Compact Elbow Prototype with Integrated Flexion-Extension and Prono-Supination Movements: Mechanical design

Tapia M. Pablo, Ciaccia S. Marco
Engineering in mechatronics, North Technical University
Ibarra, Ecuador
pdtapiam@utn.edu.ec
mciaccia@utn.edu.ec

***Abstract*— Transhumeral amputations can involve into psychological and social damages. People who suffer this kind of amputation should resort as soon as possible to any prosthetic device, in order to perform daily activities. This paper presents the design of a new elbow prototype with flexion-extension and prono- supination movements that overcome the deficiencies of the previous one developed by (Méndez, 2016). So, it's pursued to build a prototype that meets the requirements of people with a transhumeral amputation.**

For the development of the new prototype, design aims are initially stablished, where it's mainly determined the torque and maximum speed both the elbow joint and the wrist rotator should reach. Such design aims are based in daily life activities.

To determine the prototype structure size, anthropometric measurements of the user and the body perimeters of the human body are taken as reference so that the new prototype be the closest to the real upper limb. In terms of weight, the percentage of the prototype should be less than that of the body mass represented by the forearm with the hand.

As a result, it was obtained that the elbow joint's maximum continuous torque is 7,8 N·m, with 30 rpm as maximum speed, on the other hand, the wrist rotator has a maximum torque of 1,4 N·m, with 20 rpm as maximum speed. Which are enough to perform most activities of daily living.

***Index Terms*— Angular velocity, Convergence, Dowel pins, Efficiency, Flexion-extension, Maximum stress, Planetary gears, Prono-supination, Transhumeral amputation.**

I. INTRODUCTION

The transhumeral amputation is that which is done above the elbow. According to [1] this type of amputation mainly affects the functions of feeding, self-protection, survival and daily activities, so it is important that the amputated person makes use of a prosthesis of upper limb.

In the work done by [2], it is mentioned that a good prosthesis design must consider all the problems involved in using it. The first thing a person should do when has an amputation is social and psychological rehabilitation, which implies that you should feel good when using a prosthesis, and so carry out the activities of daily living without stress or mental load. The main problems associated with the use of an upper limb prosthesis is the excessive consumption of physical energy due to the weight of the device, limited speed, noise and poor reliability.

At the Technical University of the North, a first prototype of elbow and forearm prosthesis developed by [3] was constructed, which has some aspects that can be optimized in size and performance. The mechanism implemented to allow flexion-extension movement has dimensions that are relatively large, which increases the length measured from the elbow to the arm, so the prototype could not be implemented in some cases of transhumeral amputation. On the other hand, for the prone-supination movement an actuator is used without any reduction stage, so it is necessary to use a servomotor with dimensions that make the diameter of the structure of the forearm larger than that of the human body. In general, the perimeters of the prototype structure are large in comparison to the body perimeters of the upper limb of the human body, which is why, if the prototype is implemented in a person with amputation, it would affect their visual appearance.

Due to two main factors, import and price, Ecuadorians who have a transhumeral amputations can't easily access a prosthesis, since they are manufactured mainly in other countries and its price is high for Ecuador's economy.

To solve the mentioned problems, it is proposed to make a new compact prototype of low cost upper member, whose dimensions are in accordance with the anthropometric measurements of the user, and the perimeters of the structure should approximate those of the upper limb of the human body. The length measured from the elbow to the arm of the prototype should be the least possible to be able to implement it in the greatest number of cases of transhumeral amputation. The weight of the prototype should be less than or equal to the percentage of body mass represented by the upper limb. All this, in order that if the new prototype is implemented to an amputated person, it will provide reliability, comfort and satisfaction when performing activities of daily living.

II. THEORETICAL FOUNDATION

A. Commercial Prostheses

1) DynamicArm – Ottobock

This device is developed by Otto Bock, which has its headquarters in Germany, is the leading manufacturer of prostheses for more than 90 years, as they make it possible to maintain or establish the mobility of the lost limb.

DynamicArm is a prosthesis capable of performing natural movements triggered by muscular signals, shown in Figure 1. At the same time, it sends signals to the prosthetic hand allowing not only to rotate the wrist but also to open and close the hand [4].

Fig. 1. Dynamic Arm [4]

2) Utah Arm

This arm prosthesis is developed and manufactured by Motion Control, Inc., which is one of the most advanced companies in the prosthesis industry. This company was originally established in 1974 by Dr. Stephen C. Jacobsen, to market medical technology that was developed at the University of Utah's Engineering Center.

The Utah 3 arm was introduced in 2004, which incorporates microprocessor technology, allowing improved arm control, plus state-of-the-art electronics innovations, innovative design for functions, natural look and comfort. In 2008 the Utah 3+ arm, shown in Figure 2, was developed with the same characteristics as its predecessor but with the properties of blocking and silent movement [5].

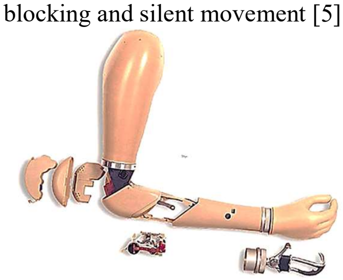

Fig. 2. Utah Arm 3+ [6]

3) Boston Digital Arm

In 2001 [7] introduced the Boston ™ digital arm, this prosthetic system incorporates microprocessor technology to improve patient performance and optimal fit.

It has a degree of freedom, for the other movements are coupled other elements as the wrist rotator Otto Bock [8].

Fig. 3. Digital Boston Arm [7]

The main technical specifications of the above mentioned marks are shown in Table I and II.

TABLE I
TECHNICAL SPECIFICATIONS OF COMMERCIAL ELBOWS

	Torque Flexion Extension (N·m)	**No load speed** (°/s)	**Load speed** (°/s)	**Range of motion** (°)	**Mass** (g)
Boston Elbow	5,9	123,5	60,7	0 - 135	960 - 1020
Otto Bock	18	-----	-----	0 - 150	1000
Utah Arm	4,3	112,5	-----	0 - 135	913

TABLE II
TECHNICAL SPECIFICATIONS OF COMMERCIAL WRIST

	Torque prono-supination (N·m)	**Speed prono-supination** (°/s)	**Mass of wrist rotator** (g)
Otto Bock	1,8	130 - 160	51 - 96
Utah Arm	1,7	300	143- 168

B. Transhumeral amputation

In a transhumeral amputation, also known as above the elbow, the section is produced through the upper bone of the arm (humerus), so that the elbow is no longer present, as seen in Figure 4 [4].

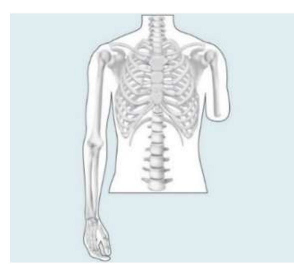

Fig. 4. Transhumeral Amputation [4]

When the arm has to be cut due to injury or illness, doctors should try to keep as much of the humerus as intact as possible. The longer the stump, the easier it is to place a prosthesis [9]..

