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ESCOLA SUPERIOR DE TECNOLOGIA I CIÈNCIES EXPERIMENTALS

GRADO EN INGENIERÍA MECÁNICA

DESIGN OF A MECHANICAL SYSTEM FOR UNDERACTUATION OF HAND PROSTHESES

TRABAJO FIN DE GRADO

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I. REPORT

1. Introduction

In recent years, numerous hand prostheses models have been developed encouraging their accessibility thanks to 3D printing techniques [1], which allow low-cost customization and self-fabrication. Nevertheless, there is still much work to be done regarding economical and lightweight mechanical actuation systems.

Hand prostheses can be classified as mechanical, if they are actuated and controlled by the human body, or myoelectric, if they are moved with electrical motors and controlled through electromyography sensors. The development of these prostheses shows some design difficulties due to the complexity of the human hand system, i.e., the human hand exhibits a large number of degrees of freedom (DOFs), five per finger, making a total of 25 DOFs. The underactuation of the different DOFs of the prostheses allows to reduce the number of components that are used to build them and, thus, their weight and cost.

Different mechanical solutions have been proposed in the literature that try to solve the previously mentioned problem of underactuation. However, previous proposals could be improved in order to reproduce the human hand motions more accurately. In prior projects undertaken by the Biomechanics and Ergonomics group at UJI, a first system configuration was designed and tested in the laboratory as part of the assigned tasks of the research group. The objective of this Final Degree Project (FDP) is to design, manufacture and test a new mechanical system for underactuation of hand prostheses that improves previous developments' weak points. In addition, the complete design of a new hand prosthesis is also developed.

2. Objectives

The project has been developed working with the Biomechanics and Ergonomics research group in the framework of the UNIQUE-HAND project that has as final objective the creation of viable artificial hands valid as prostheses for individuals and also as robotic hands for industry, as well as the improvement of aesthetics of prior designs, allowing people to wear their prostheses with more confidence and trying the designs to go unnoticed.

As mentioned above, the specific objective of this FDP is to design a mechanical underactuation system that improves weak points of previous developments and tries to reproduce as faithfully as possible the different hand grasps used by healthy people during activities of daily living. This mechanical system must be designed in order to be manufactured using the fused deposition modelling (FDM) 3D printing technique [2] and will be fitted into a completely new designed hand prototype which houses this underactuation system, the design of which is also reflected in this paper. The design of the prosthesis includes fingers, joints, returning system, flexion system, abduction and adduction of the thumb and palmar structure of the hand. This new system will be tested in the laboratory by carrying out two essays, one of them will be a grasping test and the other will be the water bottle test (WBT) that will be explained further in the paper and the other will be the Anthropomorphic Hand Assessment Protocol (AHAP) [3].

The presented design is based on differential mechanisms, such as pulleys and whiffletree mechanisms and will be explained in further detail later on. The design of the prosthetic hand has been based on the scan of a real human hand and then modified in order to adapt the different proportions and finger orientations, as well as the different mechanisms that allow the flexion and extension of the hand as mentioned above.

The actuation of the different cables that allow the movement of the hand will be obtained by using a bowden cable together with a harness and triceps cuff system and the prosthesis will be located just below the tested subject hand, thus allowing a more natural behaviour when making grasps.

This project contains the design of the underactuation mechanical system and its manufacture using a 3D printer. Furthermore, there are details about the assembly process and the different components of the design. Eventually, there is an explanation of the tests that will be carried out, which will determine the performance of the system, and the obtained results from these tests.

3. Justification

The UNIQUE-HAND project is currently ongoing in the Biomechanics and Ergonomics research group (project PID2020-118021RB-100). The Biomechanics and Ergonomics group is a research group of the Dept. of Mechanical Engineering and Construction. This project is related to that project and my involvement on it was also possible thanks to the programme *Estudia i Investiga a l'UJI*.

By the realization of this FDP, the acquired knowledge in the Escola Superior de Tecnologia i Ciències Experimentals of the Universitat Jaume I have been applied to a mechanical engineering project in order to obtain the degree in Mechanical Engineering.

This project is technically justified in such a way that it can contribute both to solving the problem mentioned in the objectives section and to helping in future research work and prosthesis design, thus carrying out important social and scientific work.

In addition, the realization of this project has allowed the student to broaden the acquired knowledge during the degree, as well as to acquire new skills in other areas such as CAD design and research involved in the biomechanics field.

4. Background

As mentioned above, this FDP takes part within the framework of the UNIQUE-HAND project, where there are several tasks looking for the development of new hand prostheses design and actuation systems. There are two prototypes in progress, one of them is a motorized and electrically actuated system and the other one, which is shown in this project, is a body-powered mechanical system. For this mechanism, not only the underactuation system was designed, but the whole structure of the prosthetic hand and the fingers' design.

Anthropomorphic designs are useful for different applications, both for aesthetic use in amputees and for use in different types of industry. Despite the tasks that a hand prosthesis can be used to perform, it has been demonstrated after the different editions of the Cybathlon Arm Race [4] that a complex design is not necessary to obtain a good performance, with simple designs outperforming sophisticated ones in the final score. Therefore, it is concluded that a simple design can help to solve the different problems encountered for both prosthetic and industrial use.

This FDP is motivated by previous work carried out in this research group, which was also based on the creation of hand prostheses, both manually and electrically actuated. These projects are the DEVALHAND, (project DPI2014-60635-R) and the BENCH-HAND (project DPI2017-89910-R), projects whose goals were to propose anthropomorphic designs, like that shown in Figure 1 together with their electromechanical actuation systems, as well as to establish objective evaluation criteria for any artificial hand to be compared with the human hand, among other objectives.

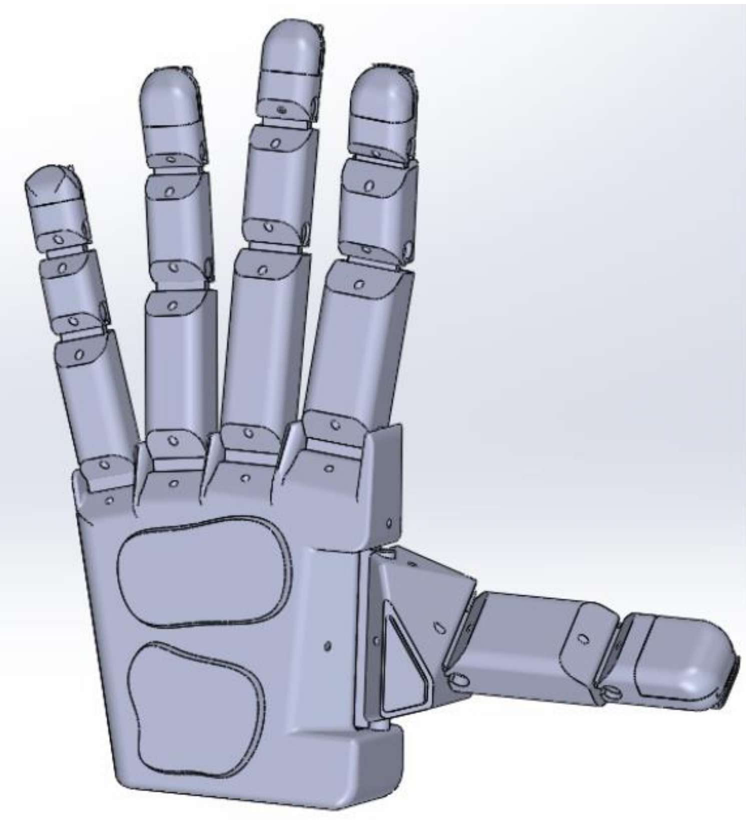


Figure 1 3D model of the IMMA hand obtained in the DEVALHAND project

4.1. The human hand

The human hand is one of the most complete and complex mechanisms found in nature. Counting with 27 bones and more than 20 DOFs. These DOFs are actuated and limited by a system consisting of tendons and ligaments, which are controlled by the human brain through the use of the nervous system, thus making an almost immediate and highly efficient network [5]. Due to the complexity of the mechanism itself and the system that controls it, technology up to this date hasn't been able to faithfully emulate its versatility and efficiency. However, the challenge that implies creating a functional prosthesis with a similar behaviour to the human hand has increased the research in the field of robotics, technology and, obviously, biomechanics.

4.1.1. Kinematic chain of the human hand

The human hand is formed by 27 bones, including those in the wrist, which are not a case of study in this project. The fingers' phalanxes, which are explained in further detail below, are 14 of the 27 bones of the hand.

The human hand DOFs are defined by the KC of the HH. Each of the long fingers is composed of four segments which are, in proximal to distal order, metacarpal segment (MC), proximal phalanx (PP), intermediate phalanx (IP) and distal phalanx (DP). Nevertheless, the thumb lacks the IP, counting only with the other 3 segments. In addition to these segments, the joints between them must also be pointed out in order to clarify further explanations. These joints are, in proximal to distal order, Carpo-Metacarpal joint (CMC), Metacarpophalangeal joint (MCP), Interphalangeal joint (IP), Proximal Interphalangeal joint (PIP) and Distal Interphalangeal joint (DIP). In Figure 2 [6] the different bones and joints of the HH are shown.

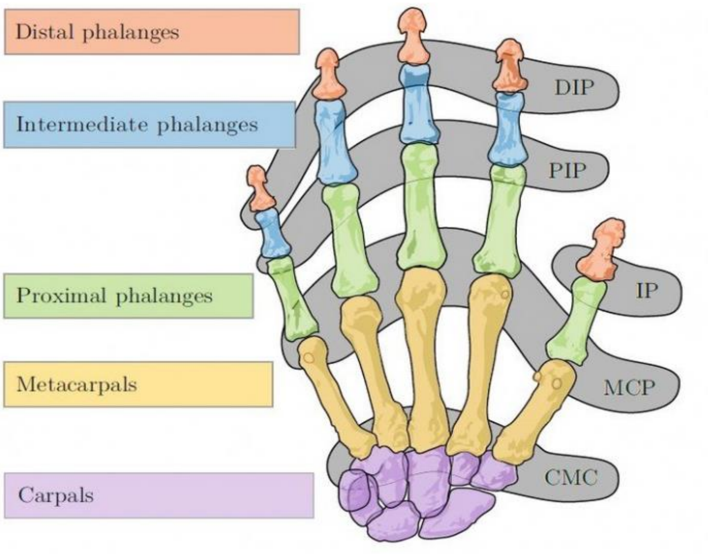


Figure 2 Joints and bones of the Human Hand [6]

The KC of the human hand exhibits 25 DOFs, five per finger, or 23 DOFs if the mobility of the CMC joints of the index and middle fingers is neglected [7]. The palm of the hand is formed by the MCs of the long fingers and the mobility between them is very limited. The CMC of the thumb has the highest mobility of the CMCs. It has two rotational DOFs that enable the opposition of it to the long fingers. The MCPs count with two rotational DOFs allowing the flexion/extension (F/E) and the abduction/adduction (AB/AD). Lastly, the PIPs, the DIPs of the long fingers and the IP of the thumb exhibit one DOF, enabling F/E.

4.1.2. Human hand dimensions

The hands of different human beings differ greatly in size and dimensions. For this reason, the measurements chosen for the design of a prosthesis are selected in such a way that they adapt to the majority of existing measurements, i.e., the average size of the hands of the population is considered and barely adapted and modified according to the design needs. Furthermore, as the majority of the population is right-handed, the measures in this project were taken on the right hand of the subjects.

Figure 3 shows the divisions made in the different fingers when taking measurements to obtain the data of the dimensions of the human hand. The study was carried out with 139 participants, 70 of male and 69 female subjects [8].

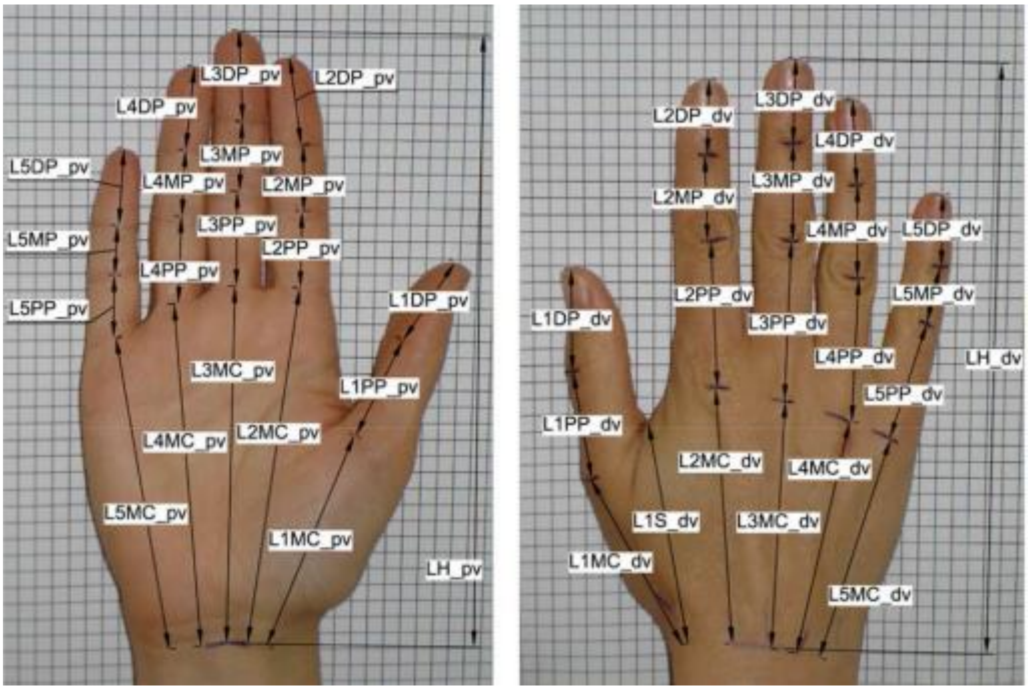


Figure 3 Hand measurements (lengths) [8]

The results obtained during the study are divided in dorsal and palmar measurements are shown in Figure 4 and Figure 5:

	Dorsal Lengths													
	Females					Males					Females and Males Jointly			
	N	Mean	*SD*	5th	95th	*N*	Mean	*SD*	5th	95th	Mean	*SD*	5th	95th
L1DP_dv	69	28.8*	2.61	24.0	32.5	70	32.5	2.30	29.0	37.0	30.6	3.07	26.0	36.0
L1PP_dv	69	31.9	3.52	27.0	37.5	70	33.9*	3.24	28.1	40.0	32.9	3.51	27.0	38.0
L1MC_dv	69	55.0*	6.06	45.0	66.5	70	59.4*	7.69	46.0	71.0	57.2	7.26	46.0	70.0
L2DP_dv	69	23.5	1.87	20.5	27.0	70	25.5	2.02	22.0	29.0	24.5	2.18	21.0	28.0
L2MP_dv	69	24.8	2.41	21.0	29.5	70	26.4	2.52	22.0	30.5	25.6	2.60	21.0	30.0
L2PP_dv	69	43.5*	3.79	39.0	49.5	70	47.0*	3.30	42.0	53.0	45.3*	3.96	39.0	52.0
L2MC_dv	69	77.9*	5.83	67.5	89.0	70	83.8	7.07	72.6	93.9	80.9	7.12	69.0	93.0
L3DP_dv	69	25.6	2.12	22.0	29.5	70	27.4	2.49	23.6	32.0	26.5	2.47	22.0	31.0
L3MP_dv	69	29.4*	2.64	25.0	34.0	70	31.6	2.39	27.6	36.0	30.6	2.74	26.0	35.0
L3PP_dv	69	48.8	3.48	44.0	54.5	70	52.4*	3.25	46.6	58.0	50.6	3.79	45.0	57.0
L3MC_dv	69	73.7*	5.28	66.0	83.5	70	79.8*	6.57	68.6	90.5	76.8*	6.69	66.0	88.0
L4DP_dv	69	25.6	1.92	22.0	29.0	70	27.1	2.20	24.0	31.0	26.4	2.19	23.0	30.0
L4MP_dv	69	27.3	2.60	23.0	31.5	70	29.6	2.49	25.0	34.0	28.4	2.79	24.0	33.0
L4PP_dv	69	44.2	3.47	39.5	50.0	70	47.4	3.20	41.0	52.0	45.8	3.68	41.0	52.0
L4MC_dv	69	69.0*	5.10	60.5	78.5	70	74.8*	6.52	64.1	84.9	72.0	6.52	62.0	83.0
L5DP_dv	69	22.6	2.43	19.0	26.0	70	23.9	2.15	20.6	28.0	23.2	2.38	20.0	27.0
L5MP_dv	69	18.5	2.29	14.5	22.0	70	20.9*	2.19	17.0	24.5	19.7	2.53	16.0	24.0
L5PP_dv	69	34.7*	3.07	30.5	39.0	70	37.4*	3.29	32.0	43.0	36.1	3.44	31.0	42.0
L5MC_dv	69	63.9	5.27	55.5	72.5	70	69.*	6.79	57.6	80.5	66.5	6.57	56.0	78.0
LS1	55	65.7	5.36	58.0	77.2	61	71.6*	7.65	59.1	82.9	68.8	7.28	59.0	81.2
LH_dv	69	177.4*	9.78	163.0	195.0	70	190.7*	9.74	176.0	206.0	184.1*	11.83	163.0	203.0

Figure 4 Dorsal length measurements of the human hand dimensions study [8]

	Palmar Lengths													
	Females					Males					Females and Males Jointly			
	N	Mean	*SD*	5th	95th	*N*	Mean	*SD*	5th	95th	Mean	*SD*	5th	95th
L1DP_pv	69	28.9	3.74	21.5	34.0	70	31.1*	4.04	23.1	37.0	30.0	4.03	22.0	36.0
L1PP_pv	69	29.8	3.69	23.5	35.0	70	32.6	4.12	26.1	38.5	31.2	4.14	24.0	38.0
L1MC_pv	69	60.3*	5.37	50.5	69.0	70	64.7*	6.75	52.6	76.5	62.5*	6.47	51.0	73.0
L2DP_pv	69	25.2	2.07	21.5	28.0	70	26.6	2.01	23.1	30.0	25.9	2.15	22.0	29.0
L2MP_pv	69	21.2	2.14	17.0	24.0	70	22.1	1.99	19.0	25.0	21.7	2.12	18.0	25.0
L2PP_pv	69	24.8	2.63	21.0	29.5	70	25.8*	2.44	21.6	30.0	25.3	2.58	21.0	30.0
L2MC_pv	69	104.3*	6.34	94.5	114.5	70	112.9*	5.92	102.1	122.0	108.6*	7.48	96.0	120.0
L3DP_pv	69	26.3	2.20	22.5	30.5	70	27.5	2.10	23.6	31.0	26.9	2.23	23.0	31.0
L3MP_pv	69	24.2	2.24	20.5	28.0	70	25.6	2.21	21.0	29.0	24.9	2.34	21.0	29.0
L3PP_pv	69	27.9*	2.61	23.5	32.5	70	29.2	2.31	25.6	33.0	28.6	2.54	24.0	33.0
L3MC_pv	69	106. 8*	6.33	97.0	116.5	70	115.4*	5.63	105.6	124.0	111.1	7.36	98.0	123.0
L4DP_pv	69	25.4	2.19	21.5	29.5	70	27.0	1.97	24.0	30.5	26.2	2.22	23.0	30.0
L4MP_pv	69	22.5	2.20	19.0	26.0	70	23.6	2.04	20.6	27.5	23.0	2.18	20.0	26.0
L4PP_pv	69	24.7	2.58	20.5	29.0	70	26.1	2.24	22.0	30.0	25.4	2.51	21.0	30.0
L4MC_pv	69	102.6*	5.87	92.5	111.0	70	110.9*	5.33	102.0	119.5	106.8	6.95	95.0	118.0
L5DP_pv	69	22.9	1.99	19.0	26.0	70	24.7	2.08	21.0	28.0	23.8	2.24	20.0	27.0
L5MP_pv	69	15.8	2.11	13.0	20.0	70	17.3	1.96	14.0	20.5	16.5	2.16	13.0	20.0
L5PP_pv	69	19.4	2.42	16.0	24.5	70	20.6	2.66	17.0	26.0	20.0	2.61	17.0	25.0
L5MC_pv	69	91.1*	5.95	81.0	100.5	70	99.3*	5.48	91.6	108.5	95.2*	7.03	82.0	107.0
LH_pv	69	184. 5*	10.35	168.5	201.0	70	197.6*	8.93	184.0	210.9	191.1	11.66	172.0	209.0

Figure 5 Palmar length measurements of the human hand dimensions study [8]

4.2. Grasping types

The human hand, as the complex machine that it is, can perform a large number of different grasps during different daily living activities or more specific ones, for example related to specific configurations during sport or grasps that require greater precision, for example when handling hazardous materials.

The different grasps that are going to be explained and considered throughout this project are the ones seen in the AHAP [3]. The AHAP is the Anthropomorphic Hand Assessment Protocol which is a tool that provides a measure for quantifying the grasping ability of artificial hands and allows to compare different hand designs. The AHAP uses 25 different objects from the Yale-CMU-Berkeley Object and Model Set (YCB set) [9], and it involves grasping with 8 of the most relevant human grasps and 2 non-grasping postures [3]. Figure 6 shows the YCB set of objects [10].

Figure 6 YCB objects set [10]

The grasping ability and the comparison between different hands is made thanks to the Grasping Ability Score (GAS), which is a numerical score based on the performance of the hand prototype throughout the different tasks. This benchmark allows to demonstrate improvements of newer designs with respect to previous ones.

The different grasps that are performed during the AHAP are the following ones:

- Hook (H) Figure 7 (a)
- Spherical grip (SG) Figure 7 (b)
- Tripod pinch (TP) Figure 7 (c)
- Extension grip (EG) Figure 7 (d)
- Cylindrical grip (CG) Figure 7 (e)
- Diagonal volar grip (DVG) Figure 7 (f)
- Lateral pinch (LP) Figure 7 (g)
- Pulp pinch (PP) Figure 7 (h)

Additionally, as mentioned before, there are 2 non-grasping postures which are also assessed:

- Index pointing/pressing (IP) Figure 7 (i)
- Platform (P) Figure 7 (j)

a

b

c

d

e

f

g

h

i

j

Figure 7 Human hand common grasps

4.3. Amputation types

The amputation of the upper limb is an intervention derived from various factors such as cancer, trauma, fractures, malformations. The level at which the amputation is performed has a direct impact on the individual's ability to perform different actions and tasks, as well as on the medical assistance required [11].

The various levels of amputation are named according to where they occur:

- Transphalangeal amputation
- Transmetacarpal amputation
- Transcarpal amputation
- Wrist disarticulation
- Transradial amputation
- Elbow disarticulation
- Transhumeral amputation
- Shoulder disarticulation
- Forequarter (Interscapulothoracic) amputation

Figure 8 shows the different levels of upper limb amputations and their names according to the part of the extremity where they are produced.

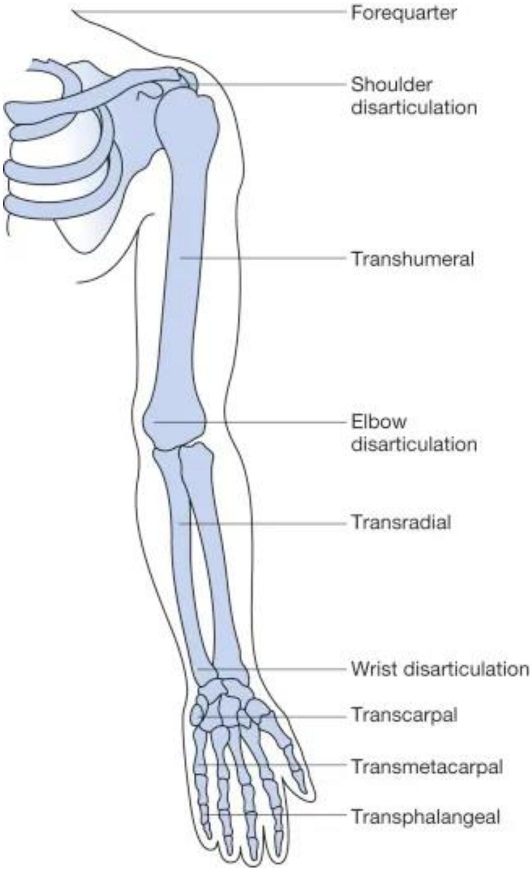


Figure 8 Different levels of amputation and its names

4.3.1. Causes of amputation

As mentioned above, the causes of amputation can be diverse. Here are some examples:

- Trauma beyond repair
- Loss of the blood supply
- Infection
- Burns
- Frostbite

It should be noted that the prostheses can not only be used by amputees but can also be used by subjects with malformations or congenital problems.

4.3.2. Phantom pain and other amputation consequences

Subjects who suffer an upper limb amputation are usually affected emotionally, psychologically and functionally [12]. Among these problems resulting from amputation is phantom pain. Phantom pain is pain that the subject feels is coming from a part of the body that is no longer there. In the first studies carried out on this topic, the experts thought that it was a psychological condition, but later it was concluded that this pain was real and that it came from the spinal cord and the brain [13].

Some experiments carried out with hand prostheses demonstrated that the embodiment of these artificial hands could help to reduce the phantom pain [12].

4.4. Prosthetic systems

There are different prosthesis designs depending on the level of amputation that the subject has. Here are some examples of prostheses for different types of amputation:

- Partial or total hand prosthesis [14]. Figure 9 (a).
- Forearm prosthesis [15]. Figure 9 (b).
- Shoulder or forequarter (Interscapulothoracic) prosthesis [16]. Figure 9 (c).

a b c

Figure 9 Prostheses for different kind of amputation

In recent years, prostheses have improved from simple designs that are only cosmetic or simple designs such a mechanically actuated double hook prototype to models reminding more of a human hand which can even be controlled through electromyography using the electrical activity of the muscles and nerves in human’s body [1].

