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MECHANICAL DESIGN OF A LOW COST TRANSHUMERAL PROSTHESIS

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Abstract. *The treatment for amputees is the use of prosthesis. In the particular case of transhumeral amputees, the available prostheses in the market are generally expensive. For this reason, the design of low cost prosthetic devices is a challenge. Nowadays, the rapid prototyping using polymers is a low cost manufacturing process that can be used to prototype prosthetic devices. Here, the mechanical design of low cost transhumeral prosthesis is explored based on the published requirements in the literature. A functional prosthesis driven by motors was modeled using Autodesk Inventor and ADAMS/View software considering the fingers flexion and thumb rotation for the hand, flexion and rotation for the wrist and flexion for the elbow. The results shown a design of a mechanical device where the most quantity of parts can be manufactured using low cost 3D printers.*

Keywords: *prosthetic arm, rapid prototyping, transhumeral prosthesis.*

1. INTRODUCTION

The number of amputations has increased significantly with the number of traffic accidents and the use of motorized working machines. In the case of upper limbs amputees, the ratio of transhumeral to transradial amputation is close to 1/3 (Da Silva and Vilagra, 2015). The best way to reintegrate these patients to their activities of daily living (ADL) is using prostheses. The main engineering challenges of these prostheses are to reproduce all movements of the amputated limb, called degrees of freedom (DOF), to be light, discreet, as fast and strong as the healthy limb.

Due to the complexity of the common bionic arms, there is a small number of prostheses on the market for individuals with transhumeral amputation, that are expensive and usually offer only 3 DOFs. Usually these prostheses are driven by motors and controlled by myoelectric signals. Examples of transhumeral prostheses are the Ottobock DynamicArm and Vanderbilt University's arm (Bennett *et a.l*, 2016). Information found in the literature about wrist prostheses are presented in Tab. 1.

Table 1. Wrist prostheses.

References	DOF	Speed (°/s)	Stall Torque (Nm)	Weight (kg)	Diameter (m)	Length (m)
Bennett, *et al.*, 2016	rotation	240	0.982	0.175	0.035/0.055	0.037
Kyberd, *et al.*, 2011	flexion and rotation	150 (flex.) 170 (rot.)	0.073	0.200	0.096	0.050
Roose, 2014	flexion and rotation	-	0.320 (flex.) 0.200 (rot.)	0.095	0.053	-
Zinck, *et al.*, 2012	rotation	246	0.060	0.087	0.040	0.065

Therefore, the present project proposes a mechanical design of a low cost transhumeral prostheses, almost totally 3D printable on polymers, with 9 DOFs, compatible with most adult users and that provides adequate strength and speed to perform the main ADLs.

2. REQUIREMENT LIST

To build the arm model is essential to define the necessary requirements that let the amputee to accomplish the ADLs. The main DOFs involved in the ADLs are the fingers flexion and thumb rotation for the hand (6 DOFs), flexion and rotation for the wrist (2 DOFs) and flexion (1 DOF) for the elbow. Besides, these movements must be nonbackdrivable.

For the hand was used the open source project Tact Hand as reference, which has compatible attributes with those developed in the academic research centers and the offered by the market. Its dimensions are 0.027x0.098x0.200 m, 0.350 kg, 6 DOFs, average speed 249.8 °/s and average strength of 4.21 N. However, the averages of maximum force and maximum speed for the fingertip in commercial devices are 8 N and 72 °/s respectively (Slade *et a.l*, 2012).

The main wrist function for the ADLs is to position the hand and keep it static, the wrist must be nonbackdrivable and driven by low torque motors. On the other hand, the human elbow applies 5.8 Nm torque in the performance of ADLs (Murray and Johnson, 2004). The maximum rotation speed of the wrist and elbow flexion for eating and drinking tasks are 400 °/s and 250 °/s respectively, but 30 °/s is sufficient for rehabilitation (Buckley *et a.l*, 1996). Currently wrist prostheses use velocities around 240 °/s.

About the dimensions, the elbow diameter for the majority of the population (99%) is largest than 0.067 m. Wrist diameter of 47.8 mm and 24 cm of forearm length is sufficient to meet the requirements of most men (98%) and women (55%) (Gordon *et a.l*, 2012).