For the placement of an upper limb prosthesis, the following requirements must be met:

- A stump long enough to create a lever, and to place an artificial elbow.
- Healthy skin to hold the prosthetic device.
- Good muscle function in the upper arm.
- Control of pain in the stump.
- Good shoulder range.
- A good rehabilitation team to help the amputee regain arm function.

It is best to use a prosthesis as soon as possible, so that the patient can feel better psychologically about having a prosthesis and can practice with it, shortly after the stump begins to heal [9].

C. Users anthropometry

To determine the correct dimensions of a prosthetic device it is necessary to determine the anthropometric measures of the user, based on the work done by [3], it is determined that they are the following:

- Weight: 70 kg
- Forearm length: 0,243 m
- Length of the palm of the hand: 0,085 m

It should be clarified that the anthropometric measures considered for the design correspond to an adult male person.

D. Percentage of body mass

Another important topic that needs to be considered in designing a prosthesis prototype for a person with transhumeral amputation is the weight of the person's upper limb. Table III shows the percentage of body mass that should have the different parts of the upper limb.

TABLE III
PERCENTAGE OF BODY MASS OF UPPER LIMB [3]

Upper limb part	Percent
Hand	0,7
Forearm with hand	2,3
Forearm without hand	1,6
Superior part of the arm	2,7
Full arm	5

III. DESIGN OBJECTIVES

The mechanisms for flexion-extension and prono-supination movements have to be designed to provide sufficient torque, velocity and range of motion, and thus enable a person with transhumeral amputation to perform most activities of daily living (ADLs).

A. Objectives for Elbow Joint

In the work done by [3] it is established that the length of the forearm should be 24,3 cm, according to the anthropometric measurements for an adult person of 70 kg. On the other hand, the length between the elbow and the arm should be the least possible, to be able to implement the prototype to the largest number of users possible.

The percentage of body mass referring to the forearm without the hand is 1,6%, so that for a person of 70 kg would result in 1,12 kg [3]. Therefore, it was determined that the weight of the forearm should not exceed 1,2 kg.

On the website [11], it is stated that most ADLs are performed between 30° and 130° for flexion-extension. Therefore, for the prototype the same functional angle will be considered.

According to [10], in some studies on upper limb movements, it has been determined that the elbow experiences a maximum angular velocity of approximately 250 degrees / sec while running the typical ADVs. In Table I, the velocity for flexion-extension of the Otto Bock myoelectric prosthesis is 123 degrees / second and for Utah Arm it is 113 degrees / second. For the design of the prototype has considered an angular velocity that is between the values; i.e., an angular velocity of 180 degrees / second would be sufficient for the user to perform most activities of daily living.

A study by [12], which contains a dynamic analysis of ten people, performing different AVDs, has determined that the maximum torque of the elbow is 5,8 N·m in flexion. Similarly, Table I shows the torque values for flexion-extension of the main commercial prostheses, where it is determined that the torque is in a range between 3,4 and 18 N·m. Therefore it has been determined that the prototype will have a maximum elbow torque of 7 N·m, enough to lift a mass of 2 kg, located in the center of the palm.

Therefore, the flex-extension mechanism must meet the following design objectives:

- Range of movement between 30 and 130 degrees
- Maximum angular speed of 180 degrees/second
- Maximum torque of 7 N·m
- Forearm length 24,3 cm
- Weight less than 1,2 kg
- The shortest possible length between elbow and arm

B. Objectives for Wrist Joint

To determine the degrees of freedom (DOFs) of the prototype, the weight, size, and complexity of prosthetic devices should be considered to increase with each DOF that is implemented in its design. This also affects device control, as more DOFs are added to the design, more control signals are needed than the person with amputation should provide. Range studies of movements indicate that of the DOFs used in activities of daily living, the highest range of motion is associated with the degree of freedom of prone-supination (PS). This observation is corroborated by surveys of people with upper limb amputations who have reported that they consider that the rotation of the forearm (prono-supination) is somewhat more desirable than the other degrees of freedom of a healthy wrist [10]. In consideration of the above, it was decided that the prototype should have a single DOF (PS) for the wrist.

Regarding size, a prosthetic wrist must match the anthropometric measurements of people. Due to the fact that in Ecuador a study of the wrist measures of the Ecuadorian population has not been carried out, in order to determine the size, it is taken into consideration the established in the work of [10], in which it is determined that the wrist should be as short as possible in length to be able to be implemented in the largest number of users, and that the average length of circumference for males is 17.5 cm, which would correspond to a wrist of circular section with a diameter of 5.6 cm. Based on this, it has been decided that the diameter of the wrist of the prototype will be 5 cm.

Regarding the weight of the mechanism, this should be as small as possible, as this would provide sufficient comfort for the user of the device. According to Table II it is determined that the weight of the mechanism should be less than 200 grams.

Pronation and supination movements have an active range of 75° and 85° respectively. Most ADLs are performed between a 50° pronation angle and 50° supination angle [11]. As mentioned, it is determined that the range of motion of prono-supination of the prototype should be 0 to 180 degrees.

A speed of 175 degrees/second for the rotation of the wrist, is sufficient to perform different tasks. The rotation speed of the Otto bock commercial device is between 130 and 160 degrees/second, and the Utah Arm device is 300 degrees/second [10]. So a speed of 150 degrees/second would be sufficient for the PS movement of the prototype.

The wrist pair should be sufficient to perform the ADLs. For example, turning a 500-ml bottle of water, if retained by the end, would require 280 mN·m of torque. On the other hand, rotating a typical carpenter's hammer, ie about 500 g, when kept at the base of the handle, would require approximately 1,4 N·m [10]. Likewise, reference is made to Table II, where Otto Bock's wrist cuff is said to be 1,8 N·m and Utah Arm is 1,7 N·m. Then, considering a maximum torque of 1,5 N·m for the PS mechanism, would be sufficient.

Therefore, the mechanism for performing the prone-supination movement must be designed to meet the following objectives:

- Range of 180 degree movement
- Angular speed of 150 degrees / second
- Torque of 1.5 N·m
- Diameter less than 5 cm
- Weight less than 200 grams
- The shortest possible length

IV. ELBOW JOINT DESIGN

A. Torque generated at the elbow

To determine the torque generated in the elbow by a mass located in the palm of 2 kg, a free-body diagram is shown, shown in Figure 5, in which the external forces acting on the prototype. Pb is the maximum weight of the forearm of 1,12 kg, expressed in Newtons and Pd is the maximum weight to be raised of 2 kg, expressed in Newtons, here also included the weight of the hand.

To determine the reactions generated at point A, as shown in Figure 5, which is where the elbow actuator, responsible for generating the flexion and extension movements of the prototype, is located by equation 1 [13] and the equilibrium equations of a rigid body in two dimensions, equation 2 [13].