Figure 10 shows an example of a myoelectric prosthesis, the handiii COYOTE.

Figure 10 handiii COYOTE myoelectric prosthesis [17]

4.5. Artificial hands

The development of the design of artificial hands, as well as their actuation systems, whether manual, mechanical or electrical, has been important in recent years. The literature related to these topics is full of designs looking for alternatives to achieve the best possible result. Some designs are more sophisticated and others simpler, but all have in common the underactuation of the fingers of the prosthetic hand in the most efficient way, thus achieving a functional prosthesis.

One of the biggest problems that researchers face when trying to replicate the human hand as a prosthesis is the aim of achieving dexterity during grasping of different objects. This is limited by the kind of controllers that both robotic and manual hands use. These systems are far simpler than the nerve network that is controlled by human minds. By the simplification mentioned above, the different prostheses are limited in the number of objects that can grasp or manipulate. This might be acceptable when talking about industry but affects the comfort and functionality of other prototypes such as the ones used on amputated people to improve the quality of their daily living activities.

There are other constraints that increase the complexity of the problem, such as the necessary low weight, size and price of the hand prosthesis. A design with less components, manufactured with a material such as plastic (which is usually lighter than metal) and with a correct distribution of the mechanisms in the prosthesis itself, can lead to a smaller, lighter and cheaper product. This cheaper product allows people with a lower economic capacity to have access to a solution that can increase their quality of life, as well as that of the people who surround them.

4.5.1. Commercial protypes

Commercial hand prostheses are designs that have been created for the purpose of helping amputees or people with malformations. These commercial designs have a lot of work behind them and are often sophisticated systems that help to reproduce the functionality of the human hand in a very faithful way. However, the problem with these designs is the high price tag. Many of these prototypes are designed on a highly customised basis, i.e., if a person who has had a limb amputated needs a prosthesis, it should not be too different in size from the remaining healthy hand. Because of this and the quality of the materials used, the prices increase and not everyone can afford them, no matter how much they are needed. To put you in the picture, there are myoelectric models available for commercial use from $25,000 to $75,000, figures far out of line with what the vast majority of people can afford. Furthermore, these designs tend to be heavy due to the complexity of the mechanisms they contain and the large number of components that make them up.

These two problems mentioned above mean that some of these prostheses are not effective solutions, either because of their price or their weight, which ends up reducing the prosthesis to an aesthetic rather than functional use.

It must be pointed out that commercial prototypes are not only meant to be used in humans as prostheses but can also be used and commercialized in order to apply them in the industry or robotic field, as mentioned above.

Some examples of commercial prototypes are shown below:

- i-Limb with 6 DOF and 5 actuators [18] is shown in Figure 11.

Figure 11 i-Limb quantum hand prosthesis [18]

- Bebionic, EQD hand, developed by RSL Steeper, with 11 DOFs and 5 actuators [19], shown in Figure 12.

Figure 12 Bebionic EQD hand model [19]

- The EH1 Milano Hand, a programmable anthropomorphic human-sized hand. This prototype uses force and position sensors and modular actuation units which are placed inside the fingers [20]. It contains 16 DOFs with 6 actuators.

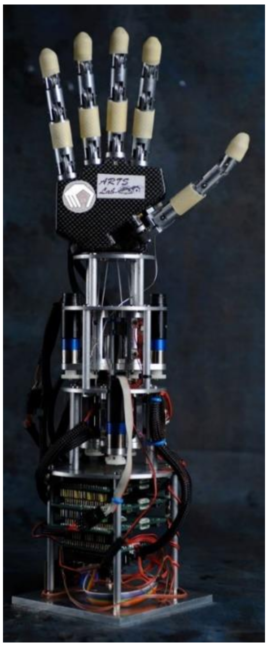


Figure 13 EH1 Milano Hand [20]

- The Elu2-Hand, a human-scale robot hand with 9 DOFs that are servo actuated. This model can be fitted onto different robot arms [21].

Figure 14 Elu-2 hand [21]

4.5.2. Research prototypes

There are also sophisticated and not so sophisticated designs that are studied and tried in order to look for improvements in this field. These models are mentioned here as research protoypes. This is because the main objective is not to sell and commercialize them, but to look further in the different techniques involved in the biomechanics and ergonomics field and the different underactuation systems, hand and finger morphology and configurations, hand assessment protocols or control interfaces.

Below some research protoypes can be seen. These designs have different morphologies, different finger configurations and different actuation mechanisms:

- The SSSA-MyHand: This is a lightweight prosthesis with 10 DOFs and 3 actuators [22]. It works with 3 electrical motors. This design is shown in Figure 15.

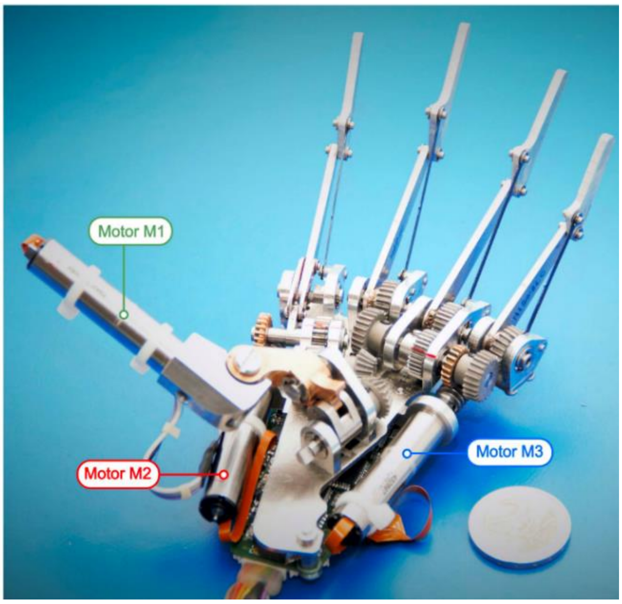


Figure 15 Actuation mechanism based on motors, worm gears and gear transmissions [22]

- The dual actuated mini X-hand [23] with 2 actuators and 6 DOFs can be seen in Figure 16.

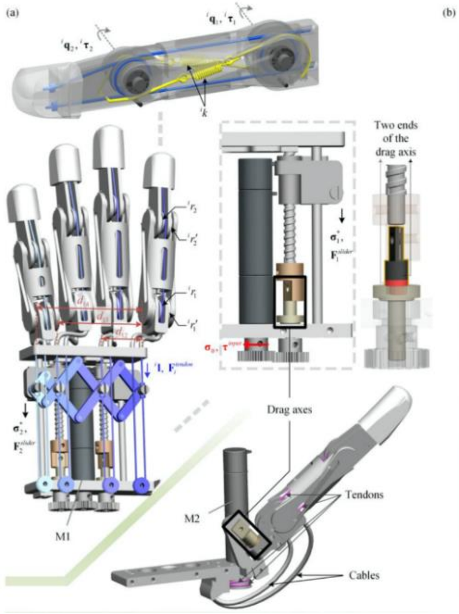


Figure 16 Gears and leadscrew mechanism [23]

- Design with soft pneumatic actuators [24] is shown in Figure 17.

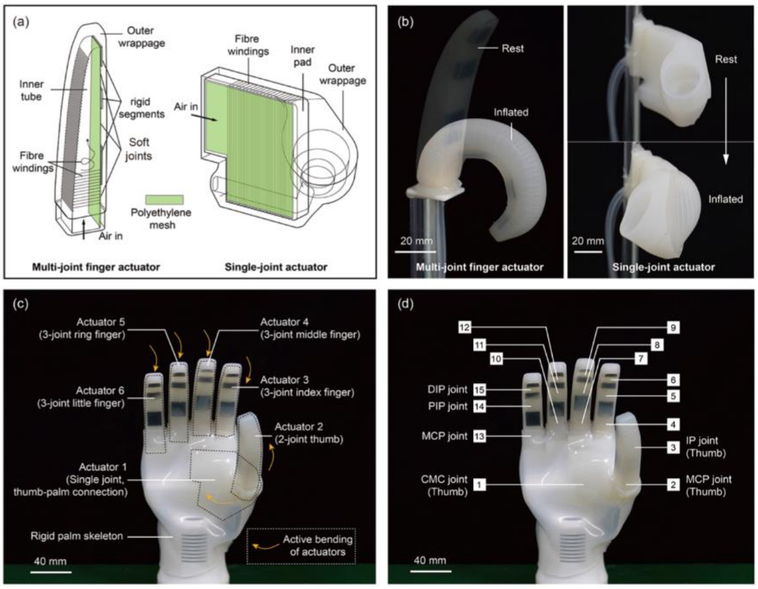


Figure 17 Soft actuators system [24]

The above designs have in common that they are all electrically or pneumatically underactuated. However, the most interesting for the development of this project are those that allow manual action, for example with the use of a single cable that pulls the designed system, allowing the flexion of the phalanges of the fingers.

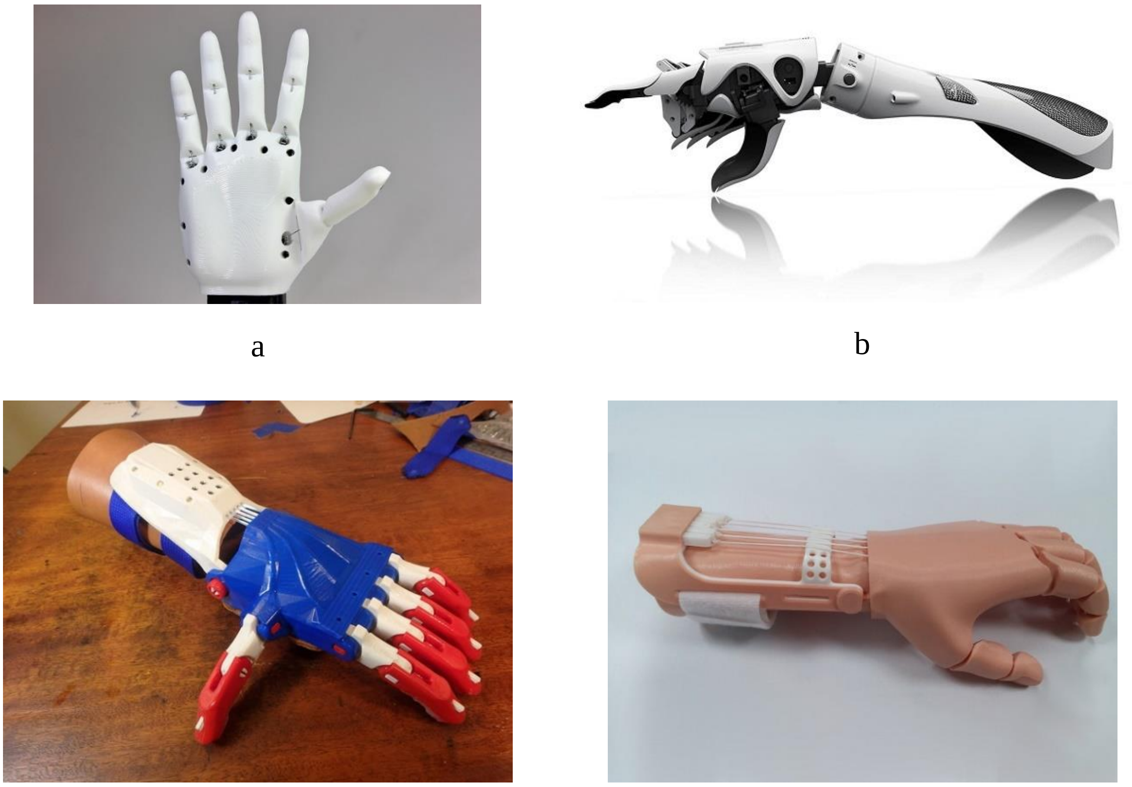
4.5.3. Low budget prototypes

Low budget prototypes are very important in this investigation because of the possibilities that these designs provide to people with reduced earning power or in difficult economical situations. The cost of these hand prostheses is usually low, or at least lower than their commercial competitors. This is due to the materials that are used to build them, and the different mechanisms that are housed inside.

These mechanisms are usually designed and printed in plastic material or similar, making the weight lower. The systems are usually simpler too, thus reducing the number and the kind of components used. Usually, commercial designs contain complex systems with gears, leadscrews or motors, which originate more complex systems. These two factors are the ones that achieve the objective of lowering the price.

Here are some examples of existent low budget prototypes:

- The Ada hand, a prosthesis from Openbionics with 5 DOFs and 5 actuators [21]. Figure 18 (a).
- The HackBerry hand from Exiii with 5 DOFs and 3 DOAs [25]. Figure 18 (b).
- The Osprey Hand by Alderhand and e-Nable, a wrist-powered mechanical prosthesis with 5 DOFs and only 1 actuator [26]. Figure 18 (c).
- The Flexy-Hand 2 by GyRobot with 5 DOFs and 1 actuator [27]. Figure 18 (d).



a b

c d

Figure 18 Different low budget prototypes

4.5.4. Biomechanics and Ergonomics group prototypes

Following the low-budget designs, the BE-UJI research group, group in which this project is made, has also developed some designs. For example, the IMMA Hand, actuated by tendons and with 6 DOFs (flexion of each finger and AB/AD of the thumb) [2], which is shown in Figure 19.

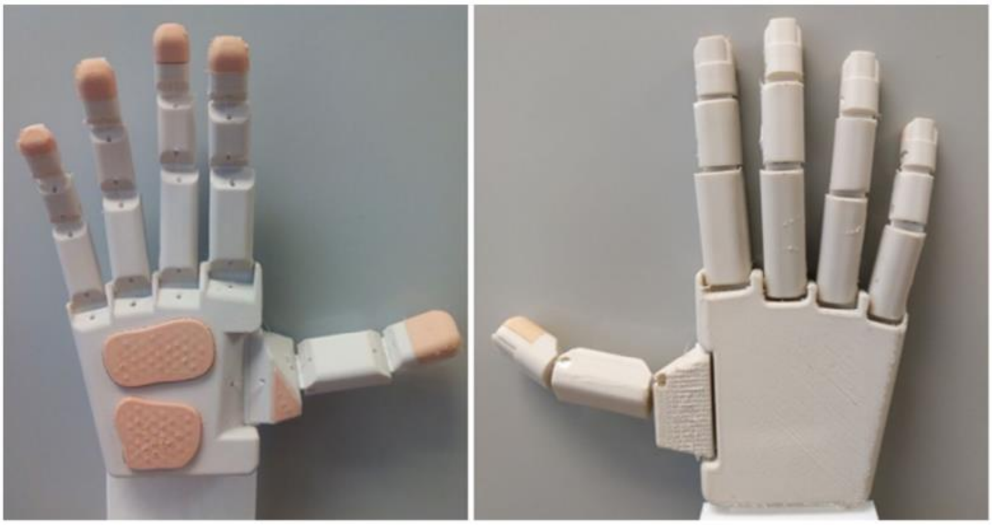


Figure 19 IMMA hand printed prototype [2]

Figure 20 shows the above mentioned IMMA Hand attached to another device developed in this group, the testing platform PACMAR developed in the BENCH-HAND project [28].

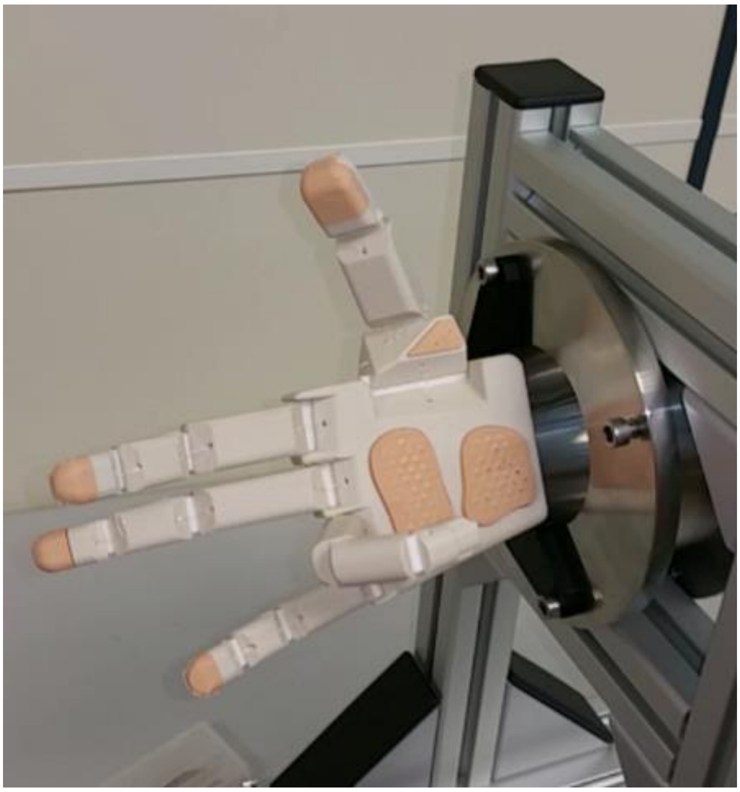


Figure 20 IMMA hand prototype attached to the testing rig developed in the BENCH-HAND project [28]

Another project carried out in the research group is the BruJa Hand developed in the DEVALHAND [29] project framework, which involved the development of three different models of the same prototype [30]:

- Model-B: Motion transmitted through linkages
- Model-T: The hand is actuated by tendons using the passing points in order to match the joints between the linkages and phalanges in the model mentioned above. This design uses elastic cords in order to guarantee the extension of the fingers.
- Model-BT: A mix of the 2 mentioned models, thus moving the linkages from model-B thanks to the pulleys from model-T.

Figure 21 shows the BruJa Hand’s model.

Figure 21 BruJa Hand's model [30]

4.6. Actuation system

4.6.1. Underactuation

In recent years, prosthetic components have been studied in order to develop new and better mechanisms which allow these prostheses to replicate the maximum number of grasps and actions from a human hand.

Anthropomorphic artificial hands can be designed as fully actuated hands and underactuated hands. Since the kinematic chain of the human hand exhibits from 23 to 25 DOFs, as mentioned in previous sections, fully actuated artificial hands need a large number of actuators. These actuators can be placed either inside the hand or on the forearm, allowing the flexion of each of the fingers as well as the AB/AD motion of the thumb (AB/AD of the long fingers is usually neglected) [5]. This kind of actuation allows a great range of possibilities regarding grasps and hand control. However, fully actuated hands have a complex control interface and a higher weight than underactuated ones, for example the Shadow Dexterous Hand [31] (shown in Figure 22) contains 20 motors, making it more complete but with a complex configuration.

Figure 22 Shadow Dexterous Hand [31]

Underactuated prototypes save space and weight, and thus money, due to the reduction of components, related with the basic principles of underactuation which are reaching the highest possible number of DOFs with fewer number of actuators. For example, instead of using six motors to actuate the flexion of the five fingers and the abduction/adduction of the thumb, there are prototypes that actuate the flexion of the fingers with one single motor and the abduction/adduction with another one or even with a manual mechanism. It must be pointed out that, for underactuated hands, DOFs are not defined as they are in the Grübler formula [32]. Instead, these DOFs represent the configuration variables [33], that is to say the number of independent parameters that allow to characterize all the possible motions of the mechanism.

Underactuation systems allow the flexion of the fingers, but not every grasp requires the same finger configuration, that is to say, when grasping an object with conic form for example, not all the fingers in the human hand flex in the same way, some of them do flex more than the others.

The even distribution of the force is related with the grasps in a way that each object has a different shape, including regular and irregular objects. This produces that some fingers contact the object´s surface before than others, blocking by this its flexion movement. If every finger was actuated by only one tendon without differential underactuation systems the blocking of one of the fingers would lead to the blocking of every finger, thus causing the grasp to be inefficient, with force only applied on points where the fingers contact the object or even producing an incomplete grasp which could make the object fall or not able to be manipulated.

For example, as Figure 23 shows, when grasping an ice cream cone, the index finger flexes less than the middle, ring and little fingers.

Figure 23 Prosthetic hand grasping an ice cream cone [34]

Differential mechanisms are studied in order to develop underactuated systems, and research is made to improve these designs. these underactuation mechanisms, allow to adapt and to distribute the applied force to more than one finger for different finger positions. The different systems are designed in order to evenly distribute forces on each side of the mechanism, allowing it to rotate and keep applying force if one of the moment arms is blocked. This is explained by the different grasping types that a human and prosthetic hand can perform. These different grasps are based on the different examples used in the AHAP [3] as mentioned in previous sections.

There are different types of mechanisms that allow differential underactuation which are based on the principles shown in Figure 24:

- Pulleys and tendon system (Figure 24 a)
- Whiffletree mechanisms shown in Figure 24 b
- Gear differentials, shown in Figure 24 c.

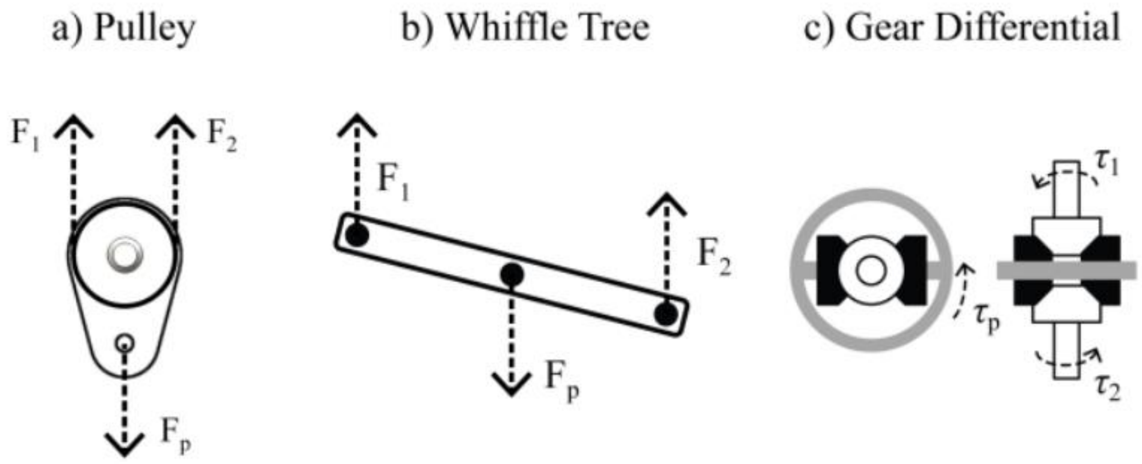
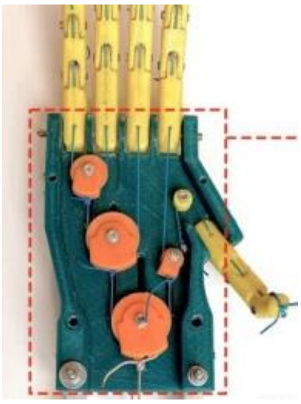


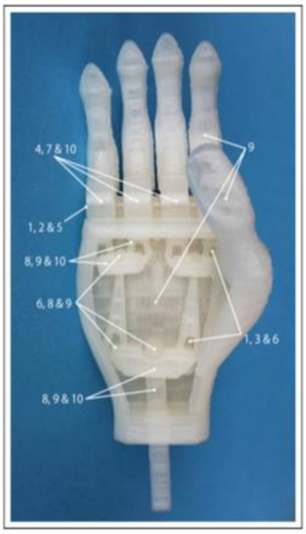
Figure 24 Differential underactuation systems [35]

Figure 25 shows different differential underactuation mechanisms applied to real printed prostheses:

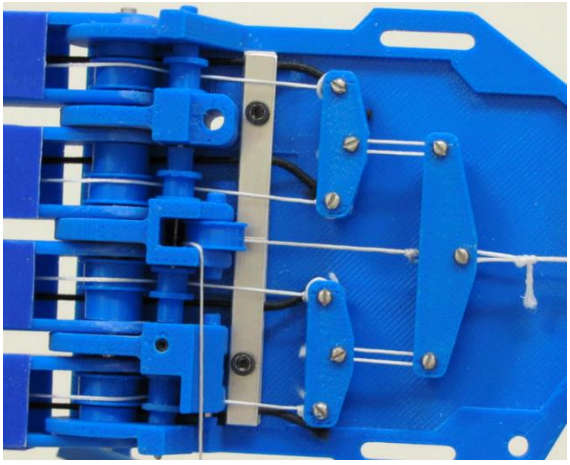
- Figure 25 (a) shows a pulleys system made out of 3D printed material. [36]
- Figure 25 (b) shows a whiffletree mechanism made out with linkages and with no need of assembly after printing the prototype [37].
- Figure 25 (c) shows a whiffletree mechanism working with tendons and pivots. [38]



(a) Esposito pulleys system [36]



(b) Whiffletree mechanisms with linkages [37]



(c) Whiffletree mechanism with cords [38]

Figure 25 Different underactuation mechanisms

In the literature there are other designs based on the functioning of the above-mentioned mechanisms, combining them together in order to reach an optimal solution. Usually, the combination of the whiffletree mechanism and the pulley system is used, as seen in Figure 26, allowing the advantages of both to be obtained, for example the distribution of forces of the whiffletree and the reduction of friction that the use of the pulleys entails. There are also mechanisms as the modular system shown in Figure 27 that combine sliders, pulleys and pivots to create the same principle.

