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Design and manufacture of a forelimb prosthesis prototype for a dog

Diseño y manufactura de prototipo para prótesis de extremidad anterior para un can

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Abstract

The objective of this writing is to develop a methodology for the design and selection of materials that allows for the manufacturing of a canine prosthesis prototype based on anthropometric measurements, element simulation, and finite analysis. The canine prosthesis aims to restore mobility to a missing limb of a dog due to amputation and/or congenital malformation. The methodological approach for this study has been determined based on the analysis of a series of parameters, such as the dimensions of the animal leg, as well as its weight and the location of the amputation, to mention just a few points. As a contribution, a prototype of an exoprosthesis is proposed for a missing front limb, where it should fit within the range of the leg length, from 35 cm to 45 cm, and its weight should range between 30 kg and 40 kg. Additionally, the amputation should be located starting from the elbow region, and the optimal design should be able to adapt to different anthropometric measurements and the needs of the dogs.

Design, Prosthesis, Amputation

Resumen

El objetivo de este escrito es desarrollar una metodología para el diseño y selección de material que permita la manufactura de un prototipo de prótesis canina a partir de mediciones antropométricas, simulación de elementos y análisis finito. La prótesis canina permite restablecer la movilidad de una extremidad faltante de un can debido a una amputación y/o malformación congénita. El enfoque metodológico para este estudio se ha determinado en base al análisis de una serie de parámetros como son las dimensiones de la pata del animal, así como su peso y la localización de su amputación solo por mencionar algunos puntos. Como contribución se propone un prototipo de una exoprótesis para una extremidad faltante anterior, en donde este ocupe estar dentro del rango del largo de su pata de 35cm a 45 cm y su peso deberá oscilar entre los 30 kg a 40 kg, aparte su amputación debe localizarse a partir de la región del codo, con un diseño óptimo pueda adaptar a las diferentes medidas antropométricas y necesidades de los canes.

Diseño, Prótesis, Amputación

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Introduction

Prosthesis

A prosthesis is an artificial substitute for a missing body part (both singular and plural; it is called a prosthesis). Physical and activity limits are the most important changes to cope with after amputation of part or all of a limb. The type of prosthesis that may be needed after surgery depends on the type and location of the amputation and how the limb has been left, any additional treatment that may be needed, the patient's lifestyle and needs.

For prostheses we have that these are broken down into two main types which are endoprosthesis and exoprosthesis (Prosthesis, 2020).

The basic components of a lower limb prosthesis and are shown in Figure 1 and these are (Alguacil *et al*., 2019):

- End devices, they refer to how the devices work.
- And what users can do with them e.g. Prosthetic foot.
- Intermediate elements: knees/hips.
- Prosthetic sockets and fittings (different depending on the level of amputation).
- Suspension systems and interfaces.
- Structures.

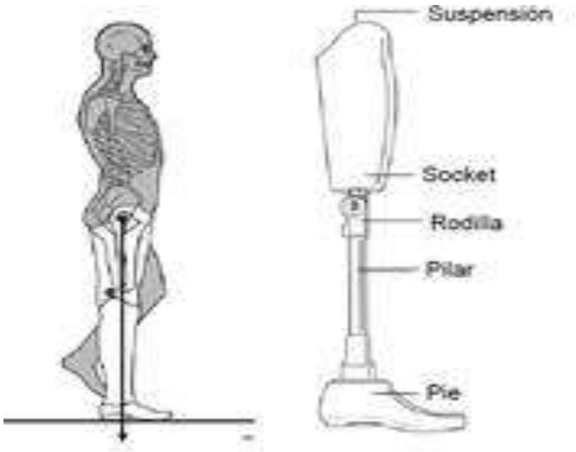

Figure 1 Components of a leg prosthesis
(Jaramillo, 2014)

Prostheses in canines

There are many variables as to why canines have their legs amputated, some of the main reasons are accidents, injuries or diseases that induce requiring the amputation of a leg, or a canine may have a congenital birth defect and is born without one of its legs. Many animals are able to adapt to a tripod or even bipedal life or any other condition they may have without any problem, this does not mean that their conditions are no longer a limitation.