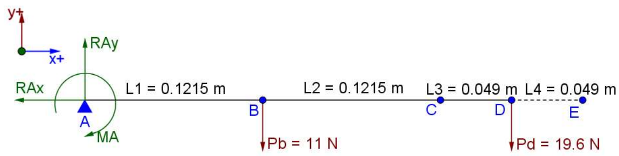

Fig. 5. Free Body Diagram of the elbow joint

$$M = F \cdot d \tag{1}$$

Where:

F = applied force.

d = arm of moment or distance perpendicular to the force.

$$\Sigma M_A = 0$$
$$\Sigma Fx_A = 0$$
$$\Sigma Fy_A = 0 \tag{2}$$

After making the respective calculations, it is determined that the torque generated in the elbow, by the force exerted by the mass of 2 kg and the weight of the forearm, is 7.06 N·m.

B. Selection of actuator and planetary gear reducer

The dimensions of the actuator and reducer should be small enough, so that the elbow joint is the right size for the prototype.

1) Actuator angular speed

To determine the angular velocity that the actuator must have, it is necessary to know the speeds of the components that make up the planetary gear train. The design takes into account one of the most common configurations of planetary gear reducers, which is shown in Figure 6, where the solar gear is the input, the planetary is the output, and the annular or crown is held fixed.

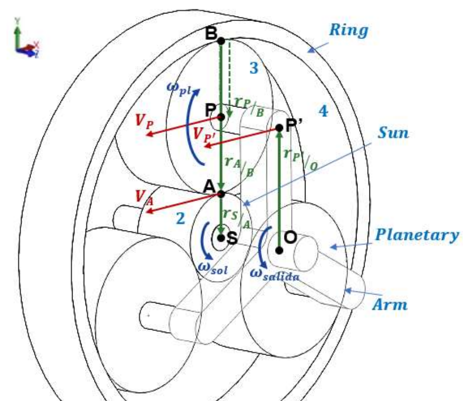

Fig. 6. Schematic of planetary gears for calculation

Because size is an important factor in the design of the new prototype, as a first step it is established that the annular gear must have a maximum diameter of 45 mm, since this is the largest dimension and is subject to the prototype structure to make possible the movement of the solar and planetary gears.

The radius of the planetary and sun gear are chosen in relation to the size of the ring, so that the highest transmission ratio is reached, but these should not be too small, since their manufacture would be complicated, the values chosen for each one of the gears are:

- $D_{RING} = 0{,}045\ m$
- $r_{SUN} = 0{,}005\ m$
- $r_{PLANETARY} = 0{,}00875\ m$

The angular output or load velocity (n_L) is:

$$\omega_{output} = 180\ \frac{degrees}{s} = 3{,}14\frac{rad}{s} = 30\ rpm$$

For the velocity calculation, we use equation 3, which is the velocity equation of the relative motion analysis, obtained from [14]. The direction of the angular velocities and the direction of the velocity and position vectors are shown in Figure 6.

$$V_B = V_A + \left(\omega\ \times\ r_{B/A}\right) \quad (3)$$

The calculations of the speeds for each of the components of a planetary gear train are:

- Midpoint speed P of planetary:

$$V_{P'} = V_O + \left(\omega_{output}\ \times\ r_{P'/O}\right) = \ -0{,}043\ i\ \ \frac{m}{s}$$

- Angular velocity of planetary gear:

$$\omega_{pl} = \frac{V_{P'}}{r_{P/B}} = -4{,}93\ k\ \ \frac{rad}{s}$$

- Velocity of point A between the planetary and sun:

$$V_A =\ V_B + \left(\omega_{pl}\ \times\ r_{A/B}\right) = -0{,}086\ i\ \ \frac{m}{s}$$

- Angular speed of the solar gear:

$$\omega_2 = \frac{V_A}{r_{S/A}} = 17{,}27\ \frac{rad}{s}$$

$$\boldsymbol{\omega_2 = 164{,}92\ rpm}$$

According to the calculations obtained, it is necessary that the actuator for the flexion-extension mechanism has an angular velocity of 165 rpm.

The ratio that the reducer must have to provide the required speed is determined by equation 4 of the formula book of [15].

$$n_{in} = n_L * i_G \quad (4)$$

$$i_G = \frac{165\ rpm}{30\ rpm} = 5{,}5$$

2) Actuator Torque

To determine the torque of the actuator, it is necessary to consider the efficiency or mechanical performance of the gear unit. This is what determines how efficient a gearbox is to deliver its output the same power as its input. To calculate the torque of the actuator, use equation 5 of the formula book of [15], it is theoretically assumed that the actuator ideally has an efficiency of 100% or equal to 1.

$$M_{in} = \frac{M_L}{i_G \cdot \eta} \quad (5)$$

Then:

$$M_{in} = \frac{7{,}06\ N{\cdot}m}{5{,}5 \cdot 1} = 1{,}283\ N{\cdot}m$$

Ideally, the actuator torque should be 1.28 N·m.

Because the dimensions of the gears are small, to manufacture the gear reducer of planetary gears, a high precision of manufacture is necessary and consequently, to obtain a high efficiency, that is why it is decided to use commercial reducer of planetary gears.

3) Actuator selection

For selection of the actuator, one of the main requirements is that the length should be small, because the space that it must occupy is limited. Maxon Motor has a range of motors called EC-Flat, which are suitable to be implemented in applications of reduced space.

The maximum diameter the actuator must have is 45 mm, which was determined in order to make the elbow joint prototype compact.

It is considered that the maximum power supply voltage of the motor must be 24 V DC, since another requirement to be considered is the supply voltage, because a prototype of a prosthesis is a portable device and needs the use of batteries to its functioning.

The actuator in the Maxon Motor EC-Flat range, which best complies with the requirements mentioned above, is the EC45Flat brushless motor, whose main mechanical and electrical characteristics are shown in Table IV.

TABLE IV
MOTOR SPECIFICATIONS EC45FLAT [16]

Parameter	Value
Nominal Tension	24 V DC
Nominal Speed	4730 rpm
nominal torque (continuous)	69,6 mN·m
Length	21,3 mm
Shaft Length	20,6 mm

4) Reducer selection

To obtain a speed of 30 rpm and a torque of 7 N·m, a single-stage planetary gear reducer with a reduction ratio of 5,5:1 was calculated, so that an input actuator 165 rpm and 1.28 N·m. Because the selected actuator has lower specifications than the desired actuator, it is necessary to implement more than one stage to the reducer to achieve a greater reduction ratio.