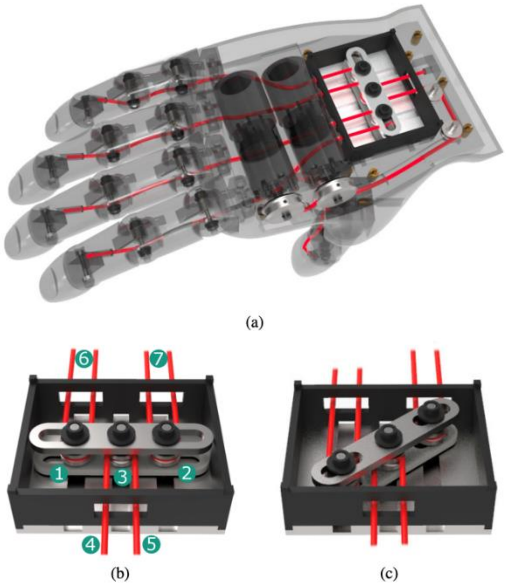


Figure 26 Pulleys and slider mechanism [39]

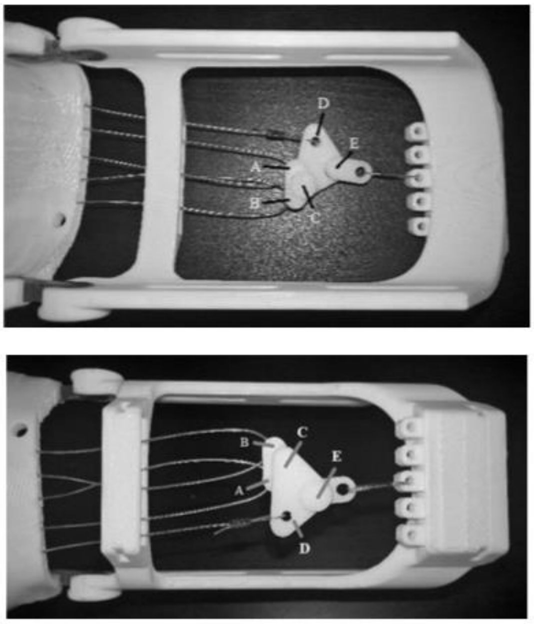


Figure 27 Modular System [40]

Mechanical underactuation systems have also improved recently, allowing better performance in grasping by the implementation of postural synergies and the division of the actuation configuration in different modules, everything self-contained inside the hand [41]. Figure 28 shows a sophisticated gear underactuation system.

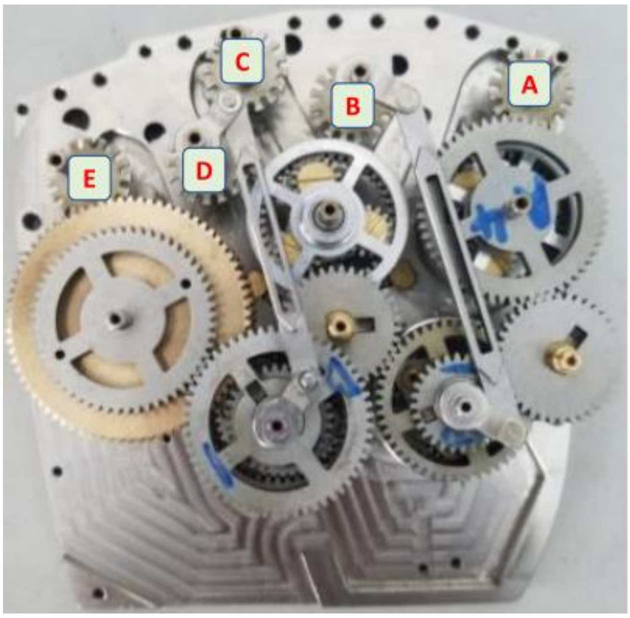


Figure 28 Example of a more complex mechanically actuated system [41]

There are also manual mechanisms which have more than one actuator, actuation rings in this case, but these ones require the use one of the hands, if healthy, on amputees and that may reduce the comfort of using the prosthesis. This mechanism design was used with the above mentioned IMMA Hand [2] and can be seen in Figure 29.

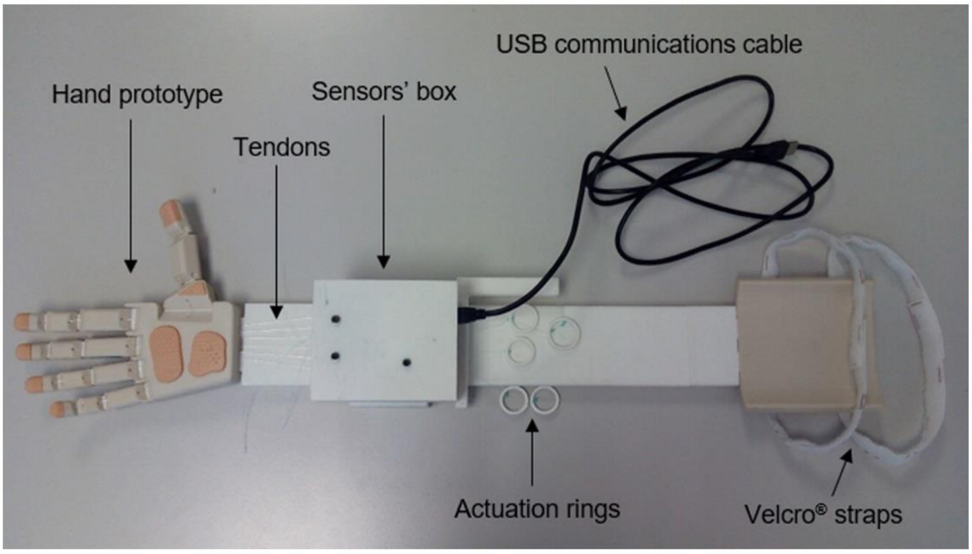


Figure 29 Manual actuation device with the IMMA hand prototype attached [2]

4.6.1.1. Finger underactuation

Underactuation is a term that not only refers to the whole hand, but each of the fingers that form it. Every finger can be underactuated itself, this is by the actuation of the DOFs of the different joints that form them by using only one cable as a tendon.

The underactuation of each finger in this specific case is based on using only one cable at each finger in order to produce the flexion of the proximal and distal phalanxes that conform them.

The main objective in finger underactuation, referring to the DOFs related with the MCP, PIP, IP and DIP joints of each finger, is the same as in general underactuation terms, reaching a configuration with fewer actuators than DOFs. Another important objective is to reach an isotropic force distribution, which means that the force is evenly distributed between the finger phalanges with independence of their configuration, allowing no deformation on the grasped object due to differences between forces applied in the contact points [32]. This underactuation can be achieved by mechanisms such as pulleys with pulling tendons altogether with springs to grant the return of the phalanx to its resting position, among others, as shown in Figure 30.

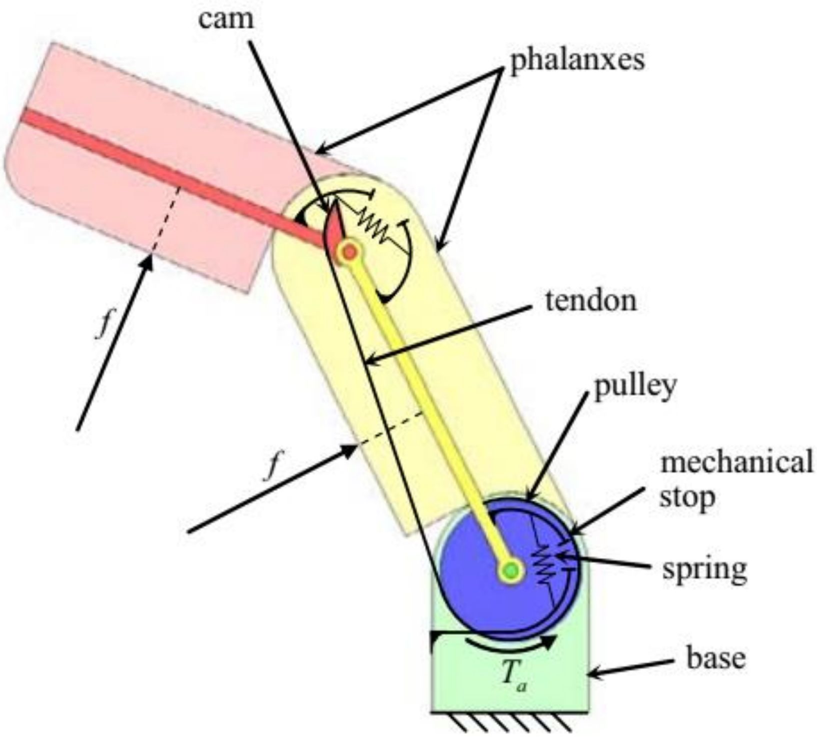


Figure 30 Underactuated isotropic finger scheme [32]

4.6.1.2. Hand underactuation

When talking about hand underactuation, we refer to achieving more DOFs with less actuators, as stated before in the underactuation general point. This means using one mechanic or electric actuator (motor, pulling system) to acquire the movement of more than one finger. This can be achieved by using different mechanical systems such as tendons [42]. Figure 31 shows an example of motor-activated tendon actuation with 4 degrees-of-actuation (DOAs).

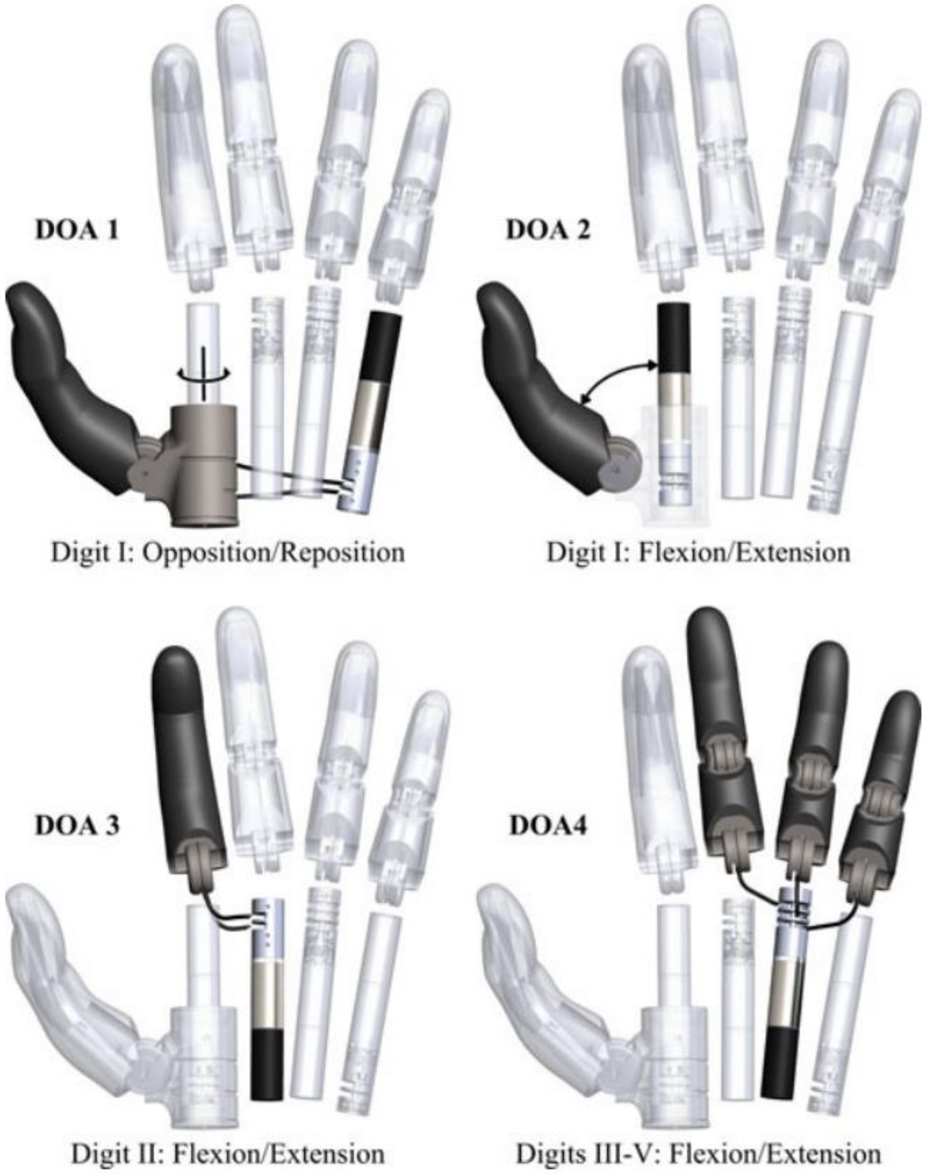


Figure 31 Underactuated hand with 4 DOAs [42]

Prosthetic hands mechanisms are designed in order to develop multiple grasps, as seen in previous chapters, that allow the hand to shape around different objects [39].

It is important to mention that mechanisms which consists of linkages are not really underactuated. This is because the degree of freedom that the mechanism contains is 1, so if the actuator is only 1 there is no underactuation, that is to say that the DOF match the DOA number. An example of these articulated linkages mechanisms is shown below. Figure 32 shows the model of the finger while being designed in the SolidWorks software and Figure 33 shows the 3D model of the whole hand assembly.

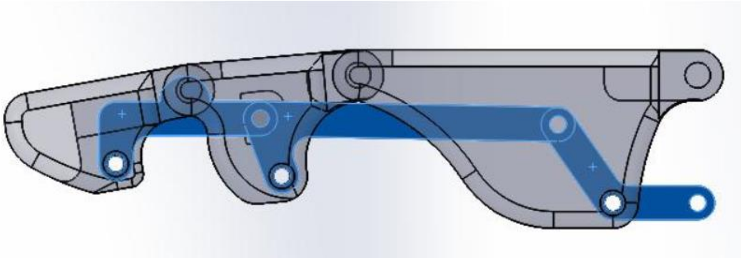


Figure 32 BruJa Hand finger SolidWorks model

Figure 33 BruJa hand 3D model

Underactuated fingers are meant to close until contact with an object is made. This raises one of the main problems of mechanical prostheses, which is adaptive grasping. Grasps are meant to be adaptive in a way that the force, as mentioned above, is evenly distributed among the fingers and their phalanges, thus causing no deformation on the grasped object.

5. Methodology

The methodology used in the framework of the UNIQUE-HAND project is the usual methodology for the design cycle. This means researching information, designing the different components which are going to be used in the prosthesis, electrical sensors, calculations, materials, printing and testing of the design.

In this paper the following methodology is based on the research and design of the prosthetic hand and underactuation system components.

5.1. Design

The design in this kind of project is very important. 3D design software is going to be used in order to design the different components. The design process started by scanning a real human male hand, then converting that scan into a 3D model, obtaining different parts and components in the SolidWorks software. These parts and components needed to be adapted and modified in order to reach an optimal size and, also, to solve some disadvantages of prostheses compared to the human hand. These disadvantages are for example the complexity of the hand mechanism and the arrangement of the fingers.

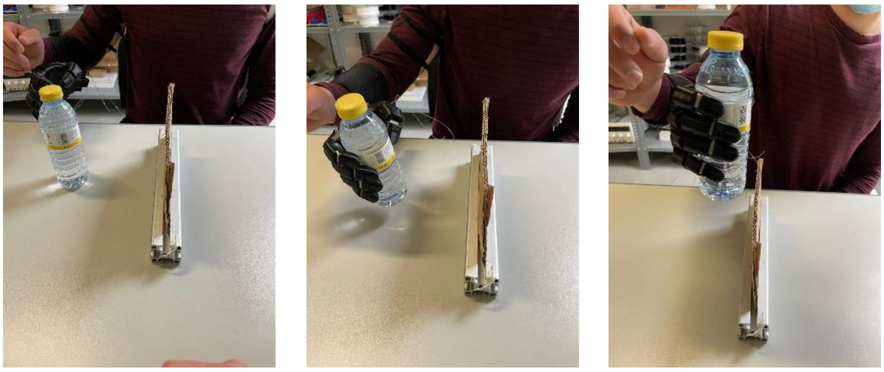
The design of the underactuation system is also included in this point, where a mechanism which could actuate the fingers with differential application of forces was needed to be located inside of the palm of the final model of the artificial hand.

In order to guarantee the functionality and performance of the prosthesis, some simulations for finite element analysis are needed. SolidWorks contains this feature and allows the research and design process to be easier.

5.2. Essays

In order to test the design and be able to have some benchmarks or results which allow the group to compare the final design, some tests and essays are meant to be carried on with the hand. These tests are mainly 2:

- The AHAP, which is mentioned previously in this document and allows to test the grasping ability of several objects selected from the YCB test.
- The Water Bottle Test (WBT). An essay created in this research group, based on the Blocks and Boxes test [43], which consists of moving as many bottles as possible in 60 seconds. The 33 cl bottles are filled with water, weighing 340 g on average. They have to be moved from one side of the table to the other, over an intermediate obstacle 14.5 cm high, 13 cm from the bottle. Figure 34 shows the succession of movements occurred during the WBT experiment and the motion that must be carried on.



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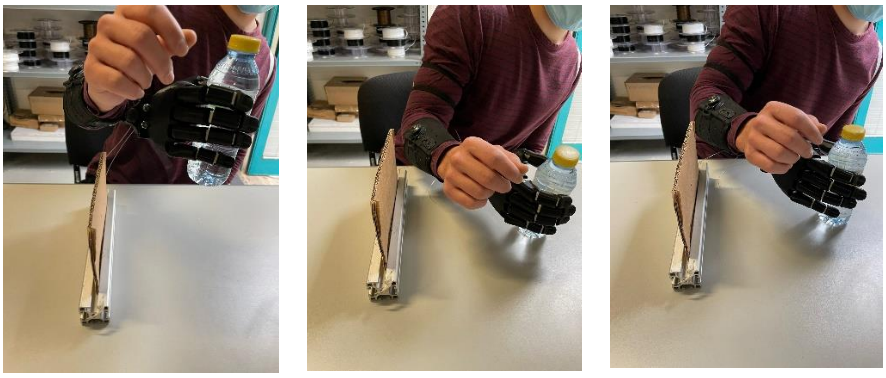


4 5 6

Figure 34 WBT experiment [44]

6. Tools used

The following tools have been used to carry out the tasks of design, file organisation, prototype manufacturing and prototype testing.

- SolidWorks
- SolidWorks PDM
- Google Drive
- 3D printing machine
- Pro Cuff system
- Harness

6.1. SolidWorks

SolidWorks is a 3D CAD software which allows to create parts, assemblies and 2D drawing in a simple and intuitive way. Some of the features that this software allows are:

- Designing parts and assemblies in an easy and efficient way.
- 2D drawings which allow to give information about manufacturing and assembly to production employees.
- Quick analysis of the physical properties of the parts, allowing to know important characteristics such as weight, center of mass or volume of any design made.
- Interference analysis, allowing to study the correct assembly of the various components before their manufacture.
- Design analysis, which allows to calculate the resistance, strength, deformation and performance of the different parts.
- Creation of plastic parts through 3D printing techniques.

6.2. SolidWorks PDM

SolidWorks PDM is an application which can be installed when installing SolidWorks. This application allows the sharing and storage of documents and file management in a common way between the different participants of the research group. By using PDM the different participants of the group can see and work with the different files that each one uploads. This allows to work as a team and help the design in a common way among everyone.

6.3. Google Drive

Google Drive is an online service which offers files storage. Google Drive has been used to share and send files, for example the ones that needed to be printed in 3D.

6.4. 3D Printing Machine

The 3D printer which is going to be used to manufacture the different parts of the prototype is the CoLiDo X3045 [45]. The designed files are converted into CoLiDo commands through the Repetier-Host software and are then transferred to the printer using an SD card or an USB cable. The procedure begins with the tip of the printer heating up, fusing the material (PLA/ABS) and extruding to create the final object. This is the FDM process.

The mentioned machine is showed below in Figure 35.

Figure 35 CoLido X3045 printing machine [45]

6.5. Pro Cuff System

The Pro Cuff is an available online product that allows people with diverse kinds of amputation get a prothesis attached to their body. Pro Cuff is useable in water and can be adapted to different forearm sizes. The material it is made from (low temperature thermo-formable laminate) allows the easy adaptation and customization to each person's forearm, being this possible by heating and re-fitting this component as many times as needed [46].

Figure 36 Pro Cuff system [46]

7. Concept design

Before starting with the conceptual design, a series of characteristics that you want the prosthesis to have must be established. Below is a list of different functions that the prototype is intended to fulfil.

- Simple underactuation mechanism.
- Reaching the largest possible number of DOFs with one actuator.
- Differential mechanism to allow the correct grasping of objects.
- Designing a prototype with the most anthropomorphic possible appearance.
- Similar to the human hand in size.
- Same number of fingers as the human hand.
- Low manufacturing cost.
- Easy assembly
- User-friendly prototype, easy to learn and easy to use.
- Adding an abduction/adduction manual system to increase the number of capable grasps.
- Have a smooth running, with low friction, making it easy to use and reducing the force required to be applied by the user.

In order to try to fulfil every function listed just above, several solutions were proposed and studied, trying to find the best of them and the ones that best adapt to the needs of the design. Below in Table 1 different options for the listed characteristics are shown. The ones highlighted in green colour are the final selected solutions for that characteristic. These characteristics are closely related to the fulfilment of the above-mentioned functions.

#	Characteristic	Possible solutions			
1	Prototype material	PLA	ABS	FilaFlex	Aluminium
2	Finger design	Anthropomorphic	Simplified		
3	Finger phalanges	2	3		
4	Thumb phalanges	2	3		
5	Finger joints	Flexible joints	Metallic pin	Bolt	
6	Mechanism stiffness	Extra plastic plate	Aluminium plate		
7	Underactuation system	Concentric pulleys	Guide with fixed cables	Pulleys, guides and slots	Rings system
8	Guidance for the underactuation	Slots	None		
9	Extension mechanism	Tension springs	Rubber bands	Constant load springs	Torsion springs
10	Abduction mechanism	No abduction	Indexing Plunger	Ball plunger	Cam
11	Tendon material	*			
12	Tendon attachment	Visible knot	Hidden knot	Ball	
13	Actuation device	Bowden cable	Rope cable		
14	Actuation device guiding	Triceps cuff	No guiding		
15	Actuation device attachment to user	Harness			
16	Actuation device attachment to mechanism	Pulling support part			

*The different cable material options are stated in Table 3 below in its specific section inside the concept design point.

Table 1 Concept design

7.1. Prototype material

As mentioned in previous sections, the objective is to achieve an affordable design. Therefore, the material cost is very important to obtain a cost reduction. In addition, this technique allows to easily modify the design and print again some parts, if necessary, without exceeding the budget. In order to make this possible the selected method of manufacturing was 3D printing, thus being the commercially available filaments used in FDM technique the only possible materials.

Most of the already existent designs are printed in these materials which include polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS), which is a resin, among others.

One of the most relevant factors when deciding a material is the quality of the properties that it has. Other factors that are relevant are for example deciding if all the parts are going to be manufactured with the same material or not and the assembly of the components once they are printed.

PLA is a low cost material which is easy to print using the FDM technique and, in addition, it is biologically compatible. The resistance of this material is similar to other compared materials such as ABS resin, but a little lower. After weighing up the advantages and disadvantages of the various options available, it was decided to print all the components in a single material, in this case PLA. Although there are some additional components which will be manufactured in aluminium or FilaFlex to provide resistance or flexibility.

7.2. Finger design

Finger design is very important when talking about artificial hands and prostheses. Even though the aim of designing a prosthesis is to achieve its functionality, the aesthetics of the design is also important to allow the user, if finally commercialized, to get familiar with it and allow him/her to be comfortable because the design goes unnoticed.

The decision was to make the hand and fingers as anthropomorphic as possible to meet all the stated needs above. Obviously, being a 3D printed design doesn't allow to mimic a perfectly human like hand, but the results are very near.

7.3. Finger phalanges

Although anthropomorphic design is key, the functionality and simplicity are important too. This is why the decision in this point was to design the fingers with only 2 phalanges, thus simplifying the design and assembly and reducing the number of components used in the interphalangeal joints.

7.4. Thumb phalanges

As stated above, the design was finally decided to count with only 2 phalanges in the thumb too.

7.5. Finger joints

Finger joints is an important point of the design because these joints have 2 key functions. One of these functions is to bear the loads that tendons apply to flex the finger phalanges when grasping an object and they can also be helpful with a smooth rotation of the phalanges if the selected solution reduces the friction produced between these components.

Flexible joints were neglected from the design because there were thoughts of an extension system using springs and because, thanks to experience with prior hand designs, the durability of the flexible joints was not good due to the fatigue that the components are subjected to. Other option was to use bolts, which have an easy fixation method by using nuts, but the notches on these components increased the friction between them, as well as deteriorating the material used for 3D printing. This led to the metallic pin solution, which has a good friction coefficient and does not deteriorate the plastic material.

7.6. Structural stiffness

When using plastic material, guaranteeing a good stiffness is important in order to keep the components and the mechanisms working correctly. This is why an extra amount of stiffness was decided to be added to the design. The solution was to add an extra plate inside the palm of the hand, the question was whether it was going to be made out of plastic or a metallic material. The plastic plate solution needed more space in order to provide a high stiffness so, eventually, the decision was to add an aluminium plate, which provides the needed stiffness but with a reduced thickness in comparison to plastic.

7.7. Underactuation system

The underactuation system is one of the most important parts of this work, since everything related to the rest of components revolves around it.

The design of the underactuation mechanism started with a long searching for information and research. As mentioned above in the background section, there are different underactuation systems that allow the flexing of the fingers of the hand. The ones that best suit the needs of this project are the differential mechanisms, which, as mentioned above, allow the flexion of the fingers to continue despite the fact that some of them have already contacted the surface an object. There are three main types of differential mechanisms which were already shown previously in Figure 24.