The forelimbs in dogs receive the thrust, while the hind limbs are the most important since they handle resistance, thrust, trotting and stability. The use of prosthesis in one or more limbs provides dogs with a better quality of life, giving a solution to the motor problem, which implies physical limitations or injuries (Zavaleta, 2020). (Zavaleta, 2020)

a) b)

Figure 2 a) Prosthetic forelimb and b) prosthetic canine hind limbs
(Montano, 2022)

Manufacturing

Various materials are used in the manufacture of prostheses, e.g. thermosetting polyurethane. For pigmenting, resin dyes in paste or liquid form are used; for hip or knee joints, metals such as steel or titanium are often used. That is why different manufacturing processes can vary some examples are:

- By molding composite materials.

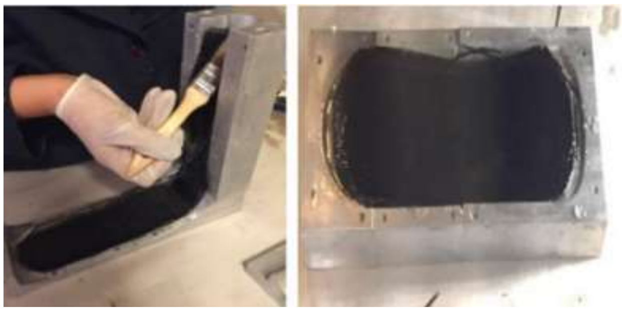

Figure 3 Manual fabrication of prosthesis with mold *(Hernandez et al., 2018)*

- By machining

Figure 4 Grinding of prosthesis
(Metalmecánica, 2019)

- By alternative methods

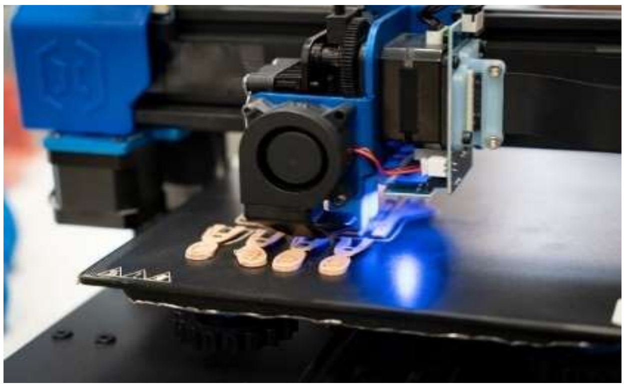

Figure 5 3D printing of prostheses
(Roldan, 2022)

Materials

Over the years different types of materials have been implemented at the time of the manufacture of prostheses going from the simplest to the most complex since due to the fact that with the passing of the years the need for the functionality of the prostheses has been increasingly demanding therefore better quality materials are required some of the main materials for the manufacture of orthopedic prostheses are:

- Woods, although these are no longer used today.
- Polymers, whether plastics, silicones, resins, polyurethanes, etc.
- Metals of different types of alloys.
- Ceramics (Galli & Pelozo, 2017), (Cely,2011).

Stress

Stress is defined as force per unit area in psi or MPa units. In an element subjected to certain forces, the stress is usually distributed as a constantly varying function within the continuum of the material. Each infinitesimal element of the material may experience different stresses at the same time. Therefore, the stresses acting on small evanescent elements within the part must be visualized as shown in Figure 6. (Norton,2011), (Beer & Johnston, 2010)

Figure 6 Stresses a) applied, b) normal and c) shear
(Norton, 2011)

2. Sketch

To start with the development of the prosthesis prototype design, we started with the sketches since it is the materialization of the ideas landed in a drawing, the considerations of the previous sections were taken into account for the prosthesis that will consist of four elements, a socket formed by a sleeve and strap, an intermediate element that will consist of a tube that will give the support and a terminal element that will be an arch that will function as a leg that will be attached to the connecting tube by means of a bolt; the sketches were made to comply with what has already been proposed.