The total weight of the prosthesis must be less than 2 kg, with 0.2 kg of the wrist, 1.3 kg of the elbow unit and 0.5 kg of the hand (Bennett *et a.l*, 2016).

Requirements of weight, speed, torque and dimensions for prosthetic arms are summarized on Tab. 2.

Table 2. Requirements List.

	DOF	Force at the fingertip (N)	Maximum torque (Nm)	Speed (°/s)	Weight (kg)	Dimensions (WxLxH) (m)
Fingers	4	> 8	-	>72	<0.5	0.027x0.098x0.200
Thumb	2					
Wrist	2	-	> 0.39(1) (Shigley, 2011)	240 – 400(2)	<0.2	<0.047x0.047x0.070
Elbow	1	-	> 5.8	30 – 250	<1.3	<0.067x0.067x0.170

(1)Flexion and rotation
(2)Flexion and rotation

3. RESULTS AND DISCUSSION

The model was designed using Autodesk Inventor and calculations of speed and force were done using ADAMS/View software. Modifications of Tact Hand project were done in order to fulfill the requirements list. The main modification was the nonbackdrivability for the actuator system, which allows full control over the finger placement, in contrast with the Tact Hand, that works in only one direction and it is not nonbackdrivable. Another advantage of this system is the elimination of the extensor elastic band that negatively acts as a resistive force to flexion, reducing capacity and efficiency. The Fig. 1 illustrates the hand and its linear actuators. The fingers have abduction angles to optimize the grasp, which are 2.5° to index/middle and ring/small and 5° for middle/ring.

The driving system consists of two cables fixed in the actuator nut and in posterior and anterior positions of the proximal phalanx of each finger, as shown in Fig. 2. When the actuator moves backward, the anterior cable pulls, while the posterior cable relaxes flexing the finger. During finger extension, the actuator and the cables move in the opposite direction. The Fig. 3 shows the mechanism responsible for the flexion of the middle phalanges.