From these mechanisms, the gear differential mechanisms are rejected because, even though these offer compactness, thus reducing the size, they are more complex and have a lot of friction [35]. They can support greater loads, but 3D printing gears is not easy due to the required level of detail, leading this to a non-efficient solution.

During the design process, several possible configurations were considered as a solution. First, the initial idea was to create a system based on the use of concentric pulleys, however, this solution was not adequate since it was not possible to obtain a differential mechanism that would work like those mentioned above, and therefore the problem of flexing the fingers at the same time was not solved. This first idea is shown below in Figure 37.

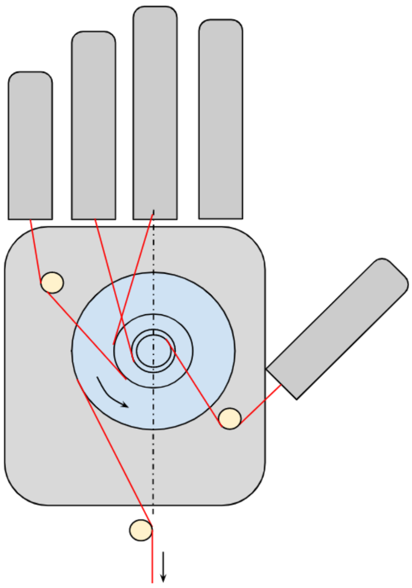


Figure 37 Concentric pulleys system

After discarding this solution, a design based on rings and cables was proposed in which the rings served as a differential mechanism, allowing the cables to rotate through them if one of the fingers got blocked. This system had the advantage of taking up less space, making it easier to incorporate into the palm of the hand. However, the guiding capacity for this system was not optimal, and steeper angles appeared in the cables, which increased the friction of the mechanism and, therefore, the force required for actuation. This mentioned system is shown in Figure 38.

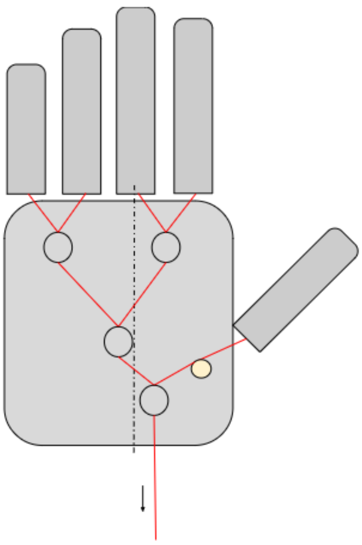


Figure 38 Rings and cables idea

In prior designs, also in this research group, a configuration was designed, manufactured and tested by the author of this project. This design was based on 3 main parts conforming the mechanism and another extra part which allowed the user to connect the mechanism to the desired hand prosthesis. These parts were: a plate were the five different cables (one for each finger of the prosthesis) were housed (Figure 39), a cover for that plate which allowed the cables to be fixed avoiding sliding (Figure 40) and finally a slotted guide where the plate was placed (Figure 41), allowing the mechanism to pull the cables and produce the flexion of the fingers. This mechanism was actuated by a harness located at the back of the subject and connected to the green part below (Figure 39) using a Bowden cable.

The complete assembly including the harness and the Bowden cable is shown in Figure 43.

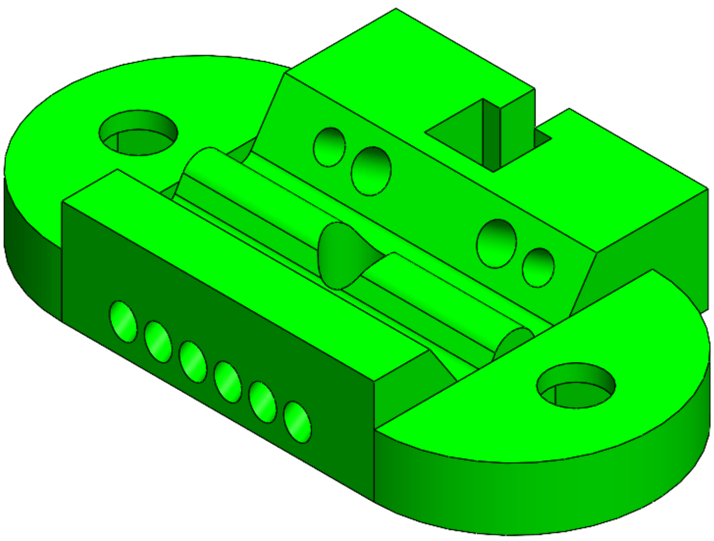


Figure 39 Plate

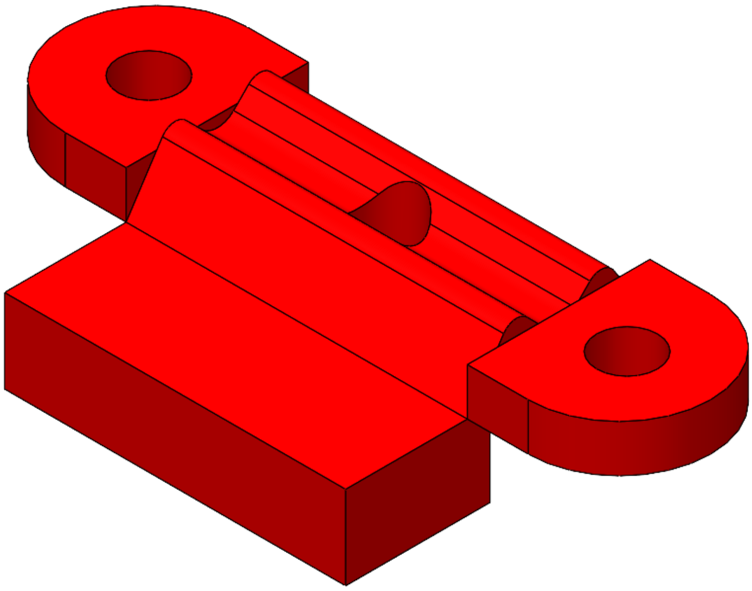


Figure 40 Plate cover

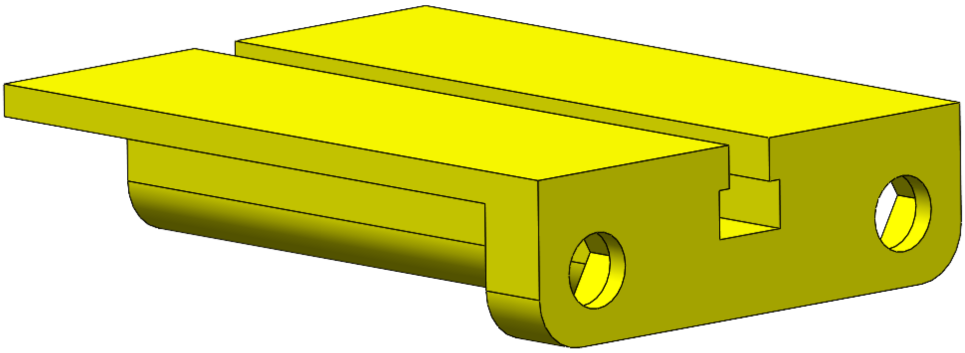


Figure 41 Guide

Figure 42 shows a picture of the whole assembly of the prior underactuation system design.

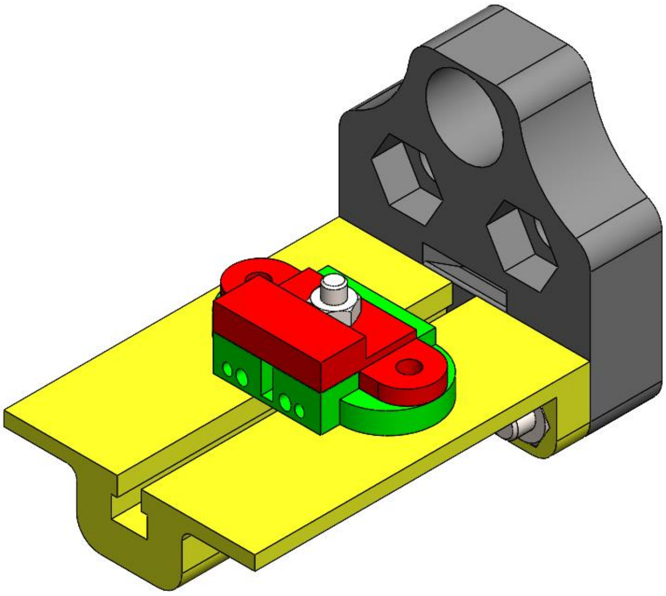


Figure 42 Prior system assembly

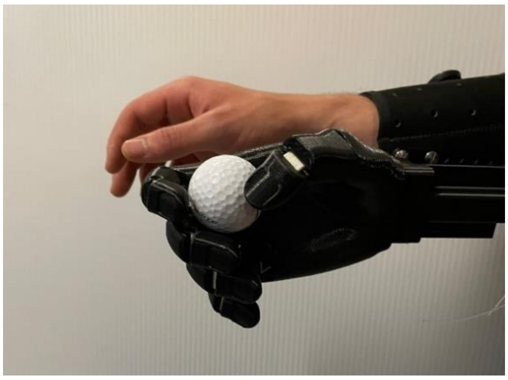
Figure 43 shows an example of the assembly of a prosthesis with the harness.

Figure 43 Prosthesis and harness assembly

In order to evaluate the viability of this design, the system was tested by an able-bodied subject using a harness and the Pro Cuff adaptor, with the Flexy-Hand [47] attached. Some grasps with different objects from YCB set, included in the AHAP [3] were made. A new test was also developed, the Water Bottle Test (WBT), inspired by the Box and Block test [43].

The results obtained showed a nice performance, but there were some grasps that couldn’t be assessed due to the impossibility of the prototype to carry them on.

Table 2 shows different examples of performed grasps with objects from the YCB set:

Tripod pinch	
Spherical grip	
Cylindrical grip	

Cylindrical grip	
Hook grip	

Table 2 Performed grasps in prior designs

Eventually, and after researching the existing systems in the literature, the final solution for the design of the underactuation mechanism was to create a mechanism based on sliders, pulleys, bolts and cables. This system, which will be explained in further detail in the next section, has 2 sliders with slots in them. Between the 2 sliders there are 2 pulleys, each one placed under the location of one of the slots and bolts are used to assembly the mechanism and as a guiding element. Figure 44 shows a simplified image of the final solution selected for the underactuation mechanism.

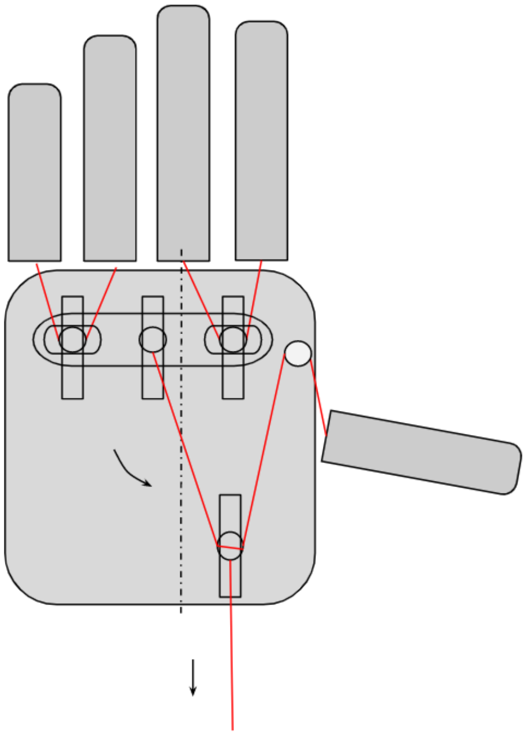


Figure 44 Final underactuation mechanism solution

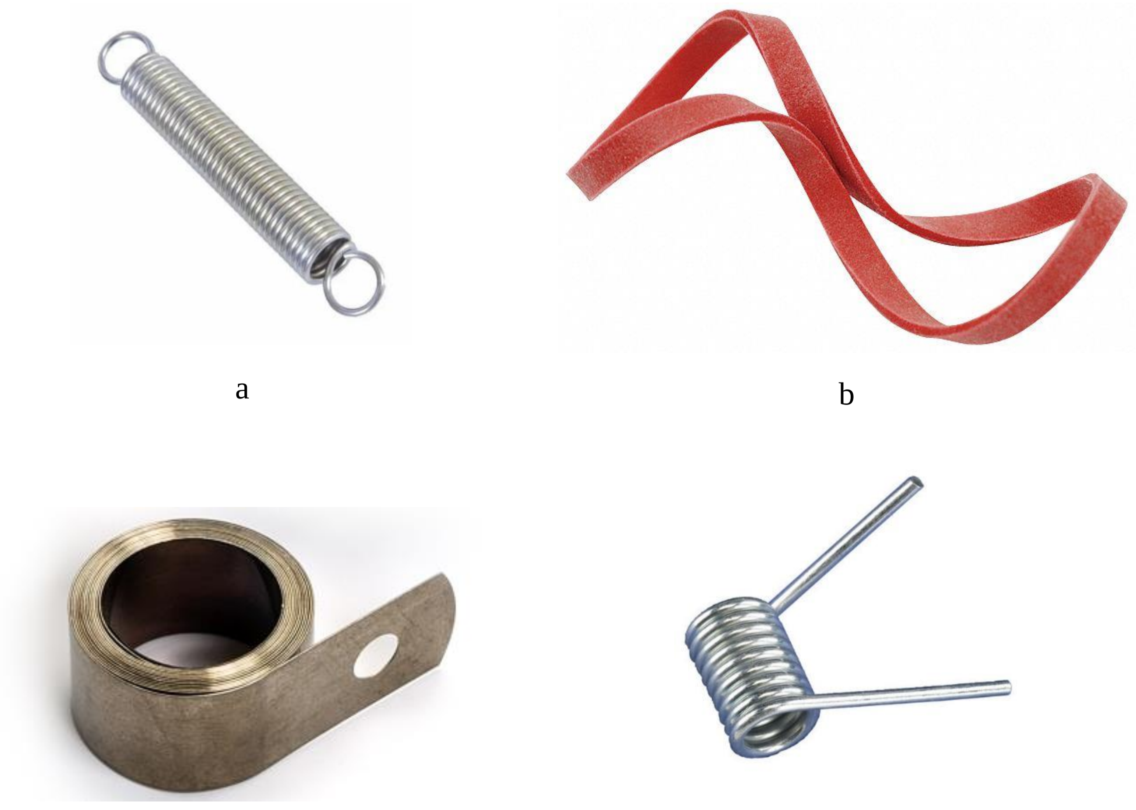
7.8. Guidance for the underactuation

In order to guide the bolts that are used in the underactuation mechanism as a support for pulleys and to assembly the different components, the decided solution was to add 2 PLA plates that will be screwed to the aluminium plate mentioned above. Each of these plates will have 4 slots to house the bolts, the lower plate bolts will be wider than the top plate in order to house the head of the bolt and the top plate is used as a stopper to avoid the bolts falling if the hand is turned upside down.

7.9. Extension mechanism

The decision on the extension mechanism was between the use of tension springs, torsion springs, constant load springs and rubber bands. The load distribution during the flexion process of the finger in tension and torsion springs and rubber bands did not fit the design idea, as the tension increases as the finger flexes, increasing the force needed to continue the movement of the phalanges. Therefore, the final decision regarding the extension system was to select constant load springs, but for the thumb, due to problems with the space and configuration of the design, a rubber band will be used. These components provide the force required for extension, but the force does not increase as the finger flexes, thus allowing a lower level of force to be applied, which is important as this is a manually operated prosthesis.

The different possible solutions for the extension mechanism are shown below in Figure 45.



a b

c d

Figure 45 Extension mechanism options

7.10. Abduction mechanism

The best idea in order to design the abduction mechanism for the thumb was to use a mini indexing plunger, which is commercially available, and add it to the assembly of the prototype. This indexing plunger allows the user to switch between 2 different positions of the thumb. These possible configurations provide the prototype the ability to perform a greater number of grasps.

Below in Figure 46, there are an example of a possible solution, which is a ball plunger and the final decision, Figure 47,which is a mini indexing plunger.

Figure 46 Ball plunger

Figure 47 Spring mini indexing plunger [48]

7.11. Tendon material

The tendon material must be resistant enough in order to allow the fingers to apply the necessary force for each application without tearing up. Furthermore, the cable must have the right rigidity, which means having enough to allow to recover the extension position at the beginning of the movement, but not an excess which would produce friction and thus power losses.

In order to select the most suitable material for the tendon cable, a comparison of different alternatives was made. These alternatives can be seen in Table 3 and the final selection is highlighted in green.

Name	Strength Limit	Length	Diameter	Price €/m	Picture
Cuerda de Dyneema para Cometa Tribord [49]	45 kgf	10 m	0,8 mm	0,50	
Bobina Dyneema (Blanco/Negro) [50]	110 kgf	50 m	1,5 mm	0,90	
Cuerda de Cometa de Dyneema [51]	62 kgf	2 x 30 m	-	0,22	
Cressi Sub CABO DYNEEMA [52]	195 kgf	10 m	1 mm	0,90	

Dyneema - Cuerda trenzada [53]	195 kgf	100 m	1 mm	0,41	
Trenza Pesca Siluro TX8 CF Gris 300 M [54]	38 kgf	300 m	0,5 mm	0,13	
EX1367 – Bobina cabo Vectran [55]	40 kgf	15 m	1,2 mm	0,72	

CORDON POLIAMIDA Y POLIESTER [56]	193 kgf	1 m	2.5 mm	0,18	

Table 3 Tendon Cable Comparison

7.12. Tendon attachment

The tendon attachment to the phalanges of the hand (in this case only one) was finally decided to be a hidden knot placed inside a hole created in the phalanx. The option of a visible knot was not optimal and then there was the option of adding an extra component used as a stopper, in this case a ball with a whole through it. The mechanism works in a way that the cable goes through the ball, then a knot is made so that the cable can’t go back and it is the ball part instead of the knot that applies the force to flex the finger. This alternative involved using an additional component without obtaining much advantage from it, so it was neglected.

Below in Figure 48 an image with a simplified drawing of the stopping ball system is shown, even though it is simplified, just to clarify the idea.

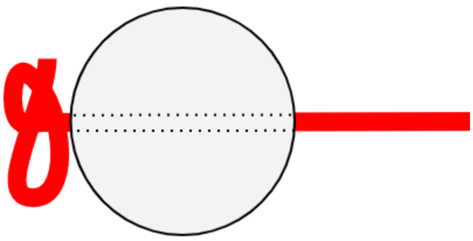


Figure 48 Stopping ball system for tendon attachment

7.13. Actuation device

The decision for the actuation device of the underactuation mechanism was to use a bowden cable, which provides better properties than other types of wire ropes, for example those discussed in one of the points above, the selection of tendon material. The compared options, despite having a good load resistance, are less viable for use as main guide wires due to their material than the bowden cable.

7.14. Actuation device guidance

In order to guide the actuation device a part which is located in the triceps was designed in FilaFlex [44] material. The part is called Triceps Cuff and will be shown in further sections.

7.15. Actuation device attachment to user

The attachment of the mentioned actuation device to the user of the prosthesis will be done thanks to a harness that has the necessary components such as rings and straps to connect the bowden cable, allowing the user to modify and adapt the size of the harness according to their needs.

7.16. Actuation device attachment to mechanism

The solution to the problem of attaching the bowden cable to the mechanism in order to pull in a balanced way, so that extra friction is not created, and the forces are evenly distributed, was to design a pulling slider which is located in the main pulling slot of the underactuation mechanism. This pulling slider allows to house the bowden cable and keep it stuck in it, so the cable doesn't fall off. This design will be explained in further detail in next section, but Figure 49 shows its 3D model.

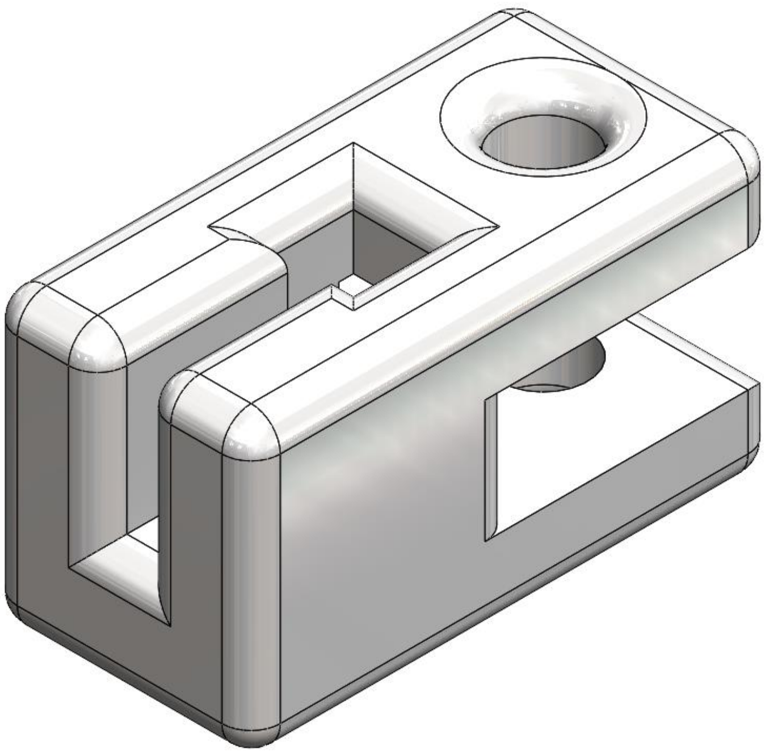


Figure 49 Pulling slider, isometric 3D model view

8. Detail design

The final design of this project began after the analysis of all the possible options to provide a solution to the different aspects previously raised in the concept design and the final choice of the option that best suited the needs.

The design process is an iterative and feedback process in which different design options are tested, seeing which are going to be more or less suitable and modifying the characteristics of those that are on the right track in order to develop them and reach the final design. This is a hard process, which takes a lot of time and dedication, as well as the ability to keep calm in ambiguous situations in which it is not easy to find the most suitable solution and continue forward with the realisation of the different pieces.

This project, as mentioned above, seeks functionality, therefore, although aesthetics is an important factor also highlighted in previous sections, during the design process there have been points where the visual and aesthetic component has been partly sacrificed in order to provide greater functionality to the prototype.

The project must be low cost and, for this reason, the FDM process has been chosen for the printing of the parts. In addition, the fact of using software such as SolidWorks allows the easy modification of the parts starting from a base model for future designs, either different versions of this one or even new projects based on this one.

To begin the design of the prototype, the 3D scan of a human hand was made, in this case the hand of the laboratory technician in which this project is being carried out. Subsequently, in order to adapt the model obtained to a design suitable for the materials and techniques used, almost all the components were modified. This is due, for example, to the fact that the orientation of the fingers of the human hand has certain degrees of inclination to each other, i.e., if the direction of the tendons is followed, a common vanishing point is reached. In the 3D design, this caused interference in the fingers when bending, so the arrangement of the fingers had to be modified and made parallel to each other to avoid complications and interference in the model.

An image of the complete assembly is shown below in Figure 50 and Figure 51. In the second figure the cables are shown in red.