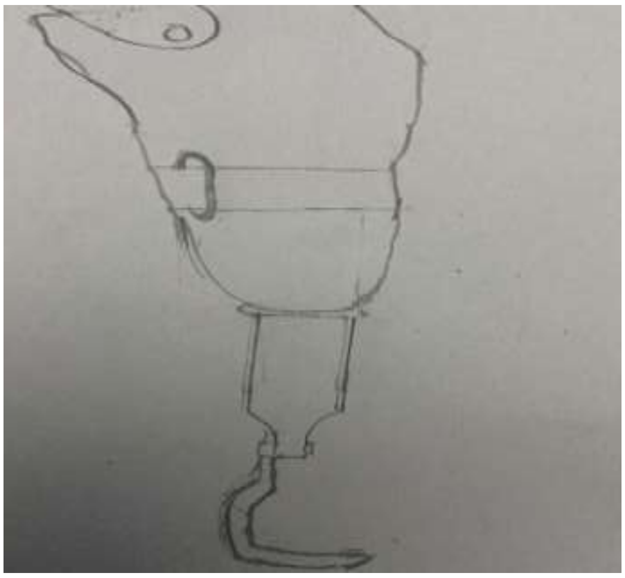

Figure 7 Prosthesis sketch

3. Drawings

Following the sketch, the drawings of the different components of the prosthesis were made in SolidWorks in order to take into account their dimensions; it is worth mentioning that only the drawings of the components that will be subjected to important efforts were made.