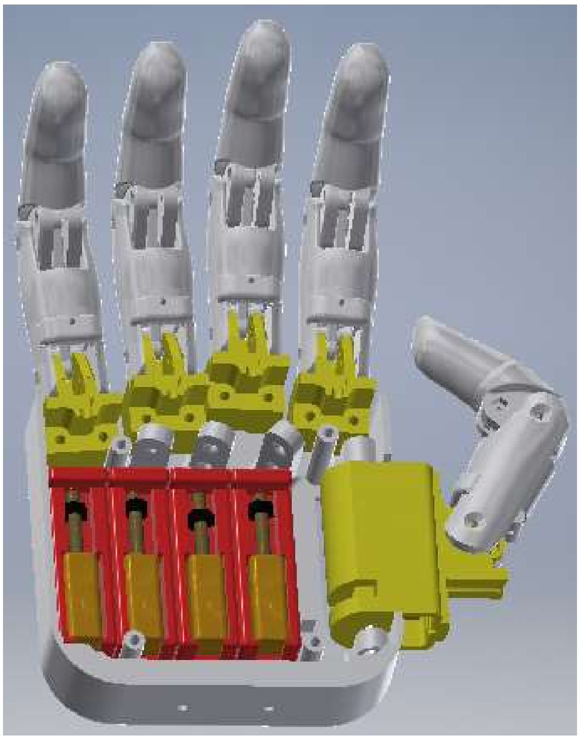

Figure 1. Internal hand view

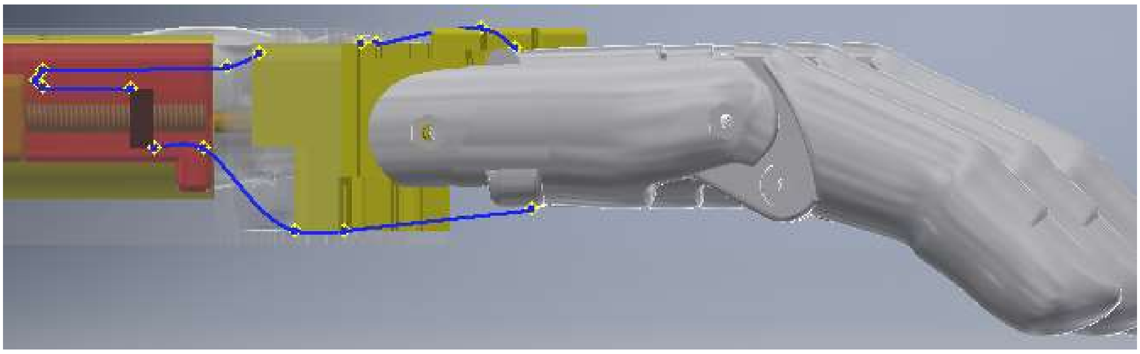

Figure 2. Driving system of the fingers

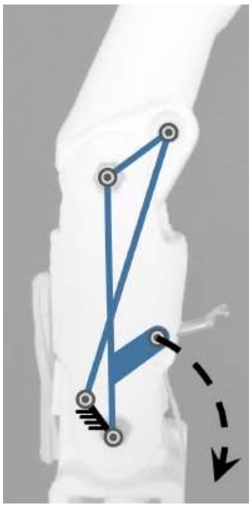

Figure 3. Mechanism of Tact Hand (Slade *et a.l*, 2012)

The mechanism for the thumb is shown in Fig. 4. The design of the thumb support two motors, one for thumb rotation in the axial direction of the arm and other for flexion/extension of the finger. In this last case, a double pulley system coupled to the motor shaft is responsible for the movements, which are achieved controlling the direction of the motor rotation.

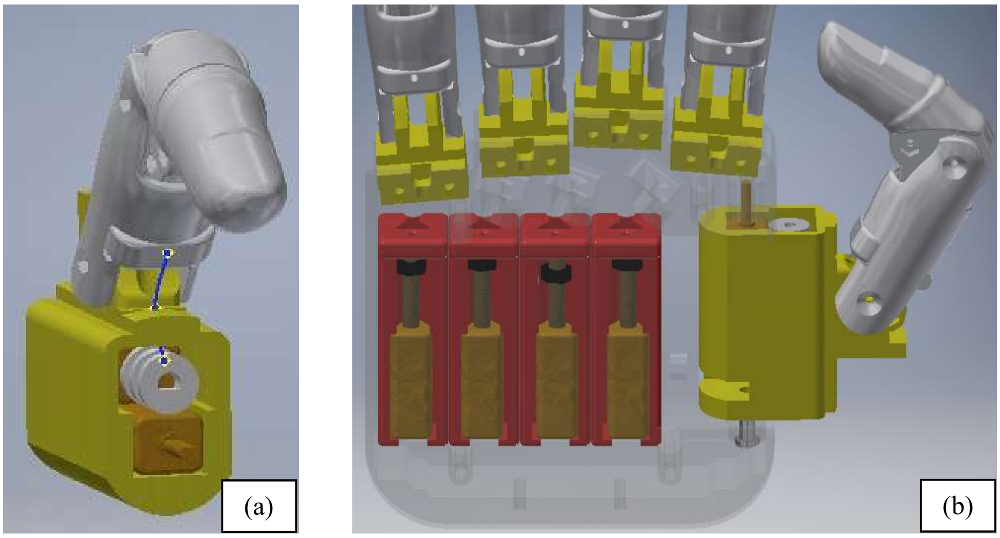

Figure 4. a) Thumb unit, b) thumb attachment

Figure 5 shows a visual comparison between the Tact Hand and the proposed hand.