To calculate the reduction ratio of 2 or more stages, we use equation 6, which is deduced from the work done by [17].

$$\mathrm{R_{Total}} = \mathrm{R_{Stage-1}} \cdot \mathrm{R_{Stage-2}} \cdot \mathrm{R_{Stage}}\ \ \dots \cdot \mathrm{R_{Stage}} \quad (6)$$

With the actuator speed selected, the reduction ratio of the reducer can be determined.

$$i_{G2} = \frac{n_{in\ actuator\ selected}}{n_L} = \frac{4730\ rpm}{30\ rpm} = 157{,}6$$

It would therefore be necessary for the calculated reducer to have three stages, the first two with the calculated ratio 5,5: 1, and a third stage with a ratio of 5,22: 1.

$$R_{Total} = (i_G)^2 * 5.22 = 158$$

For the selection of the planetary gear reducer, the length is considered the most important factor, so that together with the actuator, occupy as little space as possible, to make the elbow joint not exceed the anthropometric measures of the user.

The maximum continuous torque of the gear unit must be equal to or greater than the calculated torque, which is 7,06 N·m. It is also important to consider the weight of the reducer, since it should not exceed the percentage of body mass corresponding to the forearm.

To meet the above requirements, the Maxon Motor GP42C planetary gear reducer is selected, the most relevant technical specifications being shown in Table V.

TABLE V
GP42C REDUCER SPECIFICATIONS

Parameter	Value
Reduction Ratio	156:1
Maximum continuous torque	15 N·m
Maximum input speed	8000 rpm
Efficiency	72%
Gear unit length	70 mm
External diameter	42 mm
Weight	460 g

Then, with the selected planetary gear unit and gear unit, the output speed and torque are calculated.

The output angular velocity is determined by equation 4, in this case the input velocity is that of the actuator, and the charge velocity is the output velocity of the reducer, then:que:

$$\omega_{output} = \frac{4730\ rpm}{156} = \mathbf{30,32\ rpm}$$

The output torque is determined by equation 5:

$$M_{output} = M_{actuator} \cdot (i_{G\ Reducer} \cdot \eta)$$

$$M_{Salida} = \mathbf{7.8\ N{\cdot}m}$$

With the calculations of torque and output speed, it is concluded that with the gearbox and actuator selected, the design objectives are met.

V. WRIST JOINT DESIGN

As for the design of the elbow joint, the selected reduction mechanism is a planetary gear train; the same configuration is chosen, where the input is the solar gear, the output is the planetary gear, and the annular gear is held fixed to the forearm structure (See Figure 6).

A. Actuator angular speed

In the design objectives it is determined that the diameter of the wrist should be less than 50 mm, the angular velocity should be less than or equal to 150 °/ s = 25 rpm and the torque less or equal to 1,5 N·m. Since 50 mm is the maximum diameter the wrist should have, the mechanism must have a smaller diameter, to be able to fix it to the structure, reason why it was considered convenient that the diameter of the annular gear is of 35 mm. And just as for the design of the elbow joint, the diameters of the planetary and sun gear are set in relation to the annular. In the same way as for the wrist joint, the direction of the angular velocities and the direction of the velocity and position vectors are shown in Figure 6.

The radius of the gears are:

- $r_4 = 0{,}0175\ m \quad (ring)$
- $r_2 = 0{,}0035\ m \quad (sun)$
- $r_3 = 0{,}007\ m \quad (planetary)$
- $\omega_{output} = 150\ {}^{\circ}/_{s} = 2{,}617\ {}^{rad}/_{s} = 25\ rpm$

The calculations of the speeds for each of the components of a planetary gear train are:

- Midpoint speed P of planetary:

$$V_{P'} = V_O + \left(\omega_{salida} \times r_{P'/_O}\right) = -0{,}027\ i\ \frac{m}{s}$$

- Angular velocity of planetary gear:

$$\omega_{pl} = \frac{V_{P'}}{r_{P/_B}} = -3{,}92\ k\ \frac{rad}{s}$$

- Velocity of point A between the planetary and sun:

$$V_A = V_B + \left(\omega_{pl} \times r_{A/_B}\right) = -0{,}055\ i\ \frac{m}{s}$$

- Angular speed of the solar gear:

$$\omega_2 = \frac{V_A}{r_{S/_A}} = 15{,}702\ \frac{rad}{s}$$

$$\boldsymbol{\omega_2 = 149,94\ rpm}$$

According to the calculations obtained, the actuator for the prono-supination mechanism is required to have an angular velocity of 150 rpm.

The reduction ratio of the reducer is determined by equation 4, here we have that the input is that of the solar gear, the loading speed is the output speed, then we have to:

$$i_G = \frac{\omega_{Sun}}{\omega_{output}}$$

$$i_G = \frac{150\ rpm}{25\ rpm} = 6$$

Entonces, la relación de reducción es de 6:1.

B. Actuator Torque

To calculate the torque of the actuator, we use equation 5, ideally assuming that the efficiency is 100% or equal to 1.

$$M_{in} = \frac{1{,}5}{5{,}92 \cdot 1} = 0{,}253\ N{\cdot}m = 253\ mN{\cdot}m$$

It is necessary that the torque of the reducer must be of 253 mN·m.

C. Actuator selection

Since there are actuators that approximate the values of speed and torque calculated, and of small dimensions, proceed to make the selection of the most suitable actuator.

The type actuator that was selected is a micro servomotor, because this one has the characteristics of high torque, low speeds, mainly small dimensions and low cost. For the selection, a list of the micro-servo motors closest to the calculation values was made (see Table VI).

TABLE VI
TORQUE AND MICRO SERVO SPEED

MICRO SERVO	TORQUE (6 Voltios)	SPEED (6 Voltios)
Tower Pro MG90S	0,2157 N·m	125 rpm
HS-81 Standard Micro Servo	0,2941 N·m	111,11 rpm
HSG-5084MG Micro Heli Tail Rotor Servo	0,1863 N·m	200 rpm
KST DS115MG Servo – 3 kg	0,2941 N·m	166,67 rpm

El The micro-servomotor that was chosen is the HS-81 Standard Micro Servo, since it is one of the ones that approaches the results of the calculations, it is low cost, low noise and mainly exists in the Ecuador.

D. Reducer selection

Because the proposed planetary gear reducer gears are small, their manufacture would be complicated, and high accuracy would be required to function optimally. That is why, it is decided to acquire a gear reducer already manufactured, to resemble the dimensions of the proposed reducer.

The dimensions of the planetary gear reducer manufactured are as follows:

$D_{sun\ gear} = 6{,}75\ mm$

$D_{planetary\ gear} = 12{,}5\ mm$

$D_{ring\ gear} = 31{,}75\ mm$

With the data provided by the gearbox, and the data of the selected actuator, a new calculation is made in order to determine the angular velocity and output torque.

The angular velocity of the output of the wrist that was calculated is 19.5 rpm.

Then the reduction ratio of the manufactured reducer is determined, with equation 4:

$$i_G = \frac{111{,}11\ rpm}{19{,}48\ rpm} = 5{,}7$$

Then, the reduction ratio is 5,7:1.

To determine the output torque, equation 5 is used. Because the efficiency of the planetary gear train manufactured is unknown, reference is made to Figure 1.11, where it is determined that for a single-stage gear unit efficiency is between 80 and 100%, in this case 85%.