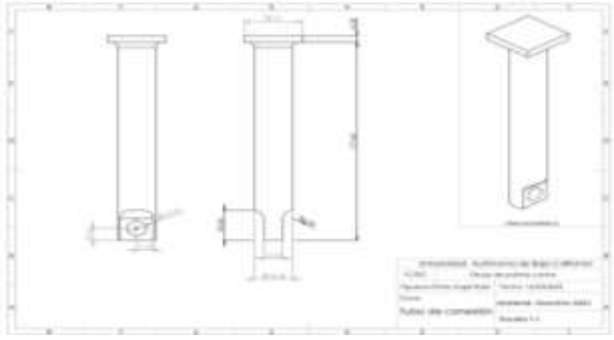

Figure 8 Drawings of the connection tuve

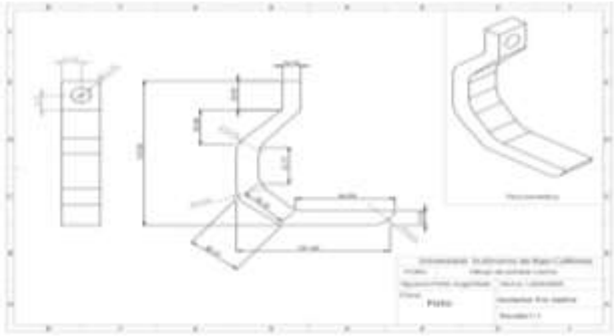

Figure 9 Drawings of the leg

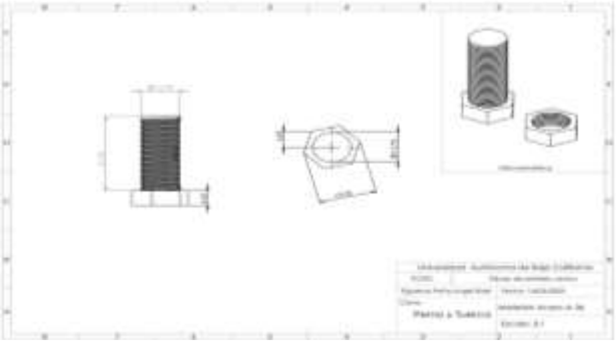

Figure 10 Bolt Drawings

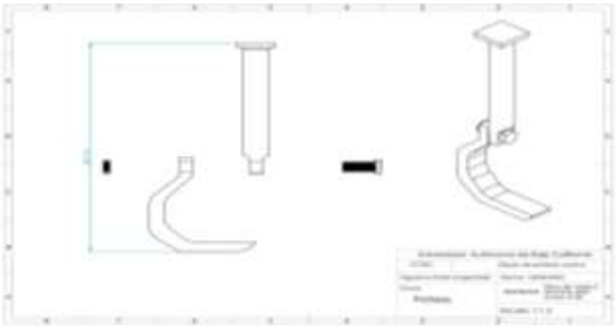

Figure 11 Assembly drawings

4. Analytical calculations

Connection pipe

For the connection tube we calculated the stress to which it would be subjected if it had a diameter of 25.40mm and it would be subjected to a load of 45 kg, which is the maximum weight over designed a can that the tube should support, therefore, we have that:

$$A = \pi \left(\frac{0.0254m}{2}\right)^2 = 0.0005m^2 \qquad (1)$$

$$P = (45kg)\left(9.81\frac{m}{s^2}\right) = 441.45N \qquad (2)$$

Once the cross-sectional area and weight data are obtained, the minimum stress that this part must support is obtained.

$$\sigma = \frac{441.45N}{0.0005m^2} = 882900Pa = 882.9kPa \qquad (3)$$

Leg

With the geometries of the leg taking into account the base of the leg which is 0.1016m and its height of 0.127m, a right triangle is formed as shown in Figure 12.

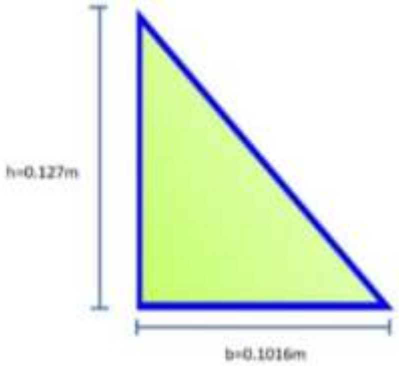

Figure 12 Construction of right triangle with measurements

With the measurements of the base and the height, we find the center of the right triangle, which is located at 1/3 of the base and 1/3 of the height. Once the center of the triangle is located, the distance from the vertices located in the X and Y components to the marked center is taken, which gives a distance of 0.09m, as shown in Figure 13.

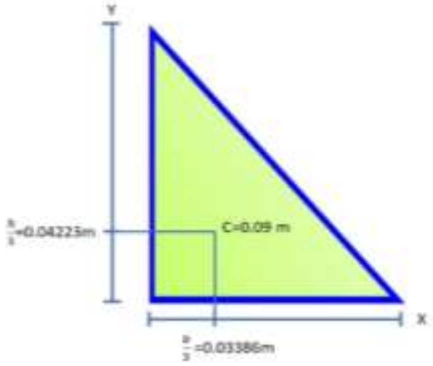

Figure 13 Distance from center to vertices

Having the distance from the center to the vertices we proceed to extract the torques acting on each component, when a load of 441.45N is applied.

$$M_y = (-441.45N)(0.09m) = -39.7305Nm \quad (4)$$

$$M_x = (441.45N)(0.09m) = 39.7305Nm \quad (5)$$

Then the moments of inertia of the cross-section with respect to the X and Y axes are calculated.

$$I_x = \frac{bh^3}{12} = \frac{(0.1016m)(0.127m)^3}{12} = 1.735x10^{-5}m^4 \quad (6)$$

$$I_y = \frac{b^3h}{12} = \frac{(0.1016m)^3(0.127m)}{12} = 1.109x10^{-5}m^4 \quad (7)$$

Once the moments of inertia have been obtained, the stresses in each axis are obtained.

$$\sigma_x = \frac{(39.7305Nm)(0.0254m)}{1.735x10^{-5}m^4} = 58.1645kPa \quad (8)$$

$$\sigma_y = \frac{(-39.7305Nm)(0.0254m)}{1.109x10^{-5}m^4} = -90.9968kPa \quad (9)$$

$$\sigma_{total} = \sigma_1 + \sigma_2 = 32.8323kPa \quad (10)$$

Bolt

The stress in each contact between the bolt and the prosthesis components was calculated.

$$\sigma = \frac{441.45N}{(0.0254m)(0.0127m)} = 1368.497kPa \quad (11)$$

5. Simulations

Once the geometries were obtained, the 3D models of the parts were made in the SolidWorks program in order to test by means of simulations the behavior of the parts that were solved by means of the finite element analysis method. Stress.