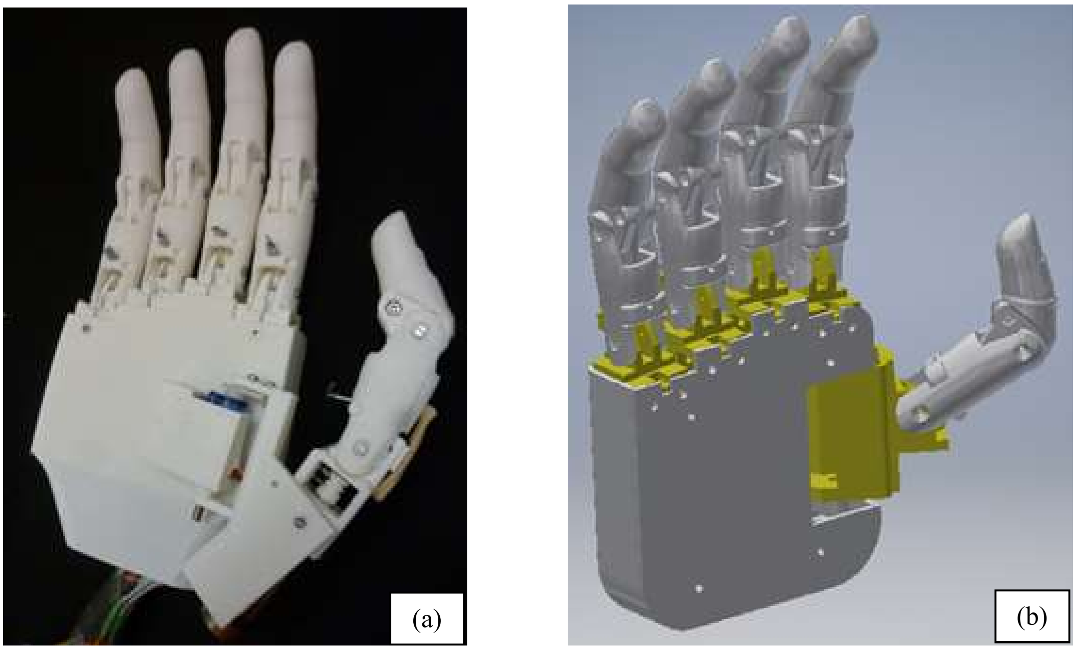

Figure 5. a) Tact Hand, b) proposed hand

From the requirements, the grasp speed is at least 72 °/s and the force must be greater than 8 N. The chosen motor to fulfill the requirement is the 12GA-12-1000/20 by Sumotor, which has a stall torque, T, of 0.096 Nm and rotation speed, rot_m, of 1000 rpm. For a linear actuator driven by an electrical motor, the force is given by Eq. (1) (Shigley, 2011) as:

$$F = \frac{2 \cdot T}{d_m} \cdot \frac{\pi \cdot d_m - \frac{f \cdot L}{\cos(\alpha)}}{L + \frac{\pi \cdot f \cdot d_m}{\cos(\alpha)}} \tag{1}$$

Considering an Acme screw, $\alpha = 30$ °, an average friction, $f = 0.20$, the pitch, $L_1 = 0.0007$ m, and the mean diameter, $d_m = 0.004$ m, the force calculated in Eq. (1) is 165 N. The nut linear velocity in m/s can be expressed as:

$$v_a = L_1 \cdot \frac{rot_m}{60s} \tag{2}$$

Therefore, by Eq. (2), the actuator velocity, v_a, is 0.012 m/s. The ADAMS/View software was used to simulate the finger dynamical behavior. The proposed model and the simulation results are presented in Fig. 6 and Fig. 7. From the results, the force at the fingertips during the grasping, the average force in the cable, the average speed at tip and the linear displacement of the actuator for total finger flexion were 11 N, 98 N, 101 °/s and 0.017 m, respectively.