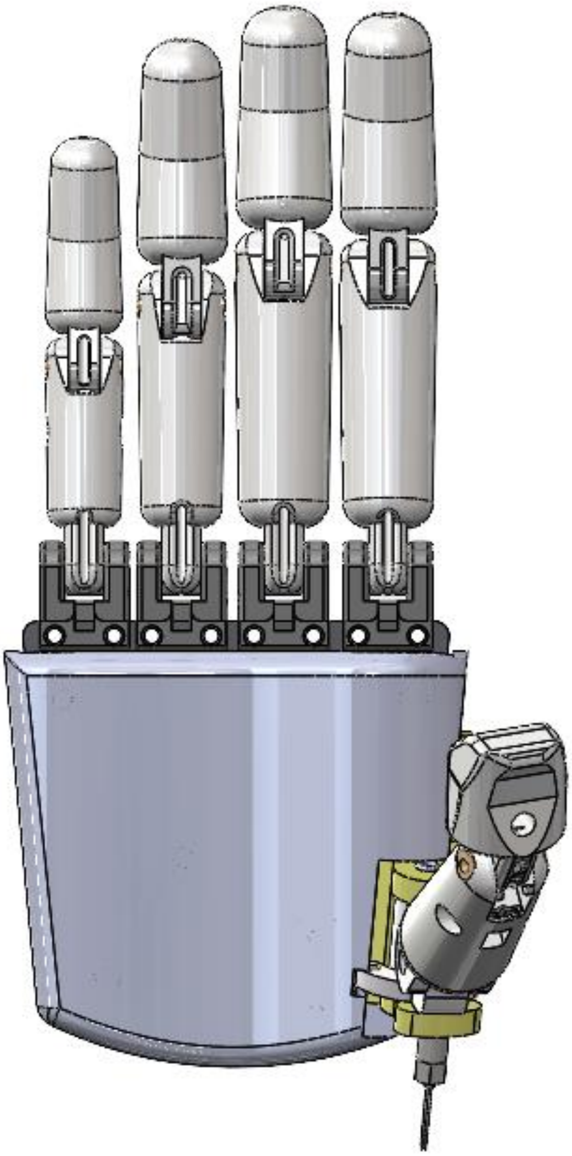


Figure 50 Full hand assembly with the palmar part

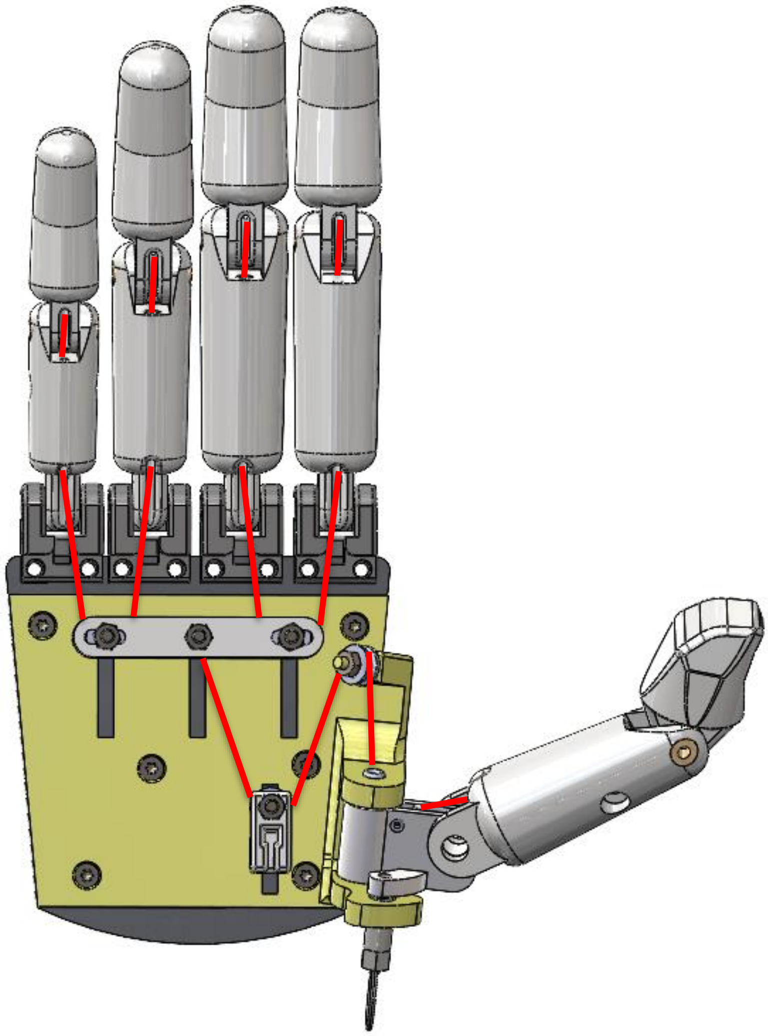


Figure 51 Whole hand assembly without visible underactuation system

8.1. Structural base plate

The first step in the design of this prototype was the metallic plate which is used to attach the different components, including the fingers, the metacarpophalangeal joints and the guidance plates for the underactuation system among others. This design includes modifications with respect to the first layout obtained from the 3D scanned model, in order to allow the redistribution of the fingers.

Furthermore, the position of the thumb is also analysed and selected during this process, even though there is no similarity between the long fingers and the thumb connection parts. The position of the thumb will be further explained in its specific section, but here, the orientation of the metallic plates defines, in some way, the flexing direction of the thumb.

When designing this plate, it is also important to take other components into account, that means generating holes for the different bolts which will keep the different parts of the design together and assembled. Figure 52 shows an image of the designed metallic plate.

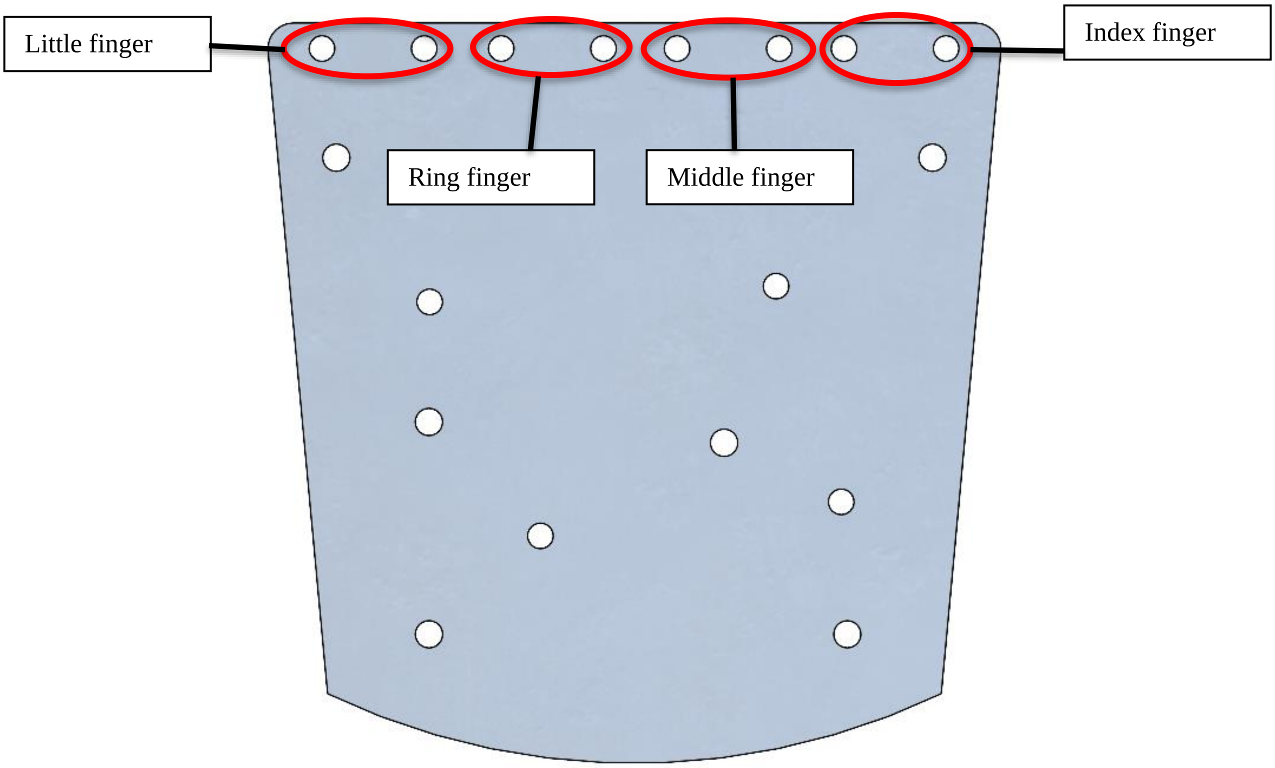


Figure 52 Structural base plate model

Figure 53 shows an image of the assembly of one of the fingers, in this case the index, with the pins, bolts, spring and extra components.

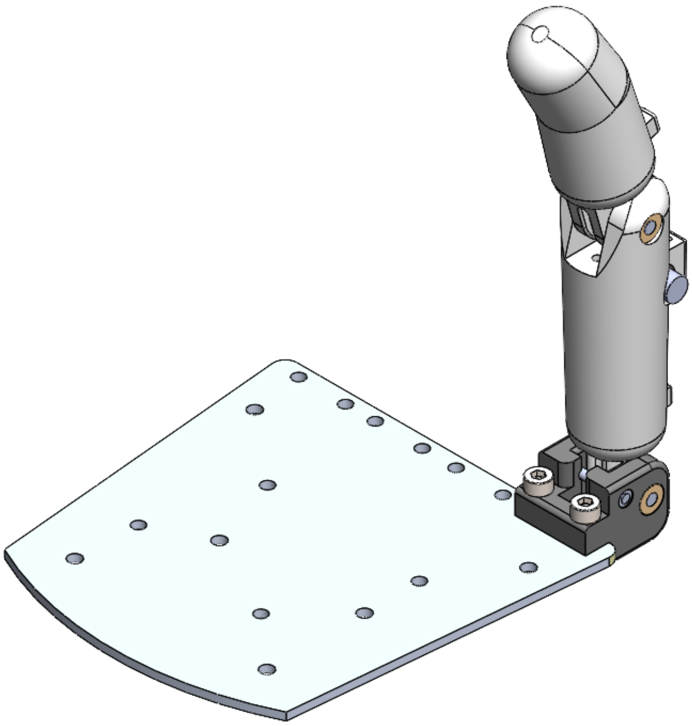
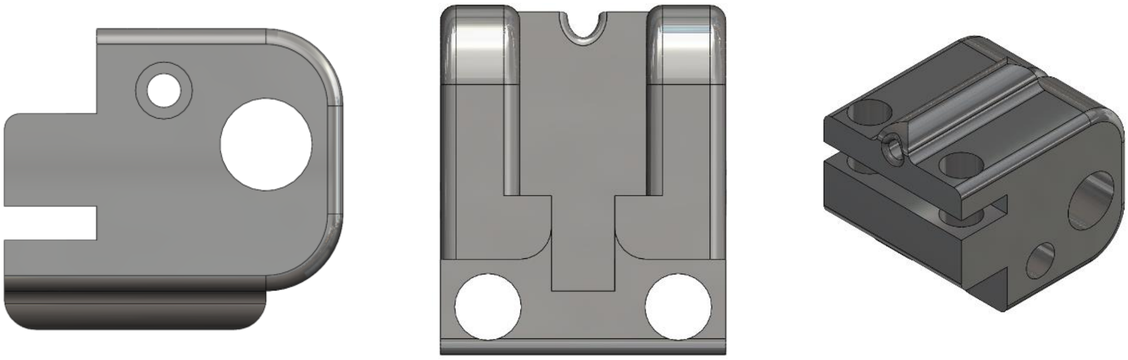


Figure 53 Structural base plate and index finger assembly

8.2. Metacarpophalangeal joints

In this section, the parts used to connect the structural base plate and the long fingers are described. This is an important part because it allows to connect the fingers to the main structure of the hand allowing the rotation of the fingers for flexion and extension. This part is also designed to guide the cables or tendons that are attached to the fingers to actuate the flexion motion . In order to guide the cables used for the extension system a hole is extruded. The model of this part is shown below.

- Figure 54 a shows a lateral view of the part.
- Figure 54 b shows the top view of the component.
- Figure 54 c shows an isometric view of the bottom of the part.



a b c

Figure 54 Metacarpophalangeal joint different views

Finally, Figure 55 shows an isometric view of the metacarpophalangeal joint between fingers and the structural base plate.

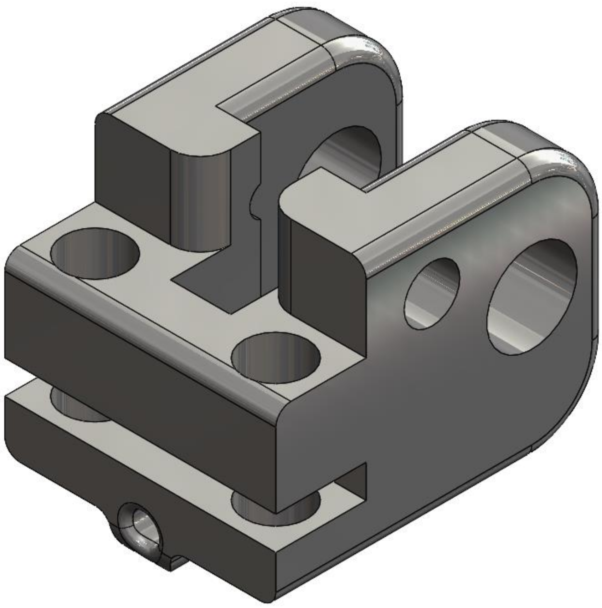


Figure 55 Isometric view of the metacarpophalangeal joint

The different holes that are designed in the components are used to include metallic pins and bolts to attach this part to the structural base plate, as well as the fingers, and adding plain bearings to allow a smooth rotation between components.

8.3. Fingers design

The design of the fingers is going to be now shown and explained. This section is divided in 3 sub-sections. The decision is to analyse the design of three fingers out of the five designed fingers. The reason for doing so is to explain the designs that contain the most differences between them. That is why the chosen fingers are:

- The index finger.
- The little finger, which has a similar design to the index finger, but with some significant differences that must be pointed out.
- The thumb, which is a completely different design with respect to the other models.

8.3.1. Index finger

The design of the long fingers started with the idea of using a cylindrical geometry. This cylindrical geometry, when extruding the different components using SolidWorks, was later given an angle of extrusion, making this to turn the cylinder into a cone, thus giving the finger phalanges a cone-shaped trunk geometry.

As stated in the concept design section, this finger was designed with two phalanges, unifying the distal and middle phalanges seen in the human hand into a unique distal one.

The model of the whole index finger can be seen in Figure 56 and in Figure 57, but the different phalanges will be explained later in further detail.

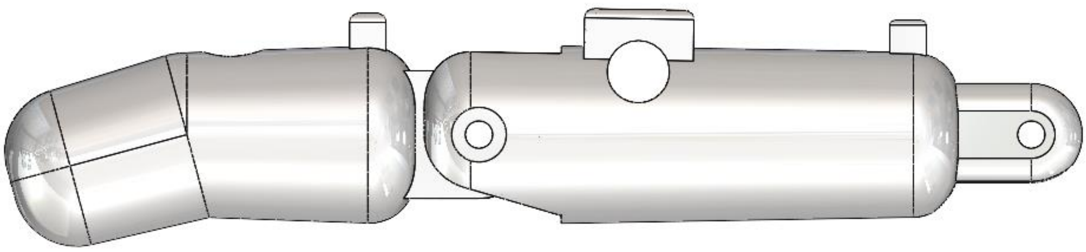


Figure 56 Lateral view of the index finger

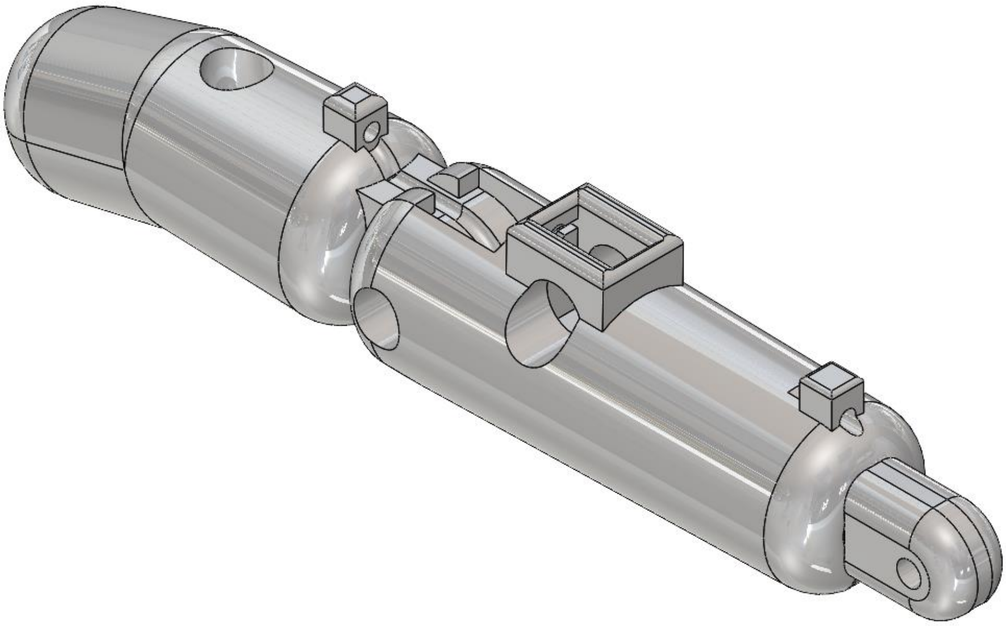


Figure 57 Isometric view of the index finger

8.3.1.1. Proximal phalanx

Once the geometry was decided and extruded, the next steps were to shape the finger into an anthropomorphic appearance and to create the different holes for the cables, either those of the tendons that flex the finger or those used in the finger extension system. In addition, and also considering the need to include an extension system to allow the finger to return to its resting position once the corresponding grasp has been performed, a housing was designed to introduce constant load springs inside the phalanx, as well as a hole to introduce a pin to fix this spring.

Below, in Figure 58, the isometric view of the proximal phalanx of the index finger can be seen.

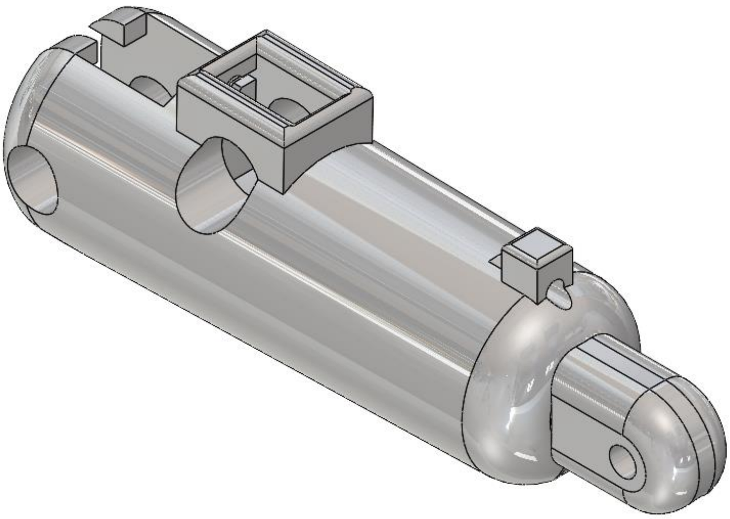


Figure 58 Index finger's proximal phalanx isometric view

Next image, Figure 59, shows a section view where the different holes to house the cables and a more detailed view, Figure 60, shows the housing for the constant load spring.

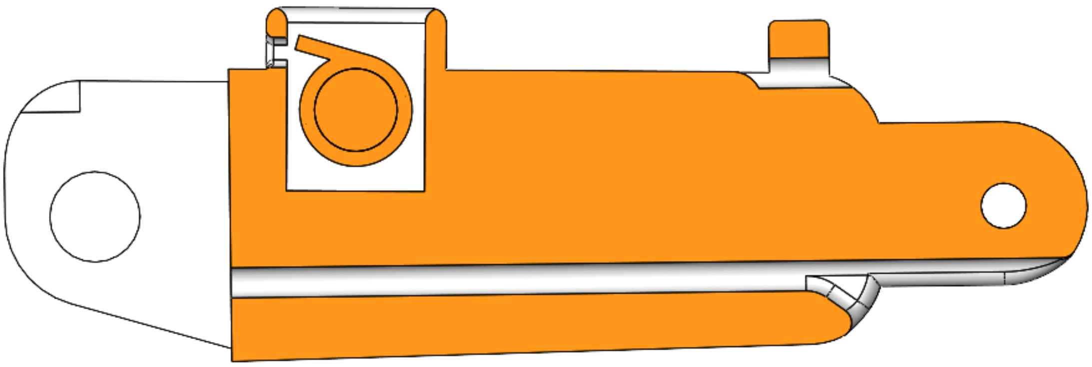


Figure 59 Index finger's proximal phalanx section view

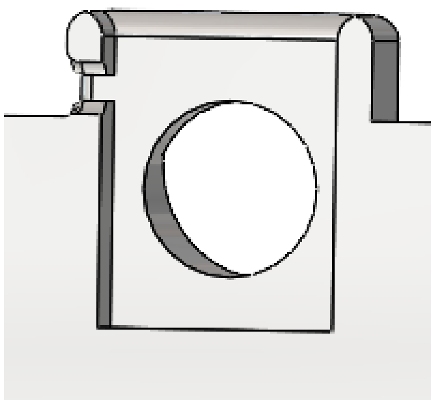


Figure 60 Constant load spring housing detailed view

An additional extrusion was added at the distal end of the proximal phalanges of the fingers. This extrusion, shown in Figure 61 and also made in 3D printed material, is used to avoid an excessive extension of the distal phalanx.

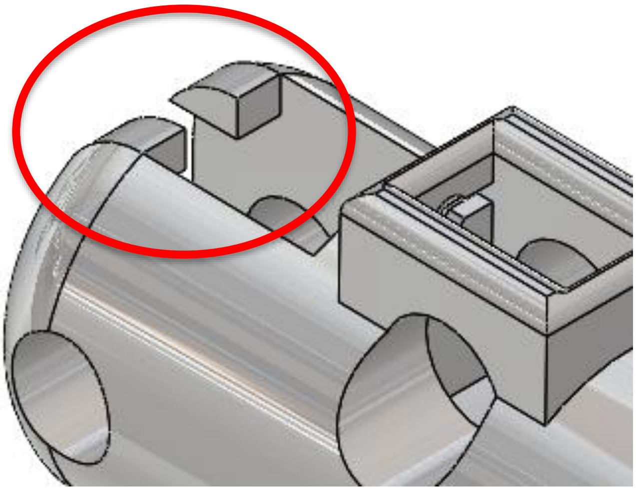


Figure 61 Detailed view of the part used to limit the extension

8.3.1.2. Distal phalanx

Starting from the cylindrical structure, an angle was added to the upper part of the piece, creating the sensation of a third phalanx, making it easier to grip different objects due to this geometry (see Figure 62). Subsequently, the different holes are made to introduce the cables related to the flexion and extension system, as well as the one that correspond to the joint to allow the flexion of the distal phalanx with respect to the proximal one. It should be noted that the holes made in this component are designed in such a way that they are aligned with those located in the proximal phalanx and serve to fulfil the same function.

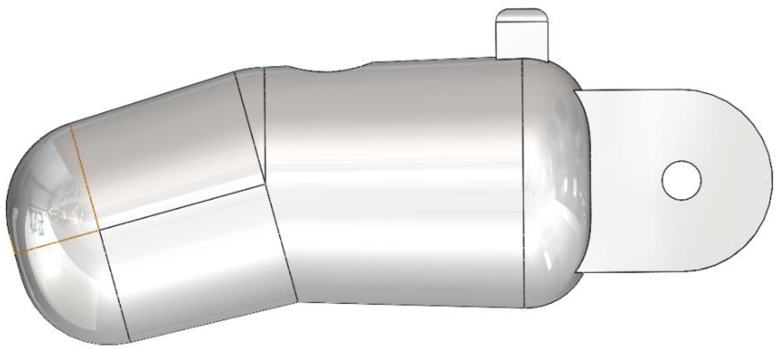


Figure 62 Lateral view of the index finger's distal phalanx

Figure 63 shows a section view of the distal phalanx for the index finger, showing the holes that house the cables.

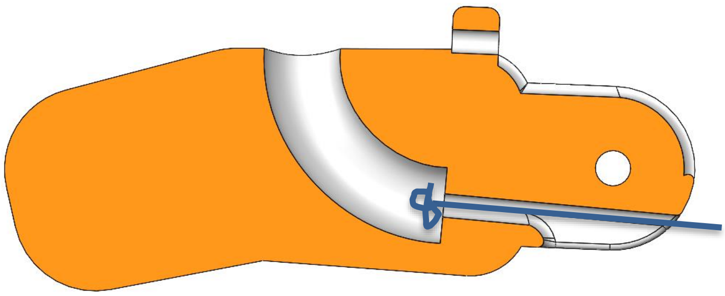


Figure 63 Section view of the index finger's distal phalanx

A similar design is used for the middle and ring fingers, with only changes in the dimensions, not described here for the sake of brevity.

8.3.2. Little finger

The little finger design differs a little bit from the other mentioned long fingers. This is because of the distance needed from the cable to the axis of rotation of the phalanges in order to overcome the different applied loads, that is to say the load of the constant load spring and the load applied by the user to flex the fingers. That is why, as it can be seen in Figure 64, there is no extra extruded material in the finger to house the constant load springs or the cable for the extension mechanism.

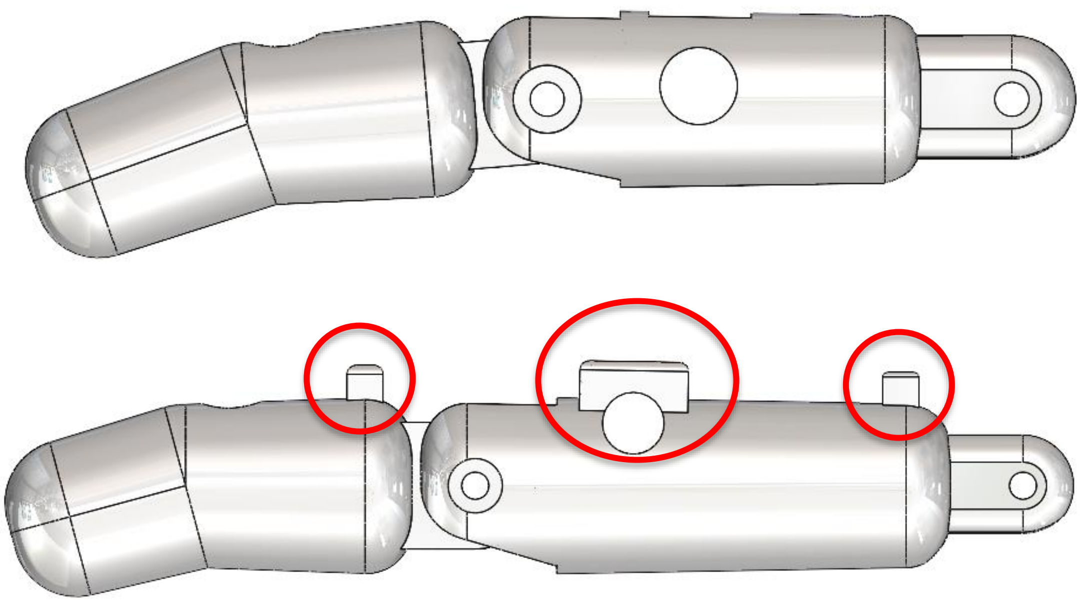


Figure 64 Little finger (above) and index finger (below) comparison

Figure 65 shows the isometric view of the little finger and, as it can be seen rounded in a red circle, the extra extrusion used as a stopping part to limit the extension is also designed.