Stress concentration and displacement tests were carried out on the different components of the prosthesis, which were tested with different materials.

In the following simulations shown in Figure 14, the areas denoted by red color inside the components are the areas where a higher stress arises at the moment of applying the load.

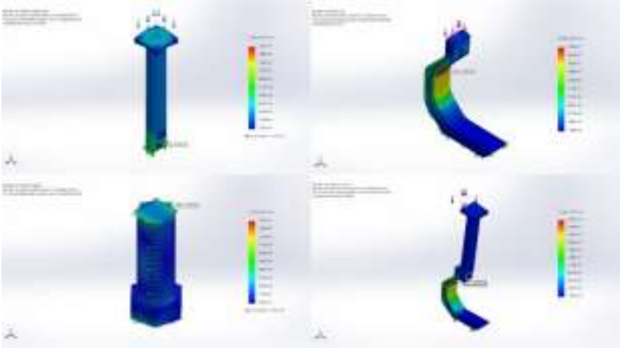

Figure 14 Stress simulations

In the following simulations, shown in Figure 15, the areas denoted by blue color are the areas where there is a higher stress concentration when a load is applied.

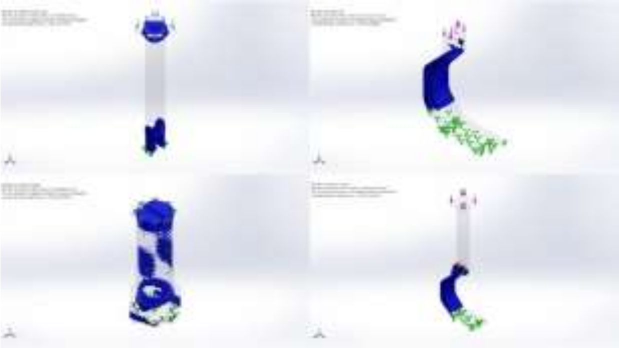

Figure 15 Stress concentration simulations

In the simulations shown in Figure 16, as in the stress simulations, the areas denoted by red color within the components are the areas where there is a greater deformation at the moment of applying the load.

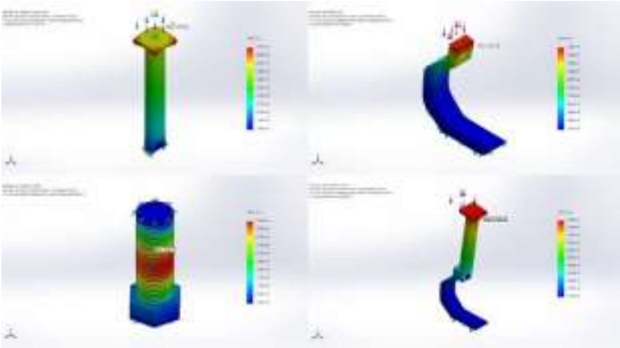

Figure 16 Displacement simulations

6. Manufacturing processes

A process analysis was carried out where the following figures show the flow diagrams that have to be followed at the moment of the fabrication of the different components of the prosthesis.