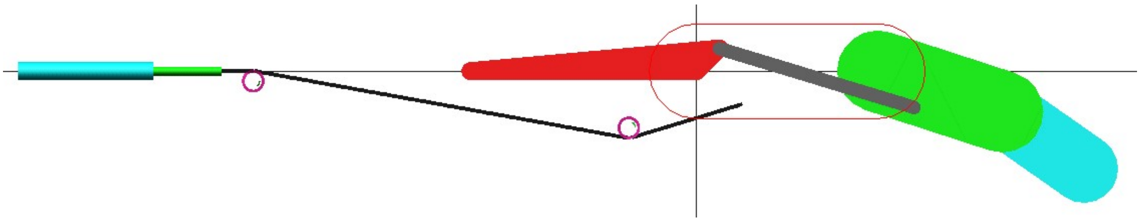

Figure 6. Finger model

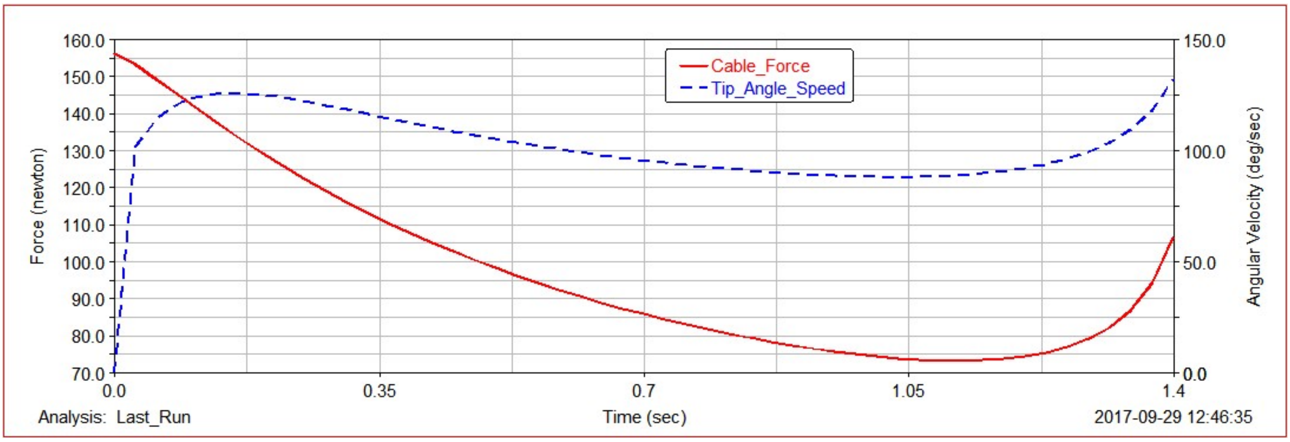

Figure 7. Finger simulation

The thumb requirements for the fingertips force and speed are greater than 8N and 72 °/s, respectively, as shown in Tab. 2. The thumb actuator velocity, v_t, and the thumb actuator force, F_{t_a} are given by:

$$v_t = 2 \cdot \pi \cdot r \cdot \frac{rot_m}{60s} \tag{3}$$

$$F_{t\_a} = \frac{T_t}{r} \tag{4}$$

Where r is the radio of the pulley attached in the motor shaft, rot_{tm} is the rotation of the motor and T_t is the torque in motor shaft. Considering the motor 12GA-12-100 by Sumotor for the thumb, $rot_{tm} = 100$ rpm, $T_t = 0.8$ Nm and $r = 0.005$ m. From Eq. (3) and (4), the calculated values for v_t and F_{t_a} are 0.052 m/s and 160 N, respectively.

The proposed model for the thumb is presented in Fig. 8. The Fig. 9 show the dynamical simulation using ADAMS/View software for 12 N at the fingertip. From the results, the calculated values for the maximum and average force in the actuator and the average speed for the fingertip were 153 N, 88.5 N and 432 °/s, respectively.