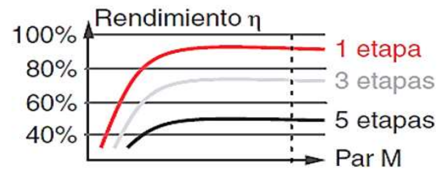

Fig. 7. Reducer efficiency [15]

Then:

$$M_L = 0{,}2941 \cdot 5{,}7 \cdot 0{,}85 = 1{,}67\ \text{N·m}$$

The torque of the wrist output is **1,67 N·m.**

With the calculations made, it is necessary that, the selected actuator and the manufactured reducer purchased provide the output at a speed of 19.5 rpm and a torque of 1,67 N·m, which approximates the maximum values established in the design objectives.

VI. DESIGN OF THE UNION BETWEEN FOREARM AND ELBOW

For the union between the forearm and elbow structure, use of dowel pins, since in this part of the prototype would be subjected to direct shear.

To define the size of the dowel pins, it is considered the space that is available in the prototype, and thus predetermines a number of pins.

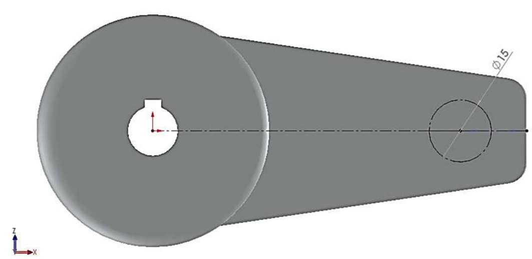

Fig. 8. Available space in the joint between the elbow and the forearm

As shown in figure 8, the space with which it is counted is 15 mm in diameter, whereby a number of three pins with a diameter of 4 mm is considered to be most suitable, in order that the hole perforations occupy a smaller area. This does not affect the strength of the joint material, because the material selected for the manufacture of the forearm is a thermoplastic. The material selected for the dowel pins is SAE 1020 low carbon steel.

$$D_{pin} = 4\ mm$$

$$D_{Total} = 15\ mm$$

In order to determine the shear loads of the dowel pins, a force diagram is shown, which is shown in Figure 9. The eccentric loads Pb and Pd shown in Figure 5 generate a force P, acting through the pin centroid of the spikes, and a moment Mc with respect to the centroid.

Therefore, two reactions are generated on each FP and FM pin. The latter is due to the moment Mc acting perpendicular to the radius existing between the centroid and each pin [18].

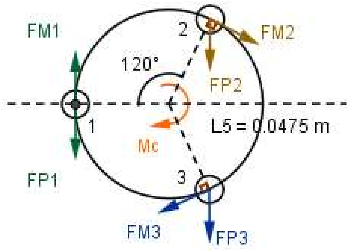

Fig. 9. Forces in the dowel pins

The calculation of the moment of force with respect to the centroid is determined using equation 1 and the equilibrium equations of a rigid body.

$$\circlearrowright^{+} \Sigma M_F = 0$$

$$Mc + (-Pb * L5) + \left(-Pd * (L5 + L2 + L3)\right) = 0$$

$$Mc = 4{,}795\ N{\cdot}m$$

To determine the magnitude of the FM force on each pin, we use equation 7. Then the force produced by the moment Mc is $F_{M1,2,3} = 213{,}11\ N$.

$$F_2 = \frac{M}{n \cdot r} \tag{7}$$

Where:
n: number of dowel pins.
r: radius comprised between the centroid and the center of the diameter of the dowel pins.

La cantidad de fuerza directa FP, experimentada en cada pasador, se determina usando la ecuación 8:

$$|F_1| = \frac{P}{n} \tag{8}$$

$$F_P = -10{,}2\ N$$

Based on the force diagram of figure 10, it can be seen that the pins 2 and 3 are the ones that are most heavily loaded, the forces resulting in these pins have different directions, but are of equal magnitude, so that the calculations are with respect to the pin 2.

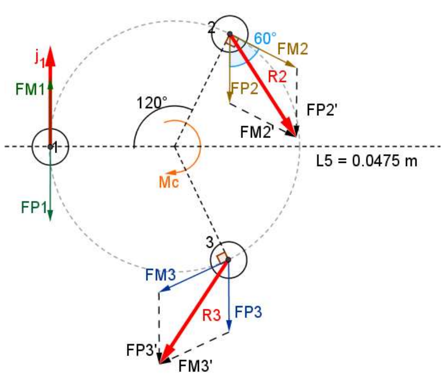

Fig. 10. Diagram of forces resulting from dowel pins

To find the resulting force R2, the sum of the vectors FP2 and FM2 is made by the parallelogram method, as seen in figure 10.

Therefore:

$$R2 = 207{,}697\ N$$

With equation 9 [18], direct shear stress is calculated on pin 2.

$$\tau_s = \frac{F}{A_s} \tag{9}$$

Where:
τ_s: Shear strength
F: Applied force
A_s: Shear area

Entonces:

$$\tau = \frac{R2 * 4}{\pi * (D_{Pasador})^2} = 16.528\ \frac{N}{mm^2}$$

The shear strength of the material is determined by equation 9 [18].

$$S_{ys} = S_y * 0.577 \tag{10}$$

Donde:
S_{ys}: Minimum shear yield strength
S_y: Yield stress (low carbon steel SAE 1020)

Then:

$$S_{ys} = 152.674\ Mpa$$

With the values calculated above, the safety factor against static shear failure.

$$N_s = \frac{S_{ys}}{\tau} = 9.237$$

In conclusion, the safety factor in the pins that are subjected to a greater direct shear force is 9, which indicates that it is correct to use 3 pins of 4mm, located in a circumference of 15 mm of diameter, made of steel of low carbon SAE 1020.

VII. PROTOTYPE DESIGN – CAD

After designing the actuators and the connection between the forearm and the elbow have been made, the next step is to design the prototype structure by means of a computer with the dimensions mentioned in section III and so as to provide safety and comfort to the patient. Figure 11 shows an isometric view of the complete design of the prototype in which the different parts for which it is composed can be observed. The connecting pieces to transmit the movement of the elbow to the forearm are located on the lateral sides of the prototype, this is where the tenon pins designed in section VI are located. At the top of the elbow is located the screw that serves to couple the prototype with the patient's socket.

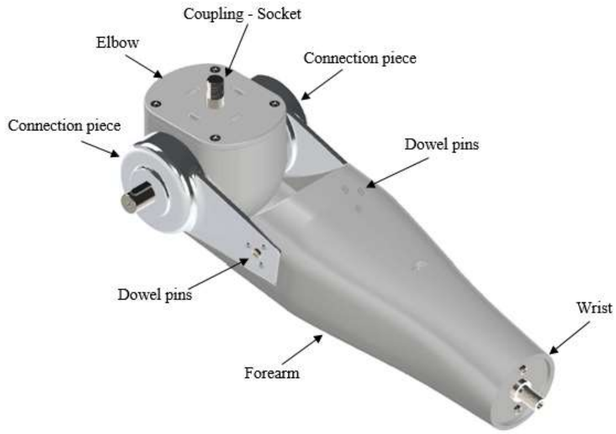

Fig. 11. Isometric View Prototype

Figure 12 shows the location of the elbow joint actuator in charge of flexion-extension, the movement is transmitted by the key located on the actuator shaft, which is connected to one of the connecting pieces.