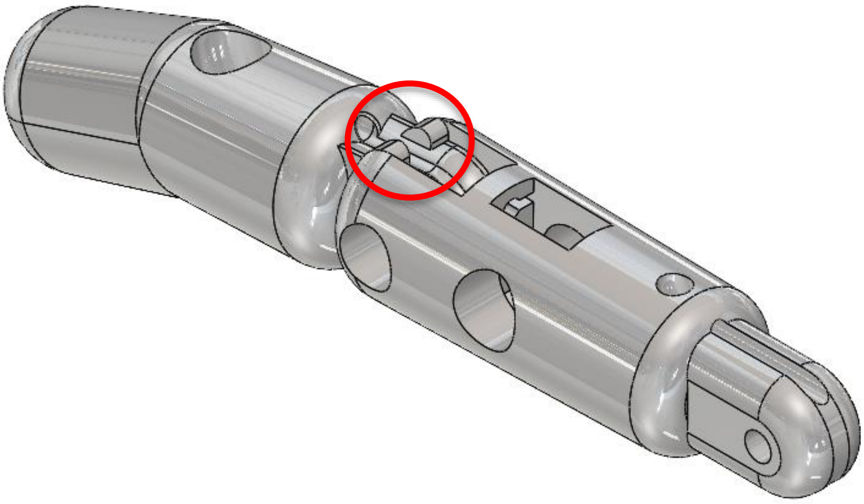


Figure 65 Little finger's assembly isometric view

8.3.2.1. Proximal phalanx

The proximal phalanx has a similar design to that of the proximal phalanx for the index finger, but without adding the extra housing for the springs because, due to the different selected distances, it is not necessary.

Figure 66 shows the proximal phalanx of the little finger in an isometric view.

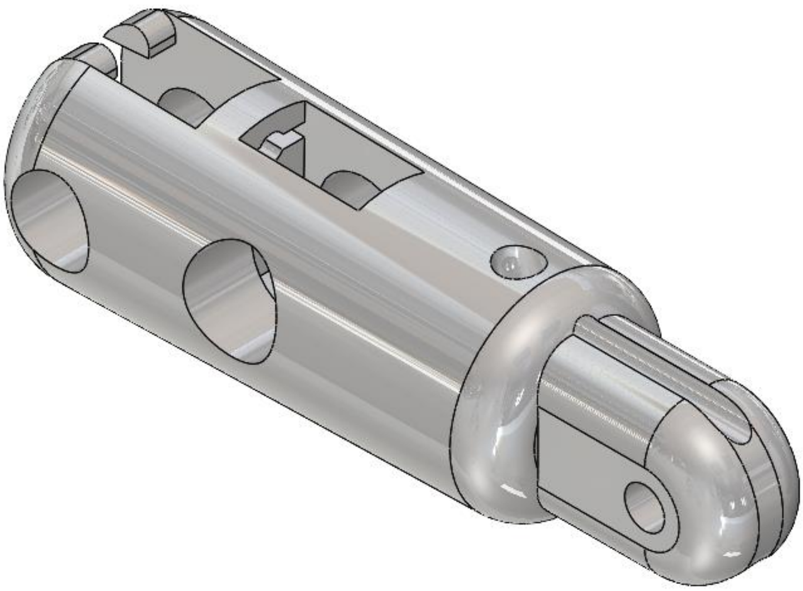


Figure 66 Isometric view of the proximal phalanx of the little finger

Figure 67 show the section view where the holes for housing the tendons can be clearly seen.

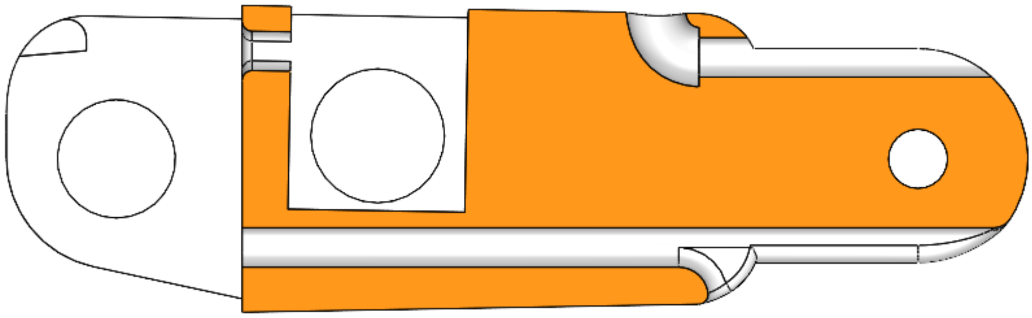


Figure 67 Proximal phalanx of the little finger, section view

8.3.2.2. Distal phalanx

The design of the distal phalanx of the little finger is similar to that of the index finger with the exception, as mentioned above, that the extrusion used to attach the cable for the extension system is missing here. A lateral view of the little finger distal phalanx is shown in Figure 68 and a section view in Figure 69.

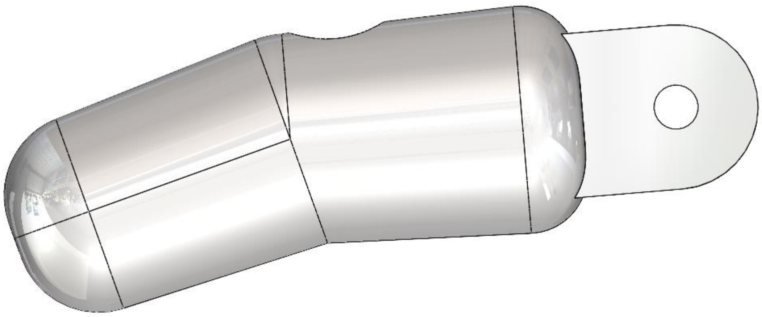


Figure 68 Distal phalanx of the little finger, lateral view

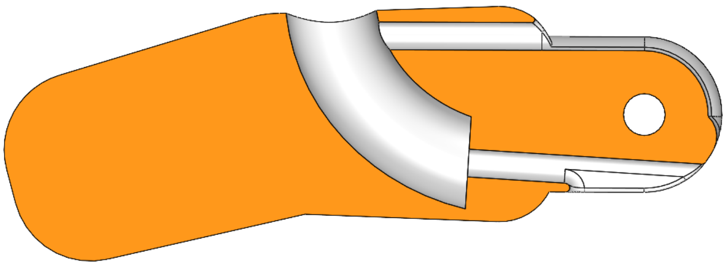


Figure 69 Distal phalanx of the little finger, section view

8.3.3. Thumb design

The thumb is a finger that differs in some aspects from the rest of the fingers designed on the hand. It can be seen that it has a slightly larger size in the trunk-cone of the proximal phalanx and, also, that the geometry of the distal phalanx is different from the others, since it does not have that characteristic cylindrical structure. This is due to the fact of wanting to make the design of the prosthesis as similar as possible to the human hand, resulting in the aesthetic modification of this component to resemble the human thumb.

There are other factors that make this design different, but they will be explained below in the next sub-sections.

Figure 70 shows the assembly of the thumb from a lateral point of view.

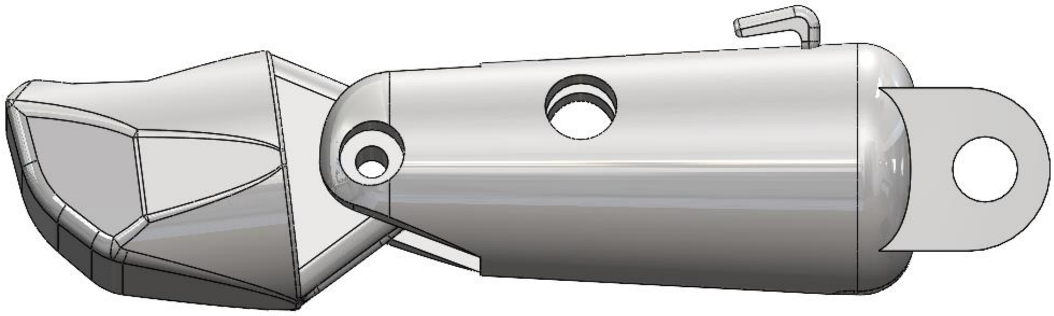


Figure 70 Thumb's assembly, lateral view

Shows an image of the assembly of the thumb with the AB/AD components and their correspondent pins and flexible joints. The spring used for the extension of the distal phalanx can also be seen in the designed housing for that task.

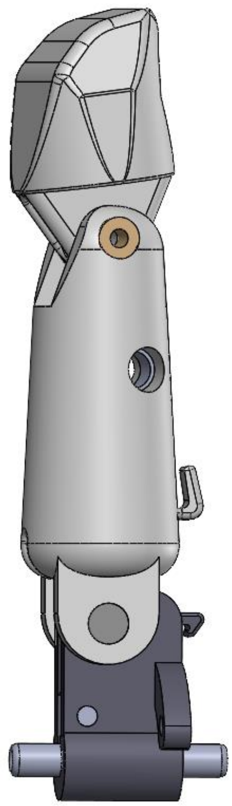


Figure 71 Thumb's complete assembly

8.3.3.1. Proximal phalanx

The proximal phalanx design for the thumb has a peculiar design. This is because, in order to be able to perform the abduction of this finger combined with a correct flexion of the same, the axis of the metacarpophalangeal joint is not parallel with respect to the interphalangeal joint. This is perhaps a confusing aspect, but it allows to perform the AB/AD and that will be shown later.

Leaving aside this important detail that provides a new function within the design of the prototype, the process of creation has a similar basis to that mentioned above in the other fingers, that is, starting from a cylindrical base, add the holes for both the cables of the extension and flexion systems, as well as the one used to house the constant load springs. The flexion limiting system is also added, as well as the different holes where the pins are located in order to allow rotation with respect to the other components of the prototype as well as assembling them.

Below, in Figure 72, an isometric view of the proximal phalanx of the thumb is shown.

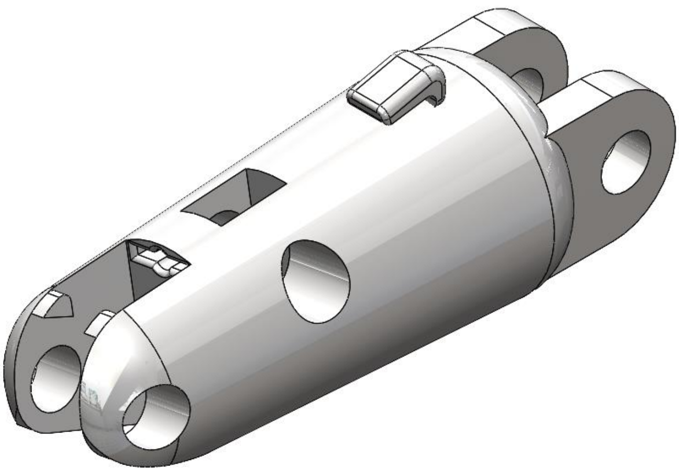


Figure 72 Thumb's proximal phalanx isometric view

The section view of the proximal phalanx of the thumb is also shown below in Figure 73, where, as in the previous figures similar to this one, the holes that house the various cables and the spring can be distinguished.

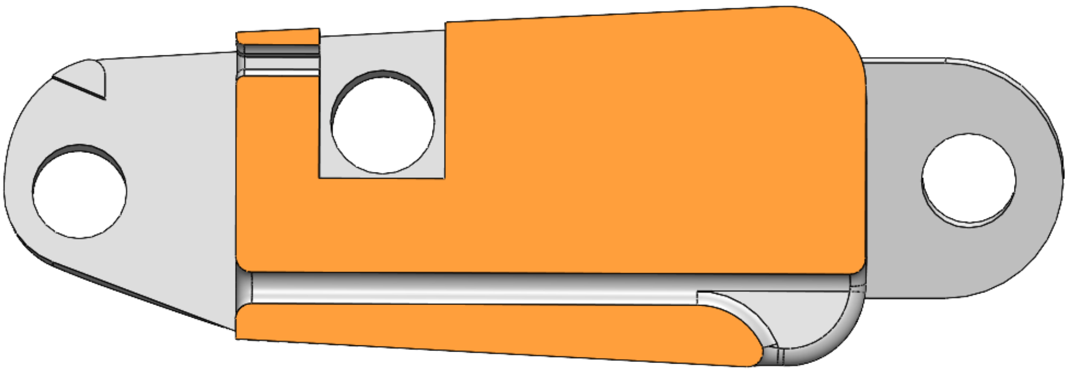


Figure 73 Thumb's proximal phalanx, section view

Next image, Figure 74 shows the mentioned misalignment between the bottom part projections and the housing for the cable.

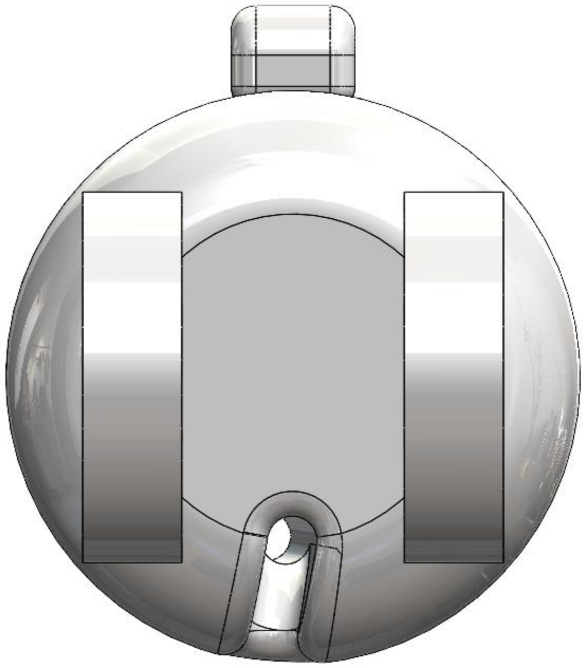


Figure 74 Thumb bottom part

8.3.3.2. Distal phalanx

Even though the geometry of the distal phalanx is different with respect to other fingers' distal phalanges, the starting point is very similar. Starting from a cylindrical structure and then giving shape to that main extrusion in order to reach de desired configuration and generating the different holes for the cables and the metallic pins which have been mentioned throughout this document.

The isometric view of the model for the thumb distal phalanx is shown in Figure 75 and the lateral view of the component is shown in Figure 76.

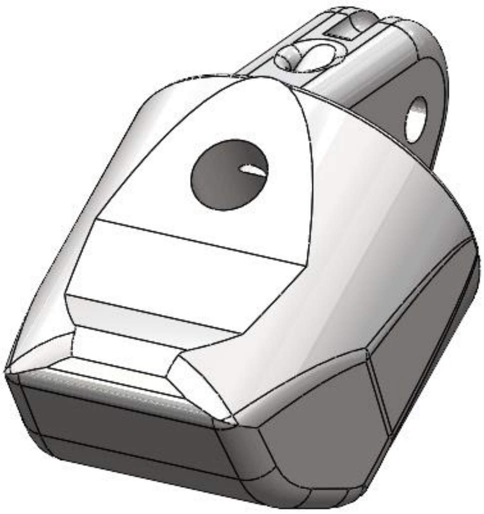


Figure 75 Thumb distal phalanx isometric view

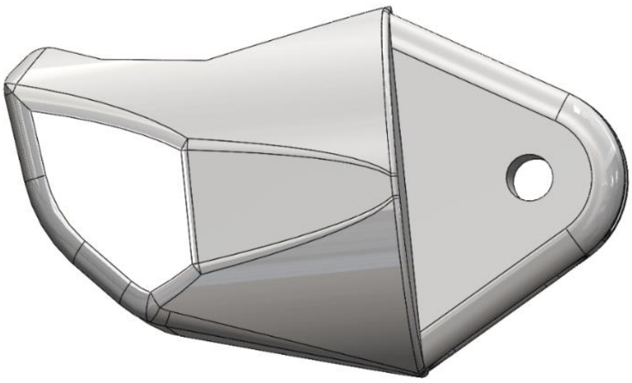


Figure 76 Thumb distal phalanx lateral view

Figure 77 shows a section view of the thumb's distal phalanx.

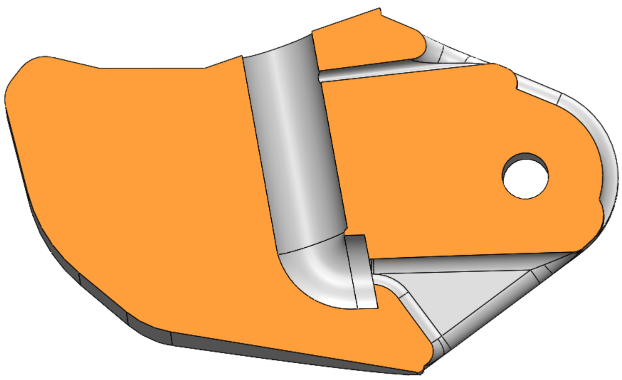


Figure 77 Thumb's distal phalanx section view

8.4. Finger joint support

Small hollow cylindrical and flexible parts are used between the pins for the finger joints (both metacarpophalangeal and interphalangeal) and the proximal part of the joint (Figure 78 and Figure 79). These parts are made of FilaFlex, which is a flexible material and are pressed fitted to the proximal part in the joints and to the pin, to limit the axial motion of the pin inside the joint and at the same time providing flexibility and adaptability to the joint under more demanding grips in terms of size or strength.

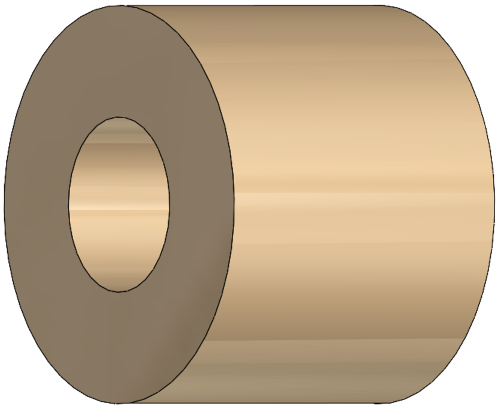


Figure 78 Finger joint support

Figure 79 shows the location of these components in the assembly of the hand prototype, using as an example the index finger.

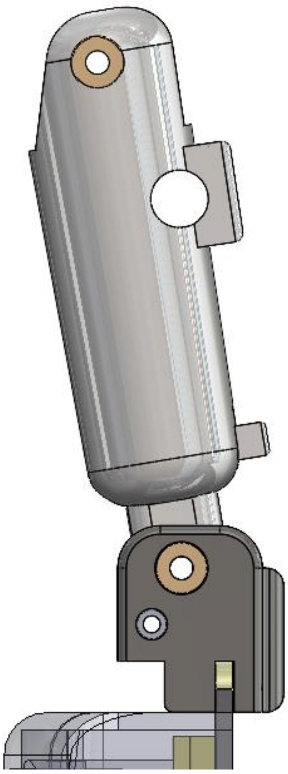


Figure 79 FilaFlex component location

8.5. Guidance plates

As the decision for the underactuation system was already defined and selected thanks to the concept design section, the starting point was decided to be the guidance bottom plate, i.e., the plate placed just above the metal plate.

This plate was designed with slots of a suitable size to accommodate the heads of the bolts to be used in the underactuation system, thus allowing, thanks to the use of the top plate too, the guiding of the bolts.

Furthermore, different holes, coincident with those in the structural base plate, are cut on both the lower and top plate in order to assemble the components together.

Figure 80 shows an image of the bottom plate design where the slots and the holes can be seen.

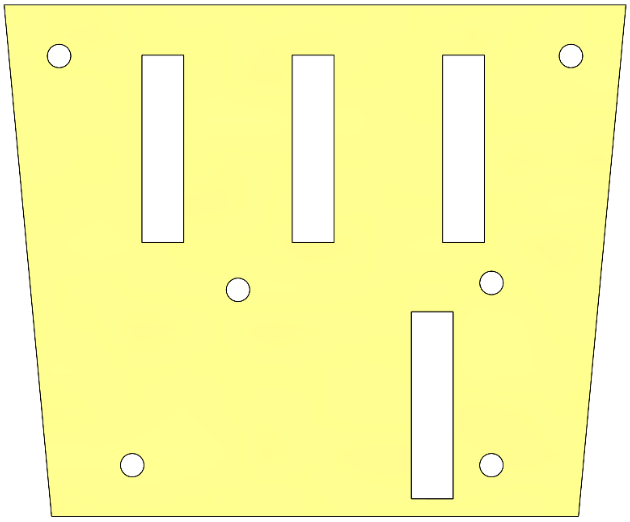


Figure 80 Guidance bottom plate model

The guidance top plate is very similar to the bottom one, with the difference in the size of the various slots, which allows the bolts used in the underactuation system to remain in place and not fall out if the prosthesis is turned upside down.

This plate has the addition of extra parts, especially designed to fulfil functions related to the AB/AD of the thumb on the one hand and the functions of the underactuation system on the other hand. These parts are highlighted below in Figure 81 will be further explained in their specific section.

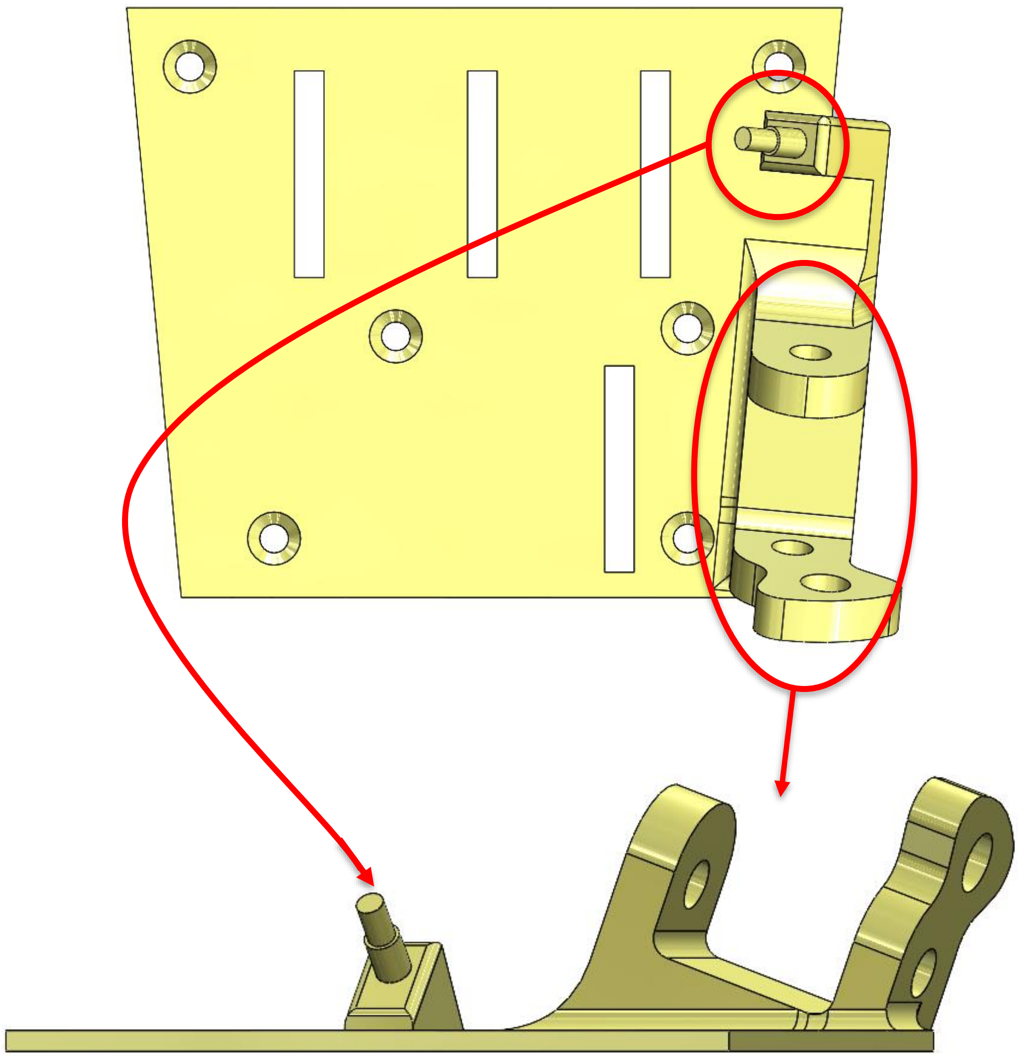


Figure 81 Guidance top plate lateral and detailed view

8.6. Abduction/Adduction system

The AB/AD mechanism was thought in order to allow the movement of the thumb to different positions, allowing by this more grasping types to be performed.

The design of this system involves various parts and components of the prosthesis in a very interesting development process.

The first step was the design of the housing for the thumb assembly. This was provided with an angle obtained from different iterations and tests with different objects and grips thanks to the SolidWorks software. At first, this system was only intended to house the thumb, but later it was decided to make some modifications for the addition of other components that would allow the discretisation of two positions manually. The fact of designing it to work manually is due to the fact that the actuations is wanted to be with only one cable in order to acquire the underactuation, thus the AB/AD needs to be made in a discrete way.

This first part of the design is shown in Figure 82 and Figure 83.