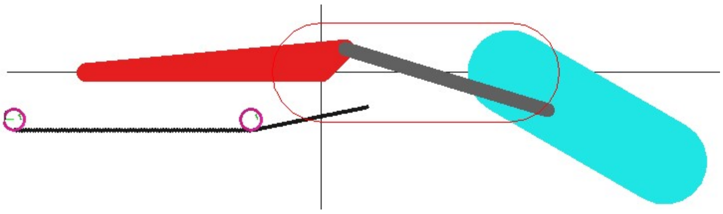

Figure 8. Thumb model

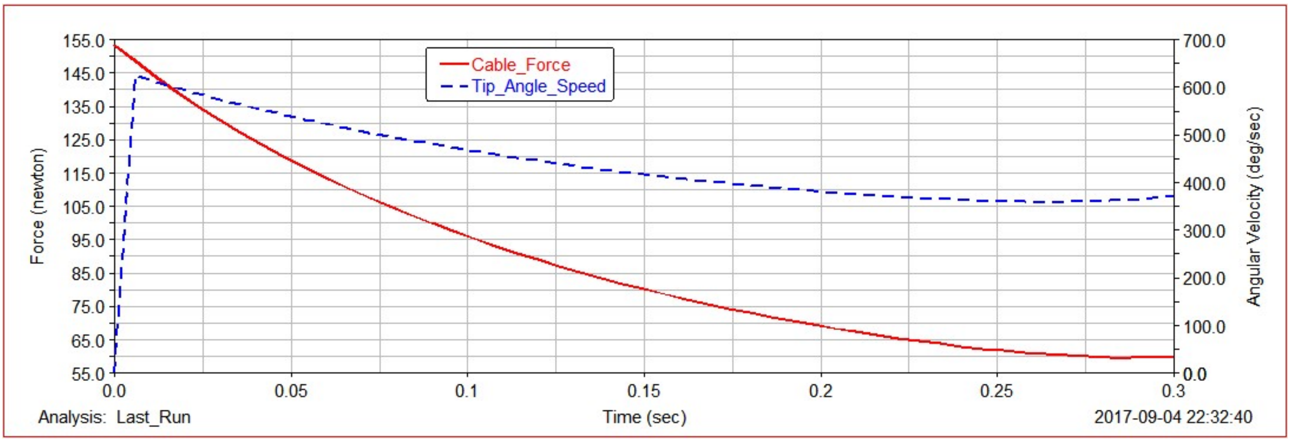

Figure 9. Thumb simulation

The wrist shown in Fig. 10 is responsible to couple the hand and the forearm. It has four pieces and two motors, one for flexion and other for rotation. According to the software Autodesk Inventor, the gravity center of the hand , d_{gc}, mesured from the drive shaft is 0.11 m and the hand weight, w_{hand}, is 3.5 N. The minimum torque of the wrist drive shaft, T_w, is given by Eq. (5) as follow:

$$T_w = w_{hand} \cdot d_{gc} . \tag{5}$$

Then, the value of T_w is 0.39 Nm. According to Tab. 2 the angular velocity of the wrist must be between 240 °/s and 400 °/s. To meet these requirements, the chosen motor was the 12GA-12-60 by Sumotor, which has a rotation speed and torque of 60 rpm and 1.2 Nm, respectively.

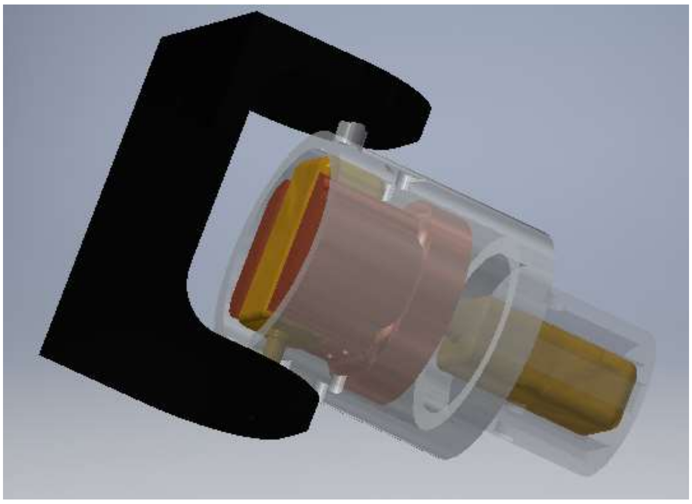

Figure 10. Wrist internal view

The elbow has one motor for the flexion and a link between the prosthetic arm and the residual limb. The requirements for the elbow are 5.8 Nm of torque and angular velocity between 30 °/s and 250 °/s. Then the selected motor are the Sumotor GW31ZY-35. The complete arm design is shown in Fig. 11.