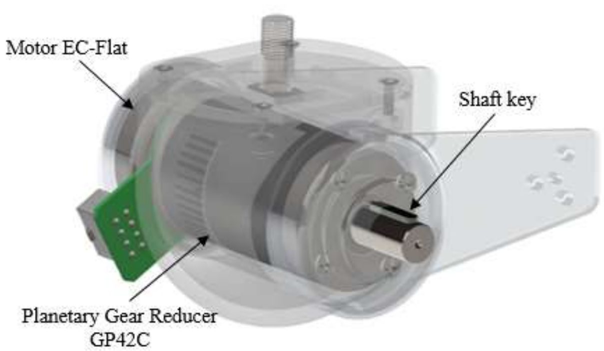

Fig. 12. Elbow joint actuator

The actuator in charge of the prono-supination movement is located at one end of the forearm as shown in Figure 13, which through an axis transmits the movement from the wrist rotator to the prosthetic hand.

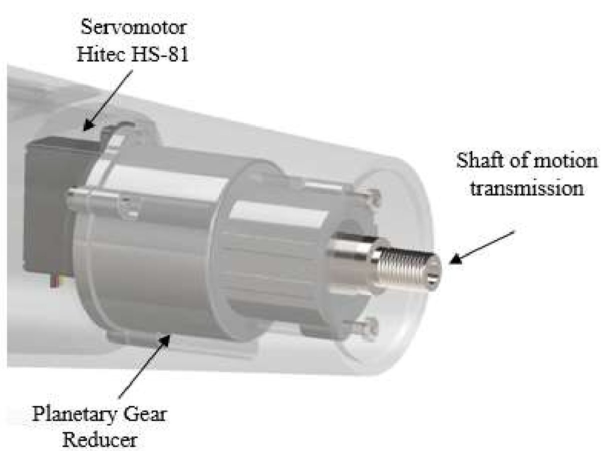

Fig. 13. Wrist joint actuator

Because actuators require direct current batteries and integrated circuits for operation, forearm was designed with two covers, top and back (see Figure 14) to place the circuitry within it, have easy access to maintenance and manipulation of circuits and batteries.

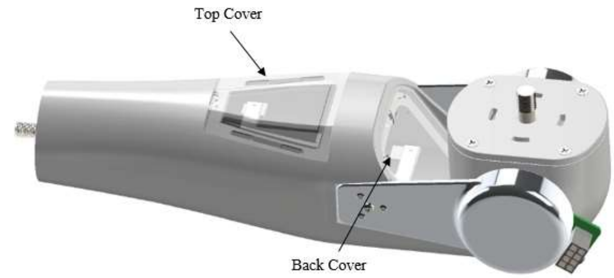

Fig. 14. Covers for electronic components

VIII. FINITE ELEMENT ANALYSIS

For the finite element analysis, the first step is to assign the material for each of the pieces that make up the structure of the prototype prosthesis.

A. Assignment of materials

It was decided that the method of construction would be by 3D printing, since the prototype structure has geometries that are complex to construct using another method. So the material selected for the construction of the structure is the thermoplastic ASB-M30.

The prototype also has pieces that need to be made of a more resistant material, depending on the function they play. The joints between the forearm and the elbow are those that need a more resistant material, because in their geometry they present critical points of analysis, which are: the pins of the pins of the pin and the slot for the key of the reducer. For the above reasons, it is decided that the joining pieces, be constructed of 7075-T6 aluminum.

To summarize, in Table VII the pieces in the prototype and its respective materials.

TABLE VII
ASSIGNED MATERIALS

Part Name	Assigned Material
Elbow Structure	ABS M30
Forearm Structure	ABS M30
Connecting pieces	7075-T6 Aluminum
Towel pins	Steel SAE 1020
Screws	Steel SAE 1020
Shaft key	Annealed Steel

B. Convergence analysis

In order to obtain the most reliable results, different simulations are performed, applying different mesh sizes, thus varying the number of elements to obtain different maximum stress data at each iteration and then performing the convergence analysis. According to Table VIII, it can be concluded that for a number of elements between 143.256 and 149.544, the most reliable results are obtained, since the variation of the stress has a percentage error of less than 5%.

TABLA VIII
MAXIMUM STRESS DATA

NUMBER OF ELEMENTS	MAXIMUM STRESS MPa	PERCENTAGE ERROR %
129555	116	
131824	124	7.22
133759	138	11.24
136098	141	1.69
140338	154	9.22
143256	147	4.16
149544	149	1.12
154684	144	3.12
159222	147	1.77
165538	145	1.48

C. *Maximum Stress*

The maximum stress generated is 148.924 MPa, this occurs in the joint between the forearm and the elbow, as shown in Figure 15. As expected, the maximum effort is generated at one of the critical points, specifically in the keyway, see figure 16.

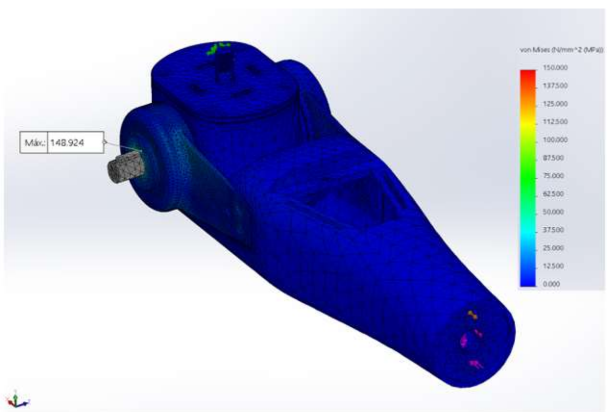

Fig. 15. Maximum Stress – Overview

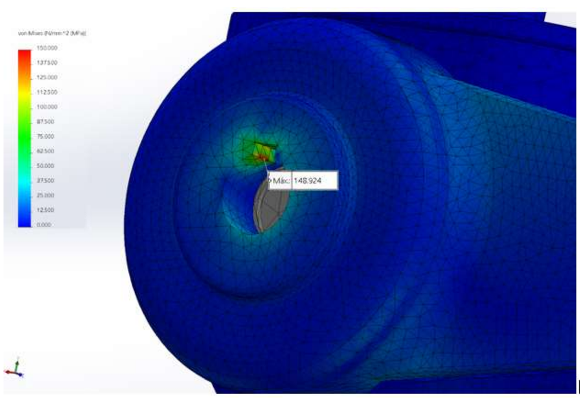

Fig. 16. Maximum Stress - Keyway

D. *Displacement*

The maximum displacement is 2,197 mm, which means that in the prototype structure there are small displacements, guaranteeing a good functioning of the prototype, in figure 17 shows the results of displacement of the analysis.