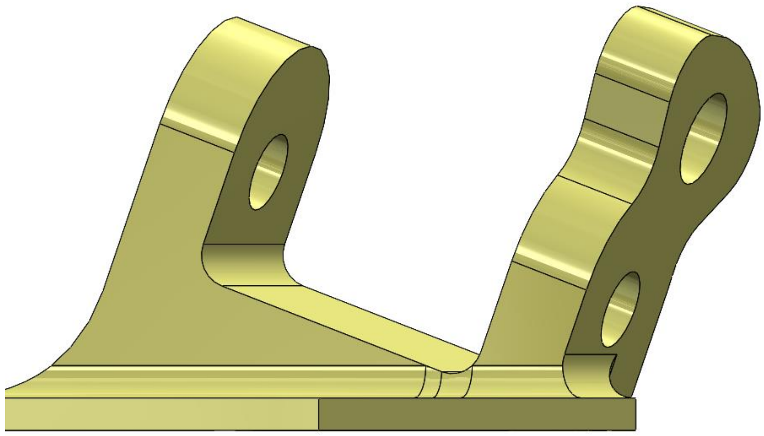


Figure 82 AB/AD plate incorporated component

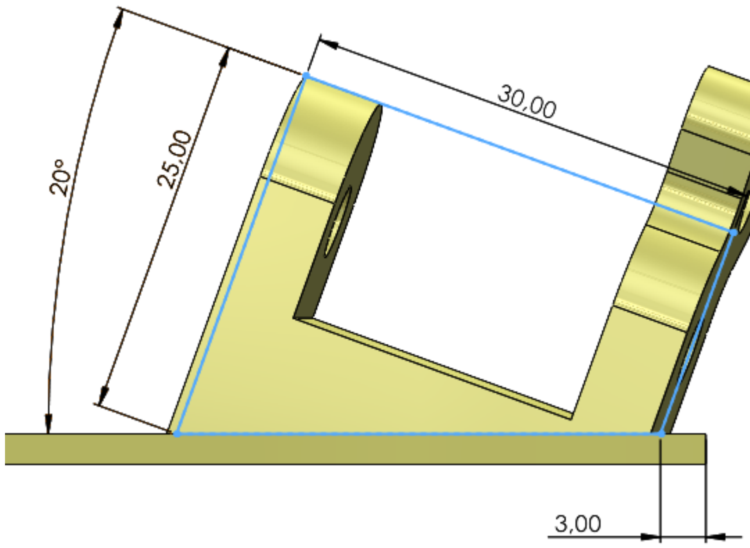


Figure 83 AB/AD Plate incorporated component initial sketch

Once this component was designed, the following step was to design the component which is equivalent to the metacarpal joint of the thumb.

This design started with a similar concept with respect to the other used in the metacarpophalangeal joints and it had to have a part which allowed the thumb to rotate with respect to a plane which is perpendicular to the flexion plane.

This component counts also with holes made to house the cable from the underactuation system to the thumb and also holes which allow the AB/AD. In the lowest part of the component there is also a hole which is made to house a pin (see Figure 84 highlighted in green).

Next images, Figure 84 and Figure 85, show the final model of this component. The mentioned mechanism to allow the discretisation is highlighted in red.

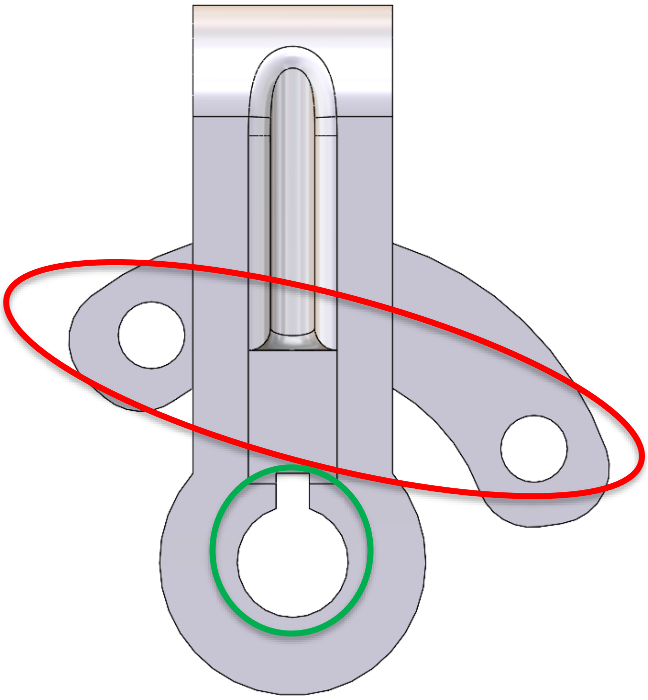


Figure 84 Frontal AB/AD component view (red: discretisation mechanism, green: pin housing)

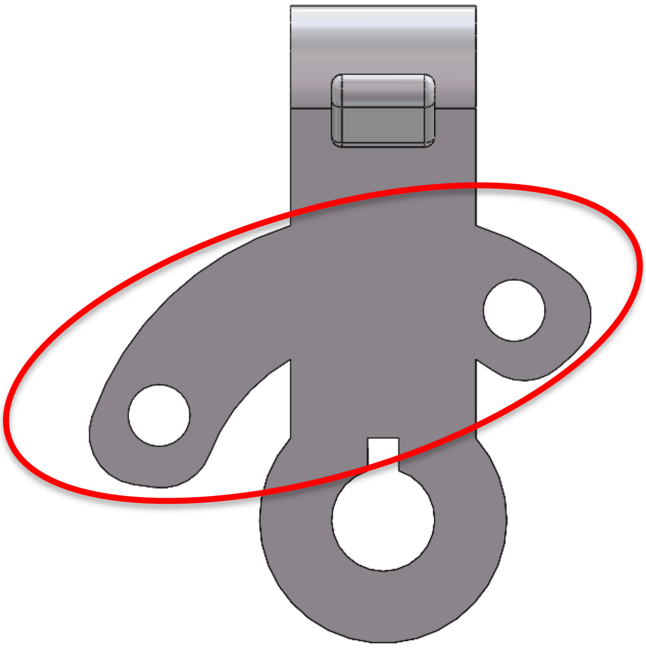


Figure 85 AB/AD component back view (red: discretisation mechanism)

Figure 86 and Figure 87 show a lateral view and a section view, of this component, which allows to see the holes inside it.

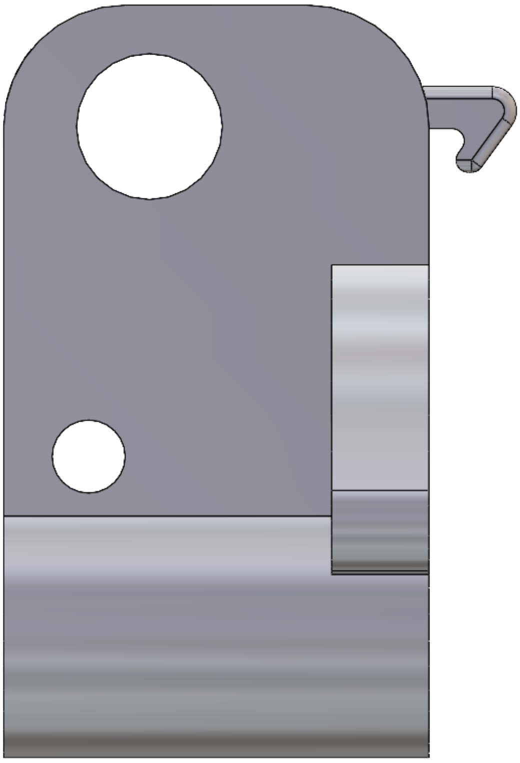


Figure 86 AB/AD component lateral view

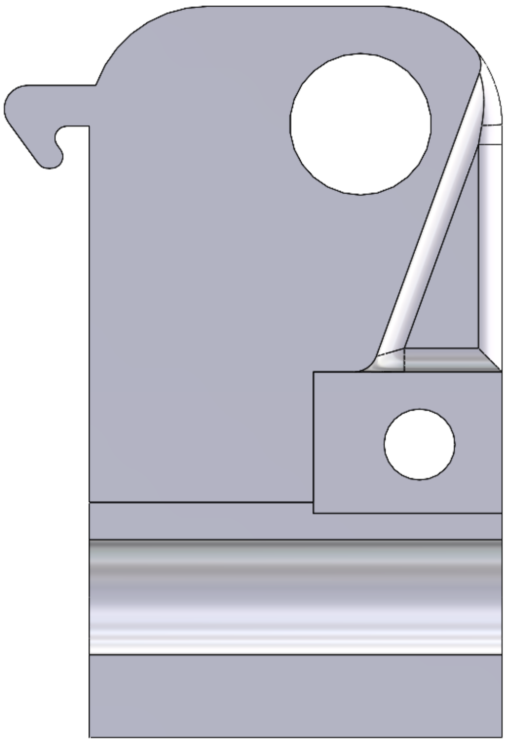


Figure 87 AB/AD component section view

The previously mentioned slotted pin, which allows the cable to go through it, is shown below in Figure 88, although this is an approximate and zoomed in representation, the final component will be bought from commercially available catalogues. The actual size of the pin with respect to its housing is shown in Figure 89 rounded in red.

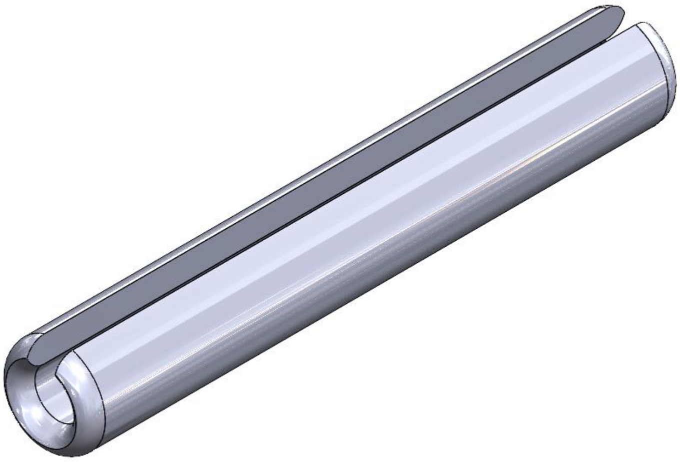


Figure 88 Slotted pin

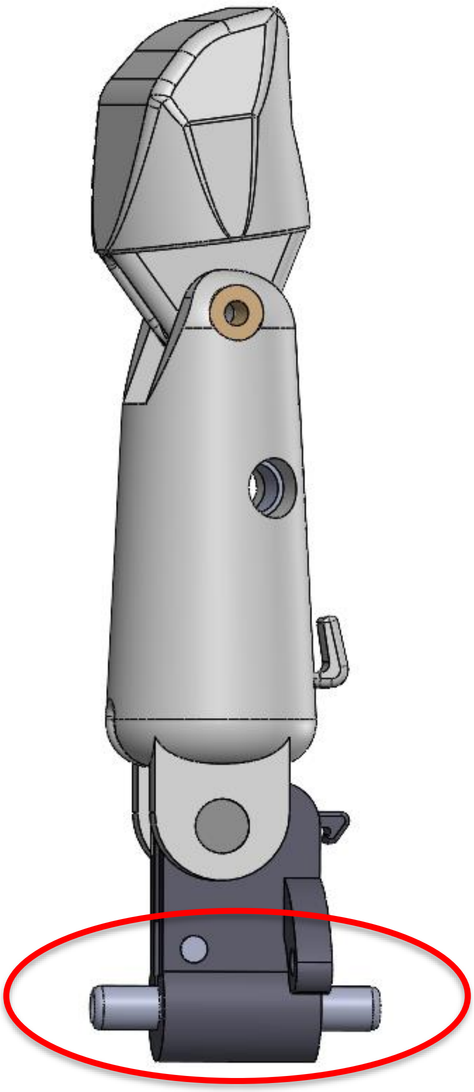


Figure 89 Slotted pin size comparison

8.7. Underactuation mechanism

The design of the underactuation system is closely related to the design of the guidance plates mentioned above, since the grooves in the guidance plates are part of the guidance system of the guidance plates. In order to create a differential underactuation system, several options were considered, as shown in the conceptual design, and the solution chosen was to use a system of slides, slots and pulleys to allow the underactuation of the fingers of the prosthetic hand.

Below in Figure 90 and Figure 91, some views of the underactuation system assembly are shown. Double hex nuts (see Figure 91) are used to fix the system but allowing some clearance in order to allow the pulleys to rotate.

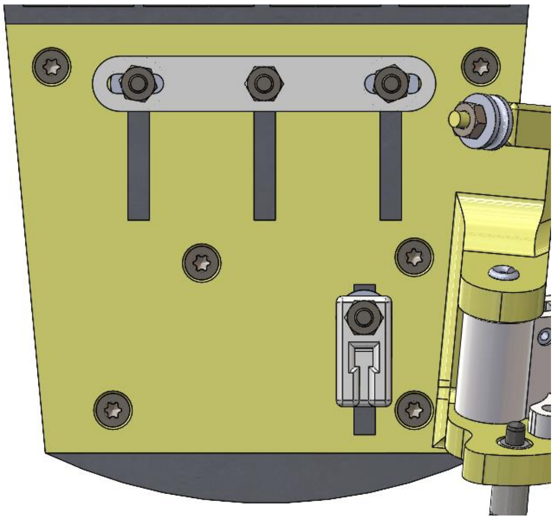


Figure 90 Underactuation system's assembly, top view

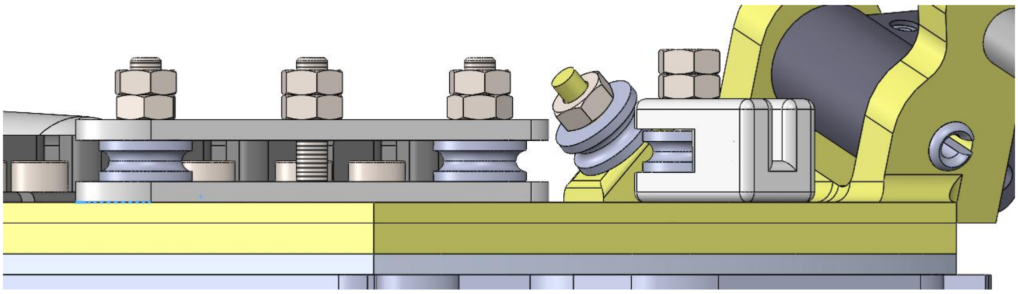


Figure 91 Underactuation system's assembly, lateral view

8.7.1. Slider bar

The underactuation system contains two identical slider bars (Figure 92 and Figure 93), connected with bolts. One of these parts is located just on the surface of the guidance top plate, while the other is located just above the pulleys that are used to guide the cables.

The slider bar includes two slots which allow the bolts that go through them to grant extra movement of the assembly if one or more fingers are blocked when grasping an object.

The slider bars are made out of aluminium to get adequate strength with a thickness of only 2 mm.

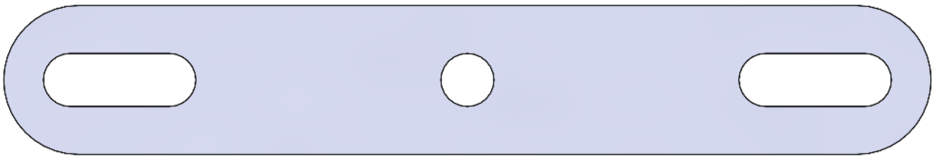


Figure 92 Slider bar, top view

An isometric view of the slider component is shown in Figure 93.

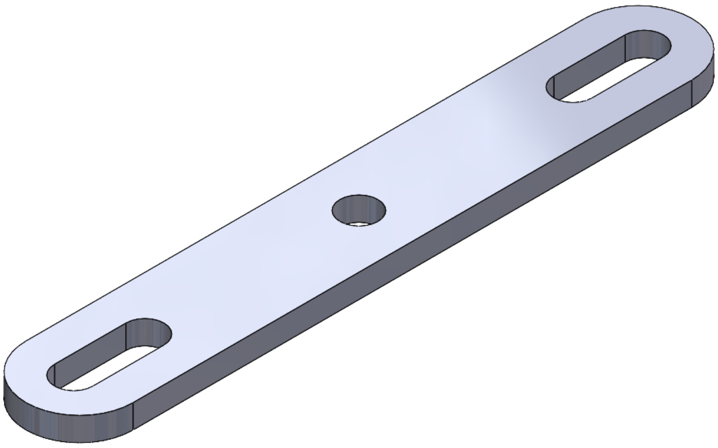


Figure 93 Slider bar, isometric view

8.7.2. Pulling slider

The pulling slider (Figure 94) is used to attach the bowden cable coming from the harness and to guide the cable coming from the fingers and the thumb. This is an important part of the underactuation mechanism because this part needs to bear the force of the initial pull that the user does with the harness and the Pro Cuff accessories. Moreover, this part needs to slide with respect to the guidance plate in the palm. In prior designs carried out by the author of this project this part was poorly designed and, when running some tests with the prototype, it broke down, leaving the system without an efficient pulling system. This is why this part was designed in a different way with respect to this previous prototype, designing a housing for the bowden cable and increasing the thickness of the areas where this cable is introduced to make it more resistant. The strength of the part is analysed in the Annexes (section 3.2 of the calculations)

Furthermore, a hole is made in order to introduce a bolt and a pulley that allow both a guidance for the linear motion of the part with respect to the guidance plate and the connection and motion of the two cable ends coming from the thumb and from the underactuation system for the fingers.

Figure 94 shows an isometric view of the final design.

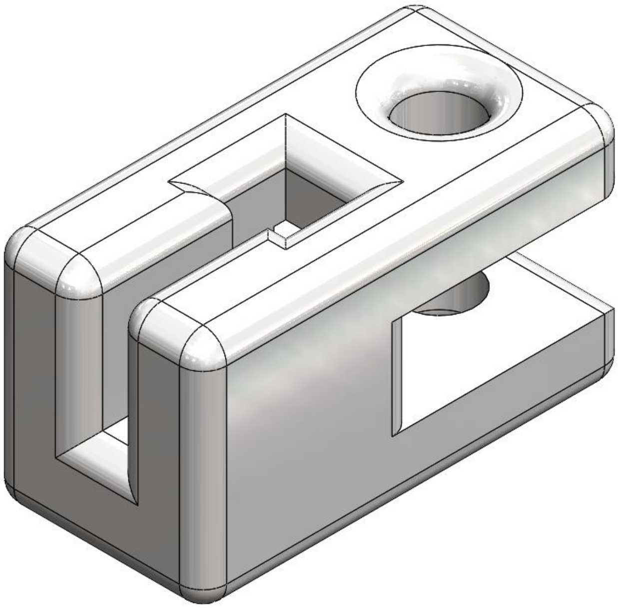


Figure 94 Pulling slider, isometric view

Next image, Figure 95, shows the top view where the squared housing for the bowden cable end and the hole for the bolt can be clearly seen.

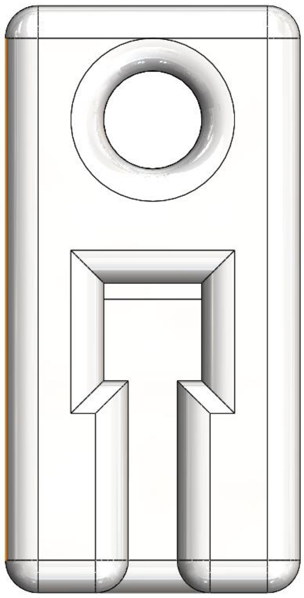
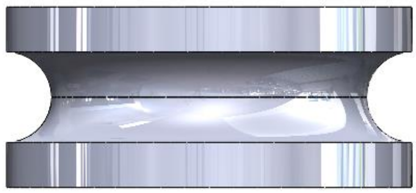


Figure 95 Pulling slider, top view

8.7.3. Pulley

This component is a simple pulley used to guide the cable motion and to reduce the friction in the motion of this cable in the underactuation system. It is 3D printed in PLA, used in four locations: two in the slider assembly, one in the pulling slider and another one to redirect the cable for the thumb flexion. The pulleys' design is shown in Figure 96.

a



b

Figure 96 Pulley 3D model

8.7.4. Cable redirection component

The next component to be explained is part of the underactuation system, but it is located in the guidance top plate. This design was made with the intention of allowing the redirection of the cable used for thumb flexion. This is because, if the pulley that forms part of this design was placed parallel to the other pulleys, the cable would acquire a vertical component of force that would cause it to pull out of the pulley.

Figure 97 shows the mentioned component highlighted in red.

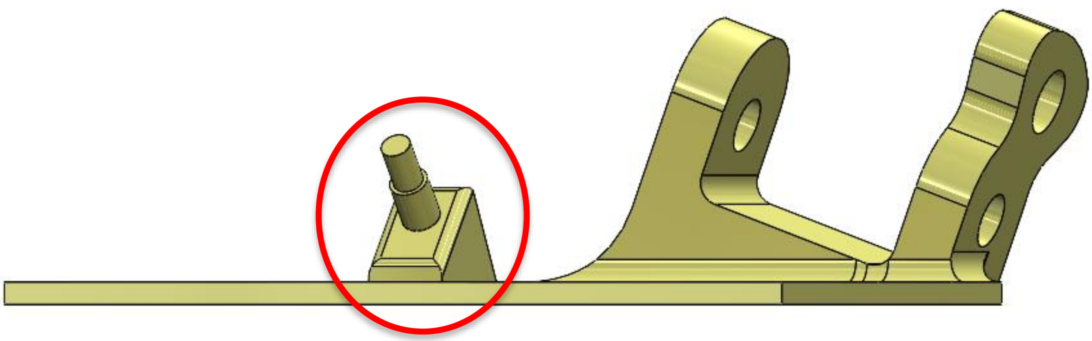


Figure 97 Cable redirection component

Next image, Figure 98, show the whole assembly of this part with the rest of the underactuation system, also showing the alignment between pulleys and the thumb to redirect the cable.

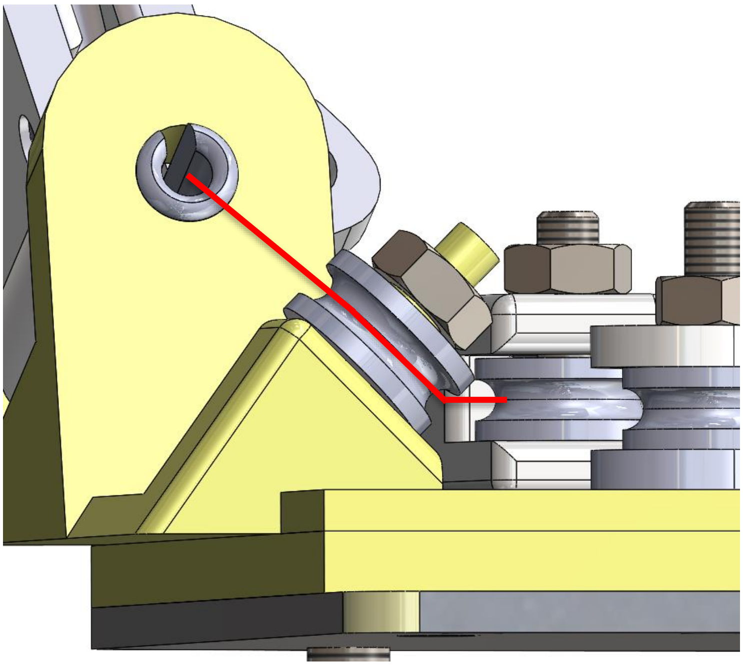


Figure 98 Cable redirection scheme

8.8. Metacarpophalangeal joints extension system

The extension system for the metacarpophalangeal joints is located at the dorsal part of the prototype. It is formed by four constant load springs which pivot in four cylindrical pins with axis perpendicular to the plate. An image of the configuration of the springs is shown in Figure 99.

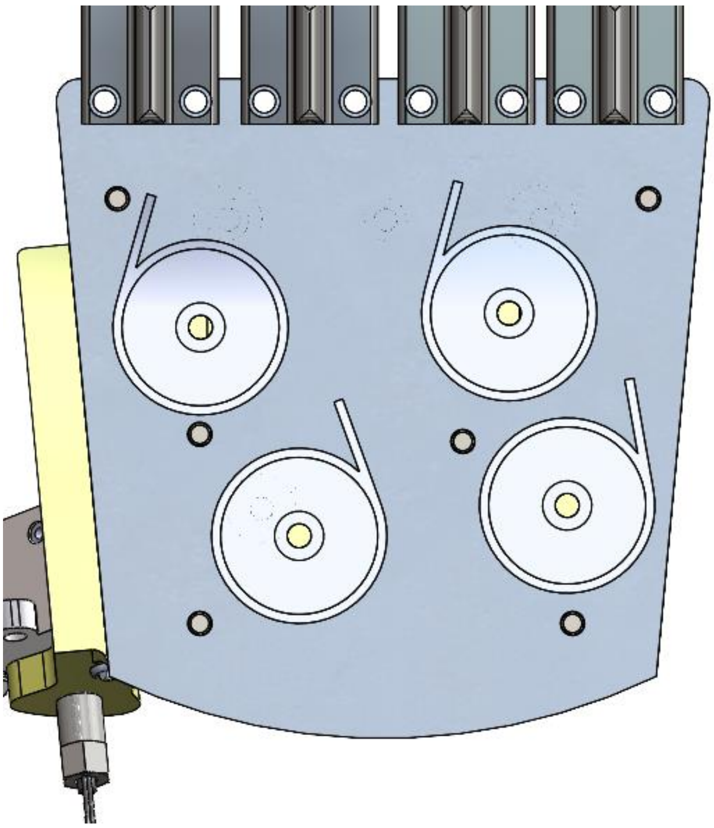


Figure 99 Spring extension system configuration

The extension system for the thumb is based on the actuation of a rubber band. The reason behind this different design is the lack of space in the thumb, which didn't allow to add these springs.

