for the extension movement, the angle at which it must arrive is 0 ° at the elbow and the shoulder, at the elbow the average angle of displacement is 0.804 ° which represents an error of 0.194%. On the shoulder, the average angle of extension is 0.414 °, which represents 0.586% error.

TABLE II. RANGE OF MOVEMENT

Angle	Flexion elbow		Angle	Flexion shoulder	
0 - 120 °	1	119,95 °	0 - 100 °	1	99,81 °
	2	119,95 °		2	98,20 °
	3	119,84 °		3	99,62 °
	4	119,84 °		4	99,81 °
	5	119,70 °		5	99,61 °
	Average	119,84 °		Average	99,69 °
	Extension elbow			Extension shoulder	
120 ° - 0 °	1	0,75 °	100 °- 0 °	1	0,61 °
	2	0,75 °		2	0,61 °
	3	0,84 °		3	0,00 °
	4	0,84 °		4	0,61 °
	5	1,00 °		5	0,2 °
	Average	0,804 °		Average	0,414 °

C. Precision Test

The precision test for the elbow is performed in segments of 30 ° making flexion-extension movements, in which data are taken to determine the average percentage of inaccuracy. For the precision test of the shoulder, it is performed in 25 ° segments performing flexion-extension movements, in which five measurements are taken to determine the percentage of inaccuracy.

In Table III, the flexion-extension movement of the elbow shows that a displacement from 0 ° to 30 ° the margin of error is ±0.662 °, from 30 ° to 60 ° the error is ±0.96 °, of 60^0 At 90 ° the error is ±0.484 and from 90 ° to 120 ° the error is ±0.84, whereby it is concluded that the margin of error of the flexion extension movement of the elbow is ± 0.7365 ° representing the 98.946% accuracy. According to Table III of the flexion-extension movement of the shoulder, for a displacement from 0 ° to 25 ° the margin of error is ±0.844 °, from 25 ° to 50 ° the error is ±0.618 °, from 50 ° to 75 ° the error is ±0.692 and from 75 ° to 100 ° the error is ±0.418°, whereby it is determined that the margin of error of the shoulder flexion extension movement is ± 0.643 representing 97.428% accuracy.

TABLE III. PRECISION TEST

Flexion-extension elbow				
Range	0 - 30 °	30 °- 60 °	60 °- 90 °	90 °- 120 °
1	30,84 °	60,95 °	89,95 °	120,84 °
2	30,84 °	60,95 °	89,95 °	120,84 °
3	30,84 °	61,00 °	90,84 °	120,84 °
4	29,95 °	60,95 °	90,84 °	120,84 °
5	30,84 °	60,95 °	90,84 °	120,84 °
Average	30,662 °	60,96 °	90,484 °	120,84 °
Flexion-shoulder extension				
Range	0 - 25 °	25 °- 50 °	50 °- 75 °	75 °- 100 °
1	25,00 °	49,24 °	75,00 °	98,21 °
2	25,00 °	49,24 °	75,61 °	99,24 °
3	24,61 °	49,61 °	75,24 °	99,24 °
4	25,00 °	50,00 °	76,30 °	99,24 °
5	24,61 °	50,00 °	75,00 °	99,76 °
Average	24,844 °	49,618 °	75,692 °	99,418 °

IX. CONCLUSIONS

An exoskeleton for upper limb was designed and implemented, capable of lifting and transporting a load of up to 120 N with minimal effort within working environments. The speed at which the elbow joint moves is 38.30 °/s and at the shoulder is 16.92 °/s. The structure was based on anthropometric data of the Ecuadorian population and its biomechanics. These aspects make the exoskeleton ergonomic and comfortable for the user.

The exoskeleton is able to move in two degrees of freedom. The first, a flexion-extension movement in the elbow joint in a range of 0 to 120 °. And the second in the shoulder joint for a flexion-extension movement from 0 to 100 °. The exoskeleton complies with all the parameters of requirements that were established for the design, with which the device is safe and reliable and will not suffer failures.

As a future project we intend to control the movement of the exoskeleton based on the intention of the movement of the user; this would be achieved by implementing sensors that can be equipped in the upper limb of the person.

CONFLICT OF INTEREST

The authors declare no conflict of interest

AUTHOR CONTRIBUTIONS

Oscar Arteaga conducted the research; Edison Arguello M. realized a cinematic analysis and analysis CAE of the exoskeleton; Héctor C. Terán built the prototype; Sonia M. Chacon wrote the mechanical content the paper; Richard Navas wrote electronic content the paper; Alexis Lamingo carried out the execution of function tests and Leopoldo Loor analyzed the data obtained from the tests carried out on the prototype. All authors had approved the final version.

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