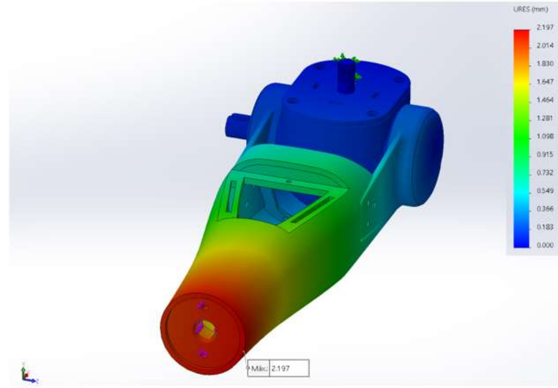

Fig. 17. Maximum displacement

E. *Safety factor*

In the results of the analysis, there was a minimum safety factor of 3.391, see figure 18, which assures that the maximum stress does not exceed the elastic limit of the material, then it can be said that the prototype is able to withstand the applied loads without that a structural failure occurs.

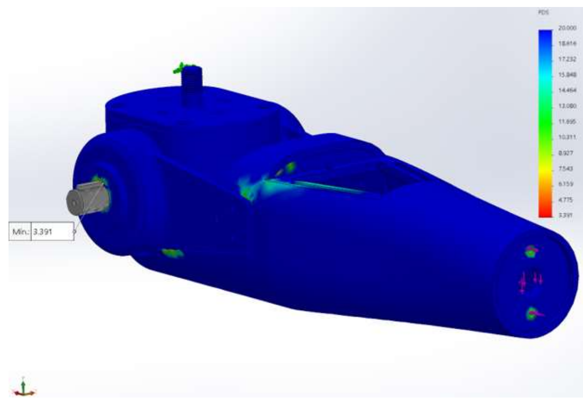

Fig. 18. Minimum safety factor

In Figure 19, it is shown that the minimum safety factor is located in the keyway, where the maximum stress is also located..

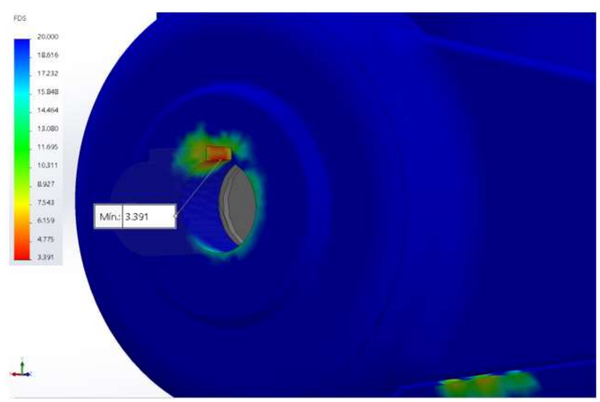

Fig. 19. Safety factor in keyway

IX. VERIFICATION AND VALIDATION

After doing the analysis of finite elements is made, the parts that compose the prototype are built, and then assembled together with the actuators purchased. Figure 20 shows the different parts of the prototype, and Figure 21 shows the prototype already assembled and mounted on a wooden base, which serves as a support for the performance tests and at the same time simulates the socket of the person with amputation.

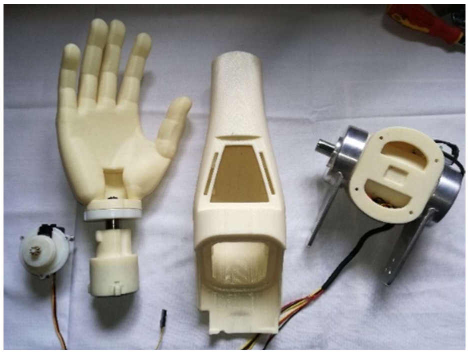

Fig. 20. Prototype parts

Fig. 21. Prototype assembled

First, the test was run without load, in order to verify that the prototype can move within the functional angles of the upper limb. To operate the prototype actuators, a basic program was used in Arduino, together with the power circuits corresponding to each actuator.

No-load prono-supination movement:

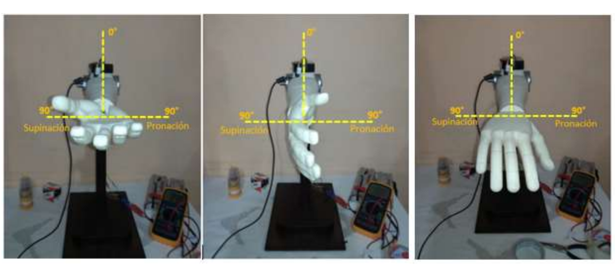

Fig. 22. Supination - 90°, normal position – 0°, pronation – 90°

Performance tests were carried out with a weight of 450 grams, located in the palm of the hand, in order to verify that the wrist rotator has the torque and speed, for which it was designed..

Prono-supination movement with load::

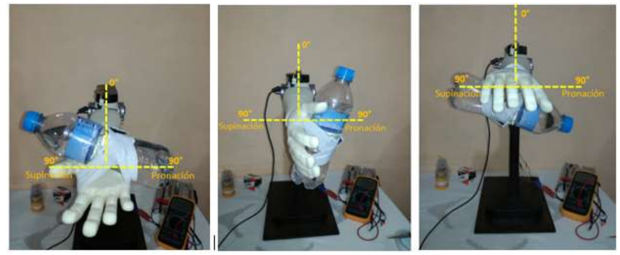

Fig. 23. Supination - 90°, normal position – 0°, pronation – 90°

To test the performance of the elbow joint, as for the wrist rotator, the tests were first performed without weight, to verify that the prototype can move 130 degrees in flexion and 30 degrees in extension.

No-load flexion-extension movement:

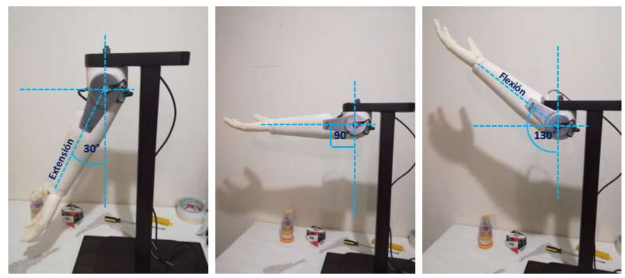

Fig. 24. Total extension – 30°, Position – 90°, Total Flexion – 130°

Because a planetary gear train has the characteristic of low reversibility, but does not self-block completely, it was determined that the maximum continuous torque for the flexion-extension movement is 7.8 N·m, that is, that the prototype can lift a maximum mass of 2 kg, but is not able to hold it in a fixed position if the actuator is energized. During the performance tests, it was determined that the maximum mass that the prototype can hold in a fixed position is 450 grams, ie the maximum torque of retention of the elbow joint is 2.6 N·m..