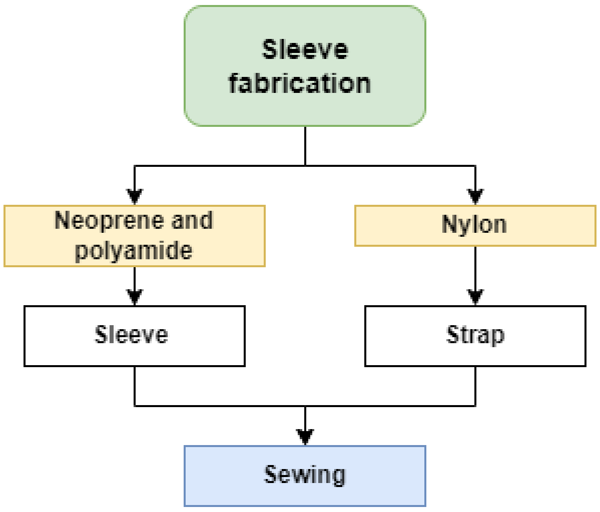

Figure 17 Flowchart of the sleeve manufacturing process

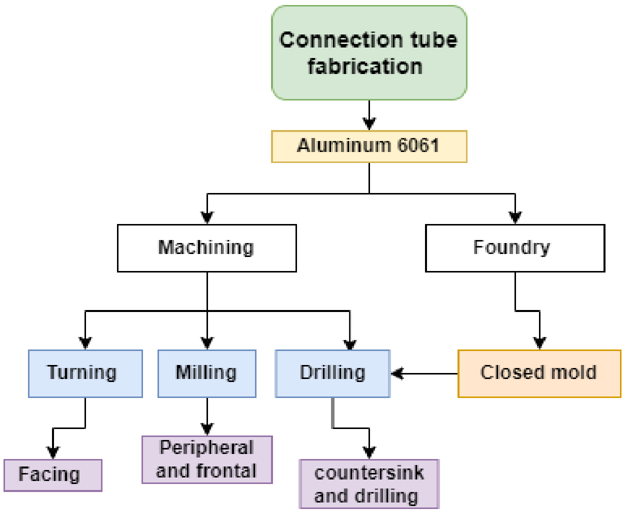

Figure 18 Flow diagram of connection tube fabrication

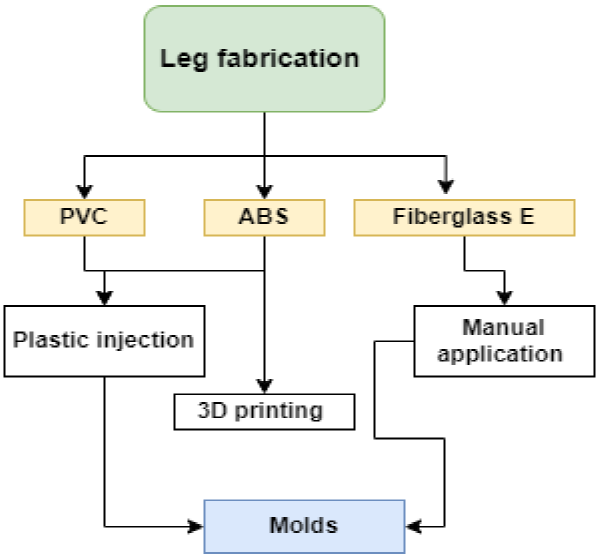

Figure 19 Leg fabrication flow diagram

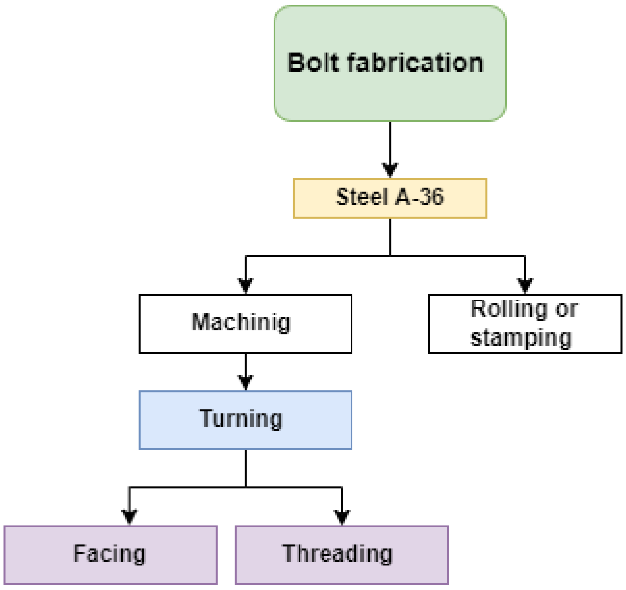

Figure 20 Bolt fabrication flowchart

7. Results

Table 1 shows the results of the components that were calculated analytically to support the minimum capacities that the parts must resist when subjected to work.