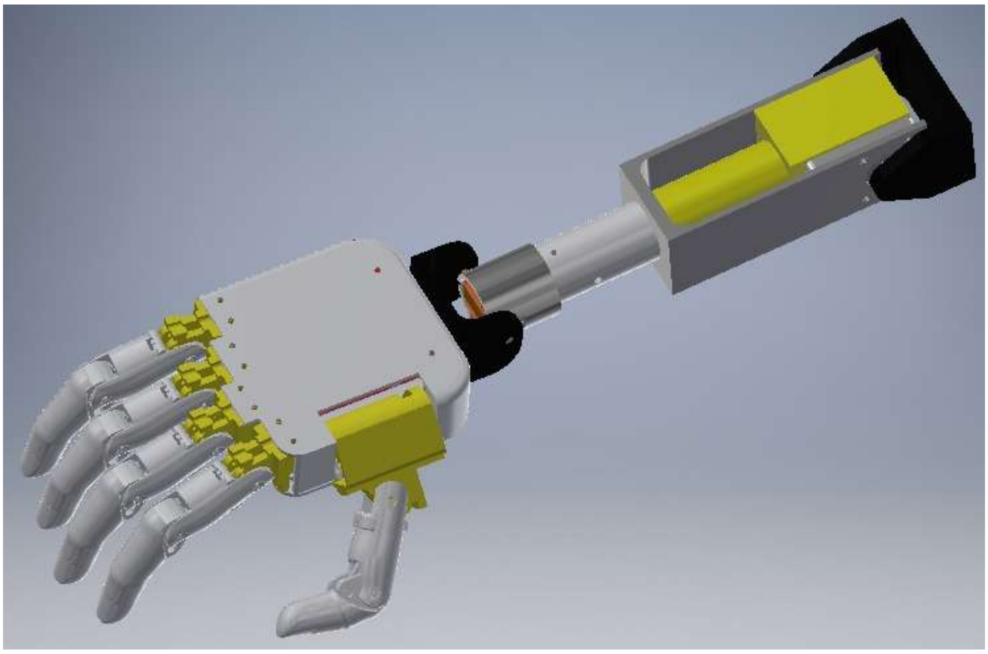

Figure 11. Complete Transhumeral Prosthesis

Finite Element Analysis (FEA) was done on Autodesk Inventor, applying on each piece the force required to carry out the daily activities, and it was verified that about 80% of the pieces can be made of ABS plastic through Fused Filament Fabrication (FFF) in 3D printer, only a few structural components will be made of aluminum. The values of the design variables and the chosen motors are report in Tab. 3.

Table 3. Results.

	DOF	Maximum force at the fingertip (N)	Maximum torque in motor shaft (Nm)	Avg. Speed (°/s)	Weight (kg)	Dimensions (m)	Motor model
Fingers	4	11	0.096	100	0.350[1]	0.027x0.098x0.200	12GA-12-1000 (threaded shaft M4)
Thumb	2	12	0.8	432			12GA-12-100
Wrist	2	-	1.2[2]	360[3]	0.065[4]	0.038x0.045x0.070	12GA-12-60
Elbow	1	-	7.5	210	0.620[5]	0.040x0.065x0.140	GW31ZY-35

[1] ABS plastic (0.270 kg), motors and additional parts (0.080 kg)
[2] Flexion and rotation
[3] Flexion and rotation
[4] ABS plastic (0.049 kg) and Aluminum 6061 (0.016 kg)
[5] ABS plastic (0.020 kg) Aluminum 6061 (0.220 kg) and motor (0.380 kg)

All motors are fabricated for Sumotor and their characteristics are presented in Tab. 4.

Table 4. Motors.

Model	Voltage (V)	Rotation (rpm)	Continuous Torque (Nm)	Stall Torque (Nm)	Current (A)
12GA-12-1000/20	12	1000	0.012	0.096	0.200
12GA-12-100	12	100	0.100	0.800	0.150
12GA-12-60	12	60	0.150	1.200	0.150
GW31ZY-35	12	35	1.500	7.500	1.800

Table 5 presents the acquisition costs of the main items.

Table 5. Costs.

	Quantity	Unit cost (US dollar)	Cost (US dollar)
ABS Plastic	0.335 kg	40.00 /kg	13.4
Aluminum 6061	0.236 kg	7.00 /kg	1.65
Motor (12GA-12-1000/20)	4	5.67	22.68
Motor (12GA-12-100)	2	5.67	11.34
Motor (12GA-12-60)	2	5.67	11.34
Motor (GW31ZY-35)	1	28.00	28.00
Manufacture and Additional parts			100.00
Total Cost			188.41

4. CONCLUSIONS

The design of the transhumeral prosthesis meets the requirements of the project, and the calculated costs are lower than the commercial devices. In addition, ADAMS/View software is appropriate to simulate the dynamic behavior of the prostheses and can be used to optimize its response (Milfont and Gómez-Malagón, 2016). In the near future, we expect to build the physical prototype and to develop the electronic control and sensing systems.

5. REFERENCES

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6. RESPONSIBILITY NOTICE