Flexion-extension movement with maximum load of 450 grams:

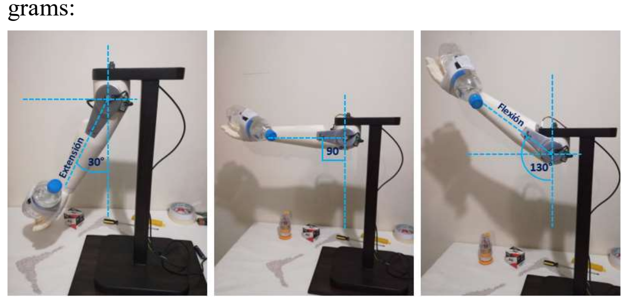

Fig. 25. Full extension with load –30°, Position with load –90°, Total flexion with load –130°

As for the prototype structure, during the operational tests, it was verified that it can support the weight for which it was designed, and like in the analysis of finite elements, the structure has small displacements with the maximum load of 2 kg, this way you can guarantee reliability and comfort, if the prototype would be implemented to a person with amputation.

X. CONCLUSIONS

The prototype of built prosthesis overcomes the deficiencies of the previous prototype, in dimensions and operation. In terms of size, the prototype meets the anthropometric measures for a person of average height. The perimeters of the prototype resemble the body perimeters of a 70 kg person. Similarly, the total weight of the prototype is less than the percentage of body mass represented by the weight of the forearm and hand. As for operation, the actuators for prono-supination and flexion-extension bridle a movement with a continuous speed, and of low noise, that gives comfort and reliability to the user.

For the flexion-extension and prono-supination movements, it was used in a planetary gear train, which has the main characteristic of reaching high transmission ratios in small spaces, allowing the prototype to have similar perimeters to the human body .

The mechanical design of the prototype can be implemented in the largest number of cases of transhumeral amputation. The length measured from the bottom of the elbow to the arm of the prototype is 7 cm, so it can be adapted for medium or long short amputations.

The elbow joint of the prototype has a maximum continuous torque of 7,8 N·m, which is sufficient to lift a mass of 2 kg, located in the palm of the hand. The maximum holding torque is 2,6 N·m, sufficient to maintain a mass of 450 grams, without actuator actuation. The maximum speed of the movement is 30 rpm, so it can be said that the prototype will allow the user to perform the most activities in daily life.

The wrist rotator of the prototype has a maximum continuous torque of 1,4 N·m, which allows to perform the prono-supination movement with a maximum mass of 500 grams located in the palm of the hand; On the other hand, the maximum mass that can be retained is 450 grams. The wrist cuff has a constant speed of 19,86 rpm. The torque and speed provided by the wrist rotator of the prototype, are enough for the user to perform the greatest number of activities in daily life.

The materials used for the construction of the prototype structure are suitable, since in the simulation the minimum safety factor obtained is 3,4 and the maximum displacement is 3,5 mm. ensure that the prototype can withstand the maximum load of 2 kg, in addition to its own weight without a structural failure. In this way, the user will also be given greater reliability in the use of the prototype.

The structure of the prototype has complex geometries which, for its construction, was mainly used 3D prototyping, using FDM technology, with an ABS-M30 material.

The joints between the forearm and the elbow were constructed with AA 7075-T6 aluminum alloy, as in this part are located the main stress concentrators, which are the groove for the key and the holes for the dowel pins.

XI. REFERENCIAS

[1] O. Pelliccioni, K. Arzola y M. Canda, "Computer assisted design of a rotational molding mold for low cost manufacturing of upper limb prosthetic device," *2013 Pan American Health Care Exchanges (PAHCE),* pp. 1 - 6, 2013.

[2] F. Casola, S. Cinquemani y M. Cocetta, "Evolution of elbow prosthesis transmission," *5th International Symposium on Mechatronics and Its Applications,* pp. 1 - 6, 2008.

[3] A. Méndez, "Construcción de una articulacón mecatrónica de codo con movimientos de flexión-extensión y pronosupinación del antebrazo," Graduate Work, Engineering in mechatronics, North Technical University, Ibarra, 2016.

[4] Otto Bock, "ottobock," 2017. [Online]. Available: http://www.ottobockus.com/prosthetics/info-for-new-amputees/information-for-upper-limb-amputees-and-their-families/. [Acceded: 27-ene-2017]

[5] Motion Control, Inc., "Motion Control, Keeping Life in Motion," 2017. [Online]. Available: http://www.utaharm.com/motion-control-company-profile.php. [Acceded: 10-jul-2017]

[6] ProsMed, "ProsMed," 2017. [Online]. Available: http://www.utaharm.com/ua3-myoelectric-arm.php. [Acceded: 10-jul-2017]

[7] Liberating Technologies, Inc., "LTI, A College Park Company," 2017. [Online]. Available: http://www.liberatingtech.com/products/elbows/LTI_Boston_Digital_Arm_Systems_for_Adults.asp. [Acceded: 08-jul-2017]

[8] A. Ramírez y D. Toledo , "Status of elbow myoelectric prosthesis: CINVESTAV-IPN prosthesis," *Revista Mexicana de Ingeniería Biomédica,* vol. XXX, pp. 66 - 73, 07 2009.

[9] E. Smith, "AUTOACCIDENT.COM," 2017. [Online]. Available: https://www.autoaccident.com/transhumeral-amputations-and-elbow-disarticulations.html. [Acceded: 27-ene-2017]

[10] Clinicalgate, "Elbow" 2017. [Online]. Available: https://clinicalgate.com/elbow-3/. [Acceded: 12-jul-2017]

[11] D. A. Bennett, J. Mitchell, D. Truex y M. Goldfarb, "Design of a Myoelectric Transhumeral Prosthesis," *IEEE/ASME Transactions on Mechatronics,* vol. 21, pp. 1868 - 1879, 2016.

[12] I. Murray y G. Johnson, "A study of the external forces and moments at the shoulder and elbow while performing every day tasks," *Clinical Biomechanics,* pp. 586-594, 2004.

[13] R. C. Hibbeler, Ingeniería Mecánica: Estática, 12da ed., México: Pearson Education, 2010.

[14] R. C. Hibbeler, Ingeniería Mecánica: Dinámica, 12da ed., México: Pearson Educación, 2010.

[15] J. Braun, Libro de Fórmulas - Maxon Academy, Sachseln - Suiza: Maxon Academy, 2013.

[16] Maxon Motor, "Maxon Motor," 2017. [Online]. Available: http://www.maxonmotor.com/maxon/view/product/397172. [Acceded: 30-ene-2017]

[17] K. Akhila y A. Reddy, "Design, modelling and analysis of a 3 stage epicyclic planetary reduction gear unit of a flight vehicle," *International Journal of Mechanical Engineering and Robotics Research,* vol. 3, nº 4, pp. 658 - 666, Octubre 2014.

[18] R. L. Norton, Diseño de máquinas: Un enfoque integrado, 4ta ed., México: Pearson Education, 2011.