Part	Calculation	Results
Connecting tube	Area	$5x10^{-4}m^2$
	Weight	441.45N
	Effort	882.9kPa
Leg	M_y	-39.7305Nm
	M_x	39.7305Nm
	I_x	$1.735x10^{-5}\ m^4$
	I_y	$1.109x10^{-5}\ m^4$
	Stress 1	58.1645kPa
	Stress 2	-90.9968kPa
	Total stress	-32.8323kPa
Bolt	Stress 1	2736.995kPa
	Effort 2	2736.995kPa
	Total effort	1368.497kPa

Table 1 Concentrate of results of analytical calculations on the different components of the prosthesis

Table 2 shows the concentrate of the results obtaining values in kPa for the efforts and mm for the displacements, the part that receives a greater amount of efforts is the leg with the ABS material in the same way is the part that obtained a greater displacement with the same material, in the same way it is denoted that the areas of the parts there is in average a greater concentration of efforts is in superior area.

Part	Material	Minimum stress	Maximum stress	Deformation	Area of highest stress concentration
Connecting	Aluminum 6061	75.32kPa	15350kPa	1.074x10-4mm	Upper Lower
Pipe Leg	PVC	7.218kPa	22820kPa	5.246mm	Upper
	ABS	7.837kPa	23550kPa	6.564mm	Upper
	Fiberglass E	5.153kPa	19940kPa	1.484x10-1mm	Upper
Bolt	A-36 Steel	30.92 kPa	15910kPa	5.918x10-4 mm	Central
Assembly	Various	100.299Pa	29760kPa	9.708x10-1mm	Lower

Table 2 Concentrated results of the simulations of the distribution of stresses and displacements in the canine prosthesis

8. Acknowledgement

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10. Conclusions

Prototype

For the prototype we have an exoprosthesis for a missing forelimb, where it must be within the range of the length of its leg from 35cm to 45cm and its weight should range between 30kg to 40kg, besides its amputation should be located from the elbow region, it will consist of four elements a sleeve, a connection tube, a bolt that acts as a pin and a leg, of which the last three of these are the components that will be subjected to significant loads, where the calculations and simulations will be carried out.

Design

For the prototype, a design process was followed in which analytical calculations and SolidWorks software were used to meet the needs or problems that arose at the time of the execution of the design stage. Thus creating the different components of the model whose combined components had a minimum stress of 100.299Pa and a maximum of 29760kPa, having a deformation of 9.708x10-1mm satisfying the geometry requirements after being simulated and tested. It should be noted that the loads were over designed in order to have a higher safety factor.

Material

For the prototype, all the different materials proposed showed to be suitable at the moment of being submitted to the loads that would be generated at the moment of being carried out the work of the prosthesis, mechanically speaking the E-glass fiber is the most suitable material at the moment of the selection of the material for the leg, although this will depend on the manufacturing process chosen.

Manufacturing process

For the prototype, the manufacturing processes will be sewing for the sleeve piece, machining for the connection tube, the bolt could also be machined but due to the easy access to these it is more profitable to get them from a tertiary supplier and for the leg the easiest process and scope is injection.

Future work

As future works, the aim is to manufacture the prototype with the materials and processes proposed, as well as to look for alternatives to improve the design of the prototype.

In such a way that in this work an anterior prosthesis is proposed for a large size dog where it must be within the range of the length of its paw from 35cm to 45 cm and its weight must oscillate between 30 kg to 40 kg, besides its amputation must be located from the region of the elbow, whose combined components had a minimum effort of 100. 299Pa and a maximum of 29760kPa, having a deformation of 9.708x10-1mm, where the manufacturing processes will be, the sewing for the sleeve piece, the machining for the connection tube, the bolt is obtained by third parties and for the leg the injection.

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