8.9. Palmar and dorsal covers

These pieces are the ones that complete the structure of the prototype, giving it the appearance of a palmar and dorsal human surfaces and enclosing the mechanisms. Both designs, despite being quite similar due to their function of closing the design and housing the different components inside, have differences, as they have to fulfil some additional function. In the case of the palmar case, it must allow the housing of the underactuation system inside, as well as to provide a firm grip on objects. In this component some holes are made in order to screw it to the other components, such as the guidance plates, structural base plate and even to the dorsal case.

The 3D model of this part is shown in Figure 100 and Figure 101.

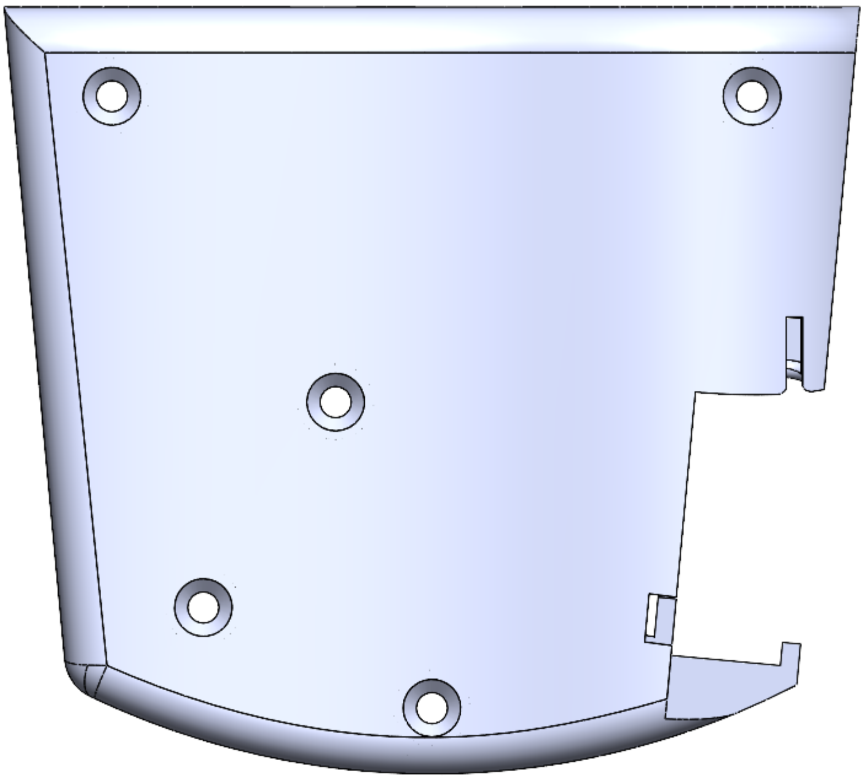


Figure 100 Palmar case, top view

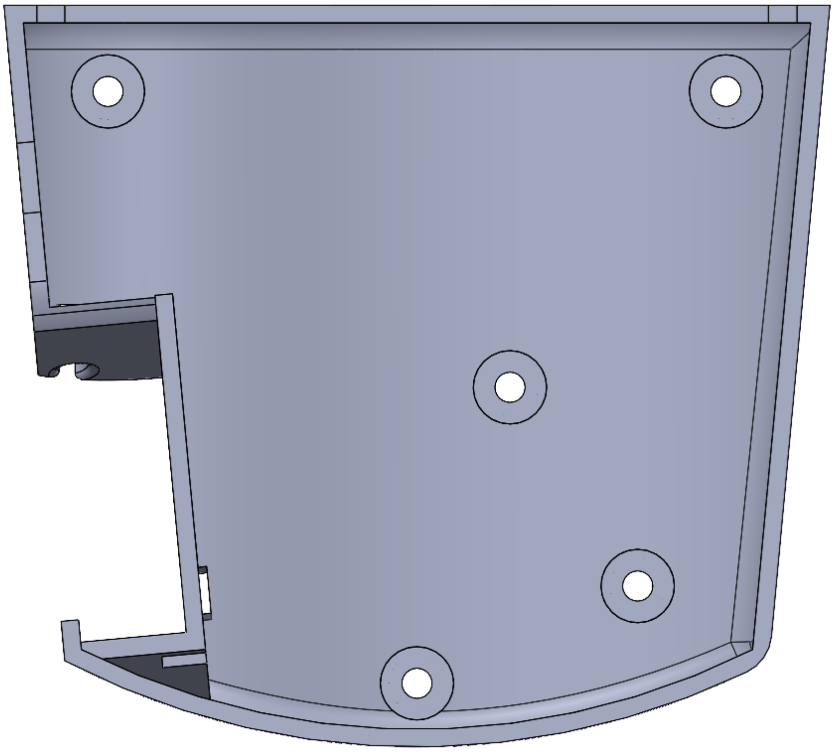


Figure 101 Palmar case, bottom view

The dorsal case is designed in order to be screwed to the structural base plate. The 3D model of this component is shown in Figure 102 and Figure 103.

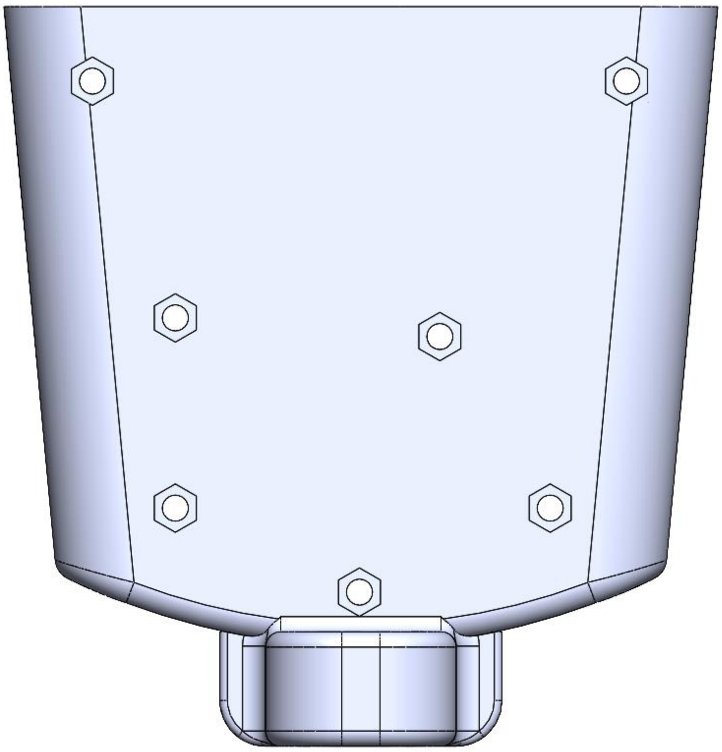


Figure 102 Dorsal case, top view

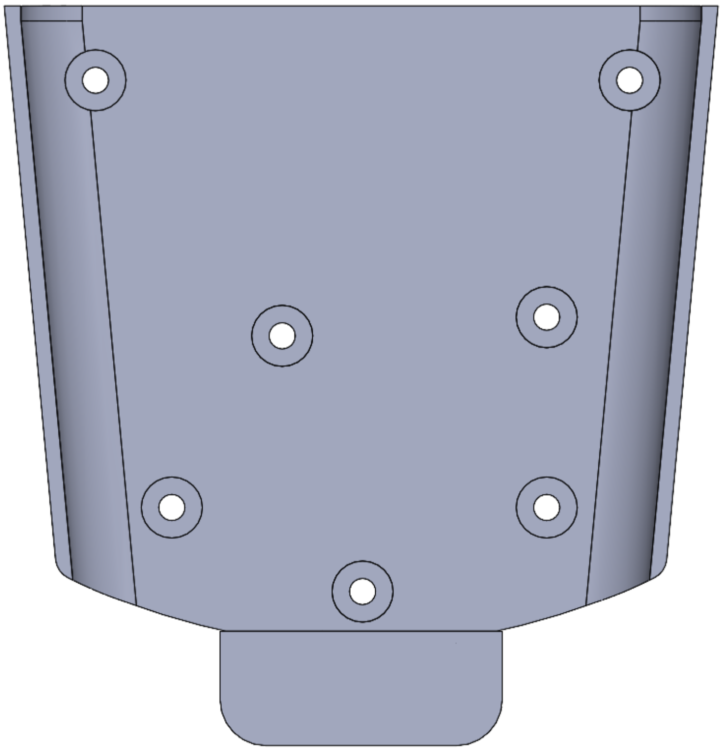


Figure 103 Dorsal case, bottom view

This component is also designed in order to allow the attachment to the Pro Cuff thanks to the hole shown in Figure 104.

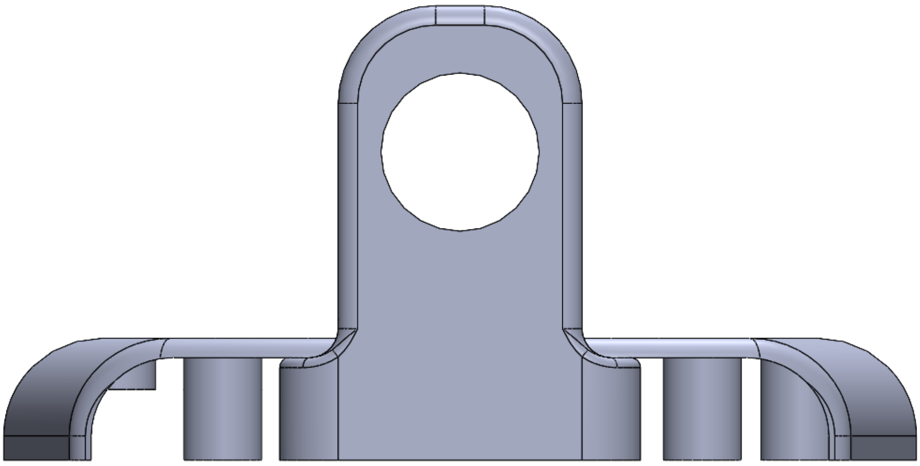


Figure 104 Pro Cuff attachment hole in dorsal case

9. Grasping postures

Two objects from the YCB object set have been selected in order to show examples of grasps that the hand is meant to perform. These examples are shown in Figure 105 and Figure 106.

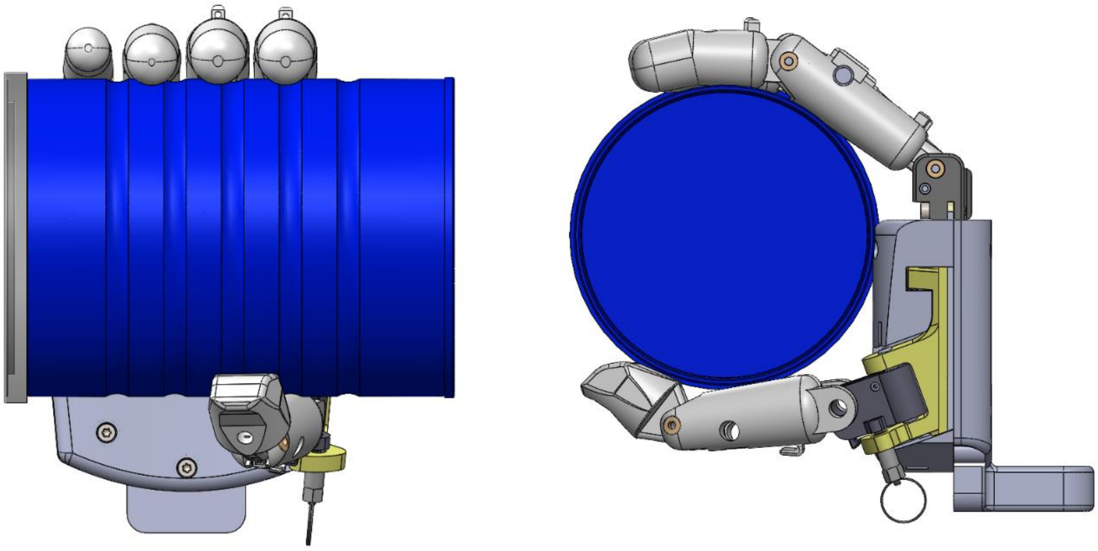


Figure 105 Cylindrical grasp, coffee can

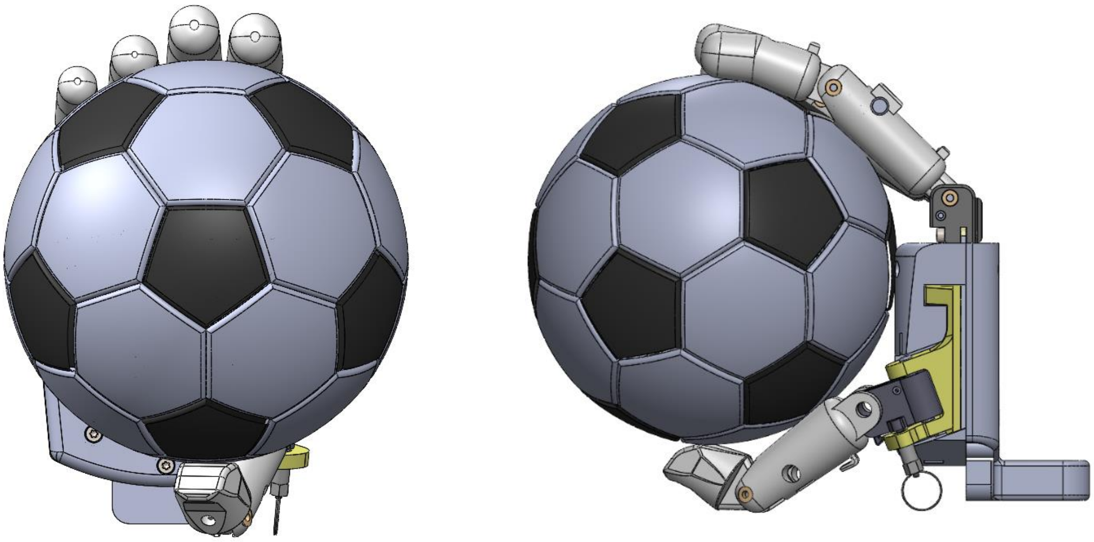


Figure 106 Spherical grasp, mini soccer ball

In order to show the other possible position of the thumb, the lateral pinch grasp is shown in Figure 107 using the key from the YCB object set.

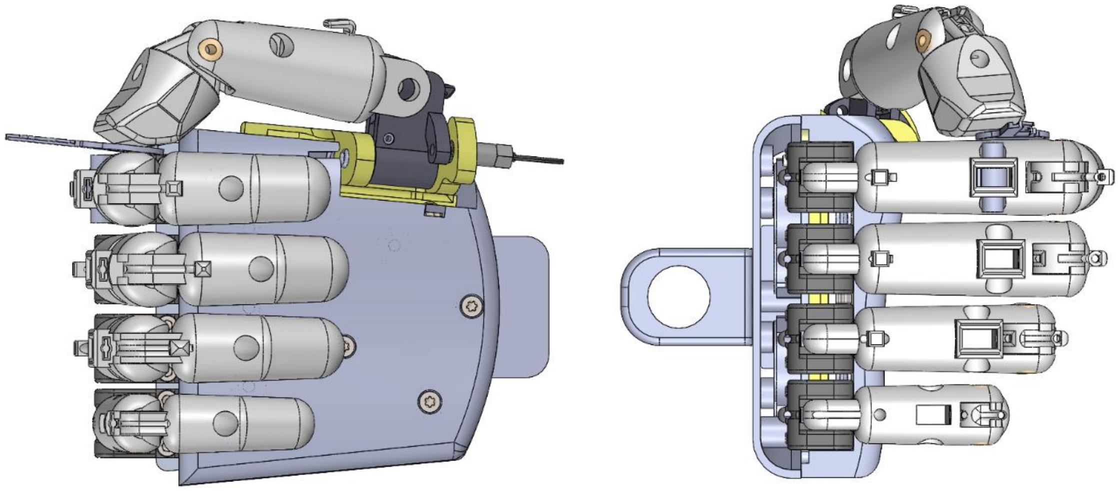


Figure 107 Lateral pinch grasp, key

10. Assembly

In this section, the components used for the hand prosthesis and the process of assembly are shown.

10.1. Components

Figure 108 and Figure 109 show the hand assembly and the harness, triceps cuff and Pro Cuff components.

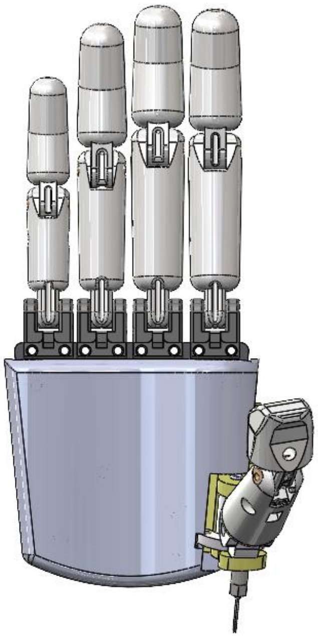


Figure 108 Hand prosthesis assembly

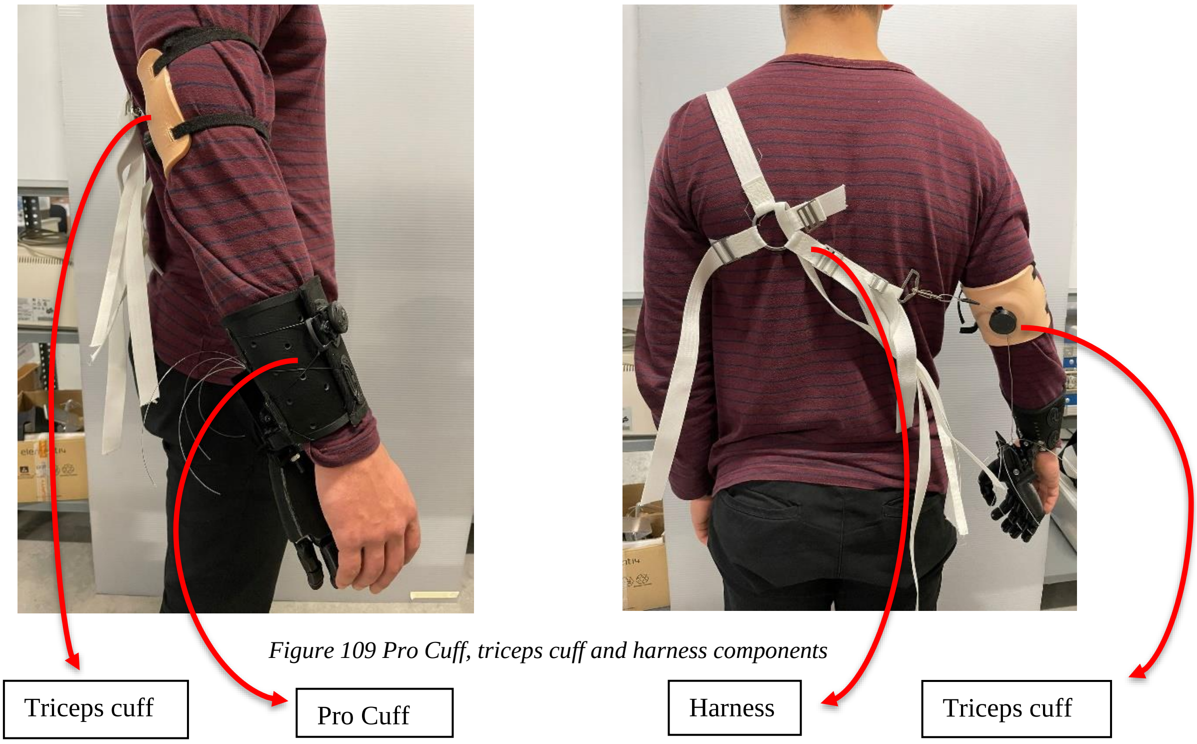


Figure 109 Pro Cuff, triceps cuff and harness components

10.2. Assembly process

- Take the structural base plate
- Take the bottom and top guidance plates
- Take the bolts for the underactuation system
- Take the sliders, the pulleys and the pulling slider
- Locate the bolts in the slots of the bottom guidance plate
- Add the guidance top plate
- Add one of the sliders on top of the guidance top plate and pass the bolts through the holes of the plate
- Add the pulleys to the bolts
- Add the second slider on top of the pulleys
- Use double hex nuts to allow the pulleys to have some clearance
- Take the pulling slider and a pulley and locate them in the bolt of the main slot which is used to pull the mechanism
- Add the last pulley to the cable redirection component located on the guidance top plate
- Screw the metacarpophalangeal joints to the metallic plate
- Take the abduction component for the thumb and the elastic slotted pin and put it in the thumb housing in the guidance top plate
- Take the thumb proximal phalanx and add a one of the metallic pins to the bottom part of the thumb
- Add the FilaFlex pin supports, a metallic pin and the thumb distal phalanx and locate it on the upper holes of the thumb

- Repeat the last to steps with every other finger, but locating them in the metacarpophalangeal joints
- Add the cable tendons and pass them through the whole system, including fingers and underactuation system
- Take the springs for the distal phalanges and include them in their respective housings
- Take the rubber band and put it in the extrusions located in the thumb and its abduction component
- Take the springs for the proximal phalanges and the fixing components and screw them to the holes in the dorsal part of the metallic plate
- Add the cables for the extension mechanism, making a knot in the springs and in the cable housings of the fingers
- Take the bowden cable and locate it in the pulling slider
- Take the palm casing
- Get the end of the cable bowden through the designed hole in the palm casing
- Take the dorsal case
- Screw the palmar case to the guidance top plate, guidance bottom plate, metallic plate and dorsal case in that order.
- Attach the prosthesis to the Pro Cuff
- Guide the bowden cable through the triceps cuff
- Put on the triceps cuff
- Put on the harness and attach the bowden cable to the harness

11. Viability

This section will evaluate the technological and economic viability of the presented design of a mechanical system for underactuation of hand prostheses.

11.1. Technological viability

The research carried out in the Final Degree Project, as well as the manufacturing of the hand prosthesis and the underactuation system parts using 3D printing are technologically viable, since the different tools (SolidWorks, PDM, CoLiDo 3D printer) and materials that were used do not present a technological problem.

11.2. Economic viability

The materials used in the manufacturing of the hand and underactuation mechanism prototypes are cheap materials that allow more people to afford these prostheses, being this solution cheaper than other available options in the market.

The economic viability of this project is assessed in the following way and by making the following assumptions.

The average cost of the prosthesis is established at around 300€ retail price [57]. By making a study of the number of hand prostheses sold per year in the world, a market share that can be acquired is established, for example at 30 prostheses per year (considering this is a small project in comparison with the already commercially available prototypes and businesses). In addition, the price charged by the designer of such a prototype is considered, which, considering the engineering degree, will be about 25 €/h. Assuming that the duration of the design process has been approximately 200 hours, this means that the engineer's salary will be 5000€. This added to the technician fees, hardware and software amortization and industrial components (this information will be explained in further detail in the budget section) gives a total of 8093,12€. This value is considered only for one hand, in order to analyse the viability, the 30 prototypes which are sold in a year must be taken into account. As it will be further explained in section 4 of the budget, 5000€ correspond to the engineer fees; 1500€ for the laboratory technician fees; 1426,99€ for the amortisation of software and hardware and 166,13€ for the manufacturing materials.

For the prototypes which are sold in a year (30 units), the first year every expense is consider, including the engineer fees, the technician fees, the materials for each of the prototype and the amortisations. For the following years, only the materials for each prototype (30 units x 166,13€) and the technician fee (1500€) are considered, giving a total value of 6483,90€. Table 4 shows the economic viability analysis.

Year	**1**	**2**	**3**	**4**
Expenses	12910,89€	6483,90€	6483,90€	6483,90€
Earnings	9000€	9000€	9000€	9000€
Cash Flow	-3910,89€	-1394,79€	1121,31€	3637,41€

Table 4 Economic viability analysis

Considering those hypotheses, a return on the initial investment is obtained in the period of approximately 2,5 years, this being an admissible period to consider that the project is economically viable.

12. Tests and results

The essays planned to be carried out have been mentioned throughout the paper. These tests were two: the AHAP, which consists of performing different grips with a selected number of objects from the YCB objects set, and second, the WBT test, which was created, as mentioned above, in this research group, as part of the development of this project.

Due to time limitations, it was not possible to carry out those tests before the end of this document, but they will be done as soon as the designed pieces can be printed and the rest of the components acquired. However, due to the design and the planning that this has entailed with respect to previous projects carried out by the author of this work, better results and a better performance of the system are expected.

13. Conclusions

This project presents the complete design of an anthropomorphic body-powered hand prosthesis, with special emphasis on the underactuated system that allows the motion of the different DOFs with a single cable actuation from a body harness.

As mentioned throughout the document, the aim was to create and design a differential system that allows the rest of the fingers to continue flexing, even if one of them is blocked in contact with an object, allowing by this a more efficient and adaptative grasping.

With reference to the thumb, a system has been designed that allows to regulate the AB/AD motion in two different positions. This allows to increase the number of possible grasping types considerably with respect to having only one position, as done in other existing hand prostheses. This AB/AD is necessary when grasping with very different thumb configurations, e.g., a spherical grasping versus a lateral pinch grasping.

It is worth noting that this was a complicated challenge for me. Designing a complete prosthesis requires a great deal of research, as well as many hours of work and tests that do not always turn out well. The initial and main objective of this project was to design an underactuation system for an existing prosthesis, however at the time of starting the work, this prosthesis did not exist, as the intention was to look for a new one, therefore, the author of this document immersed himself in the design of a new complete prototype, including from the fingers and stiffness plates to the underactuation and AB/AD system. Indeed, the fact of having to design the complete prototype of the prosthetic hand and not only the underactuation system has led to significant delays in the making of both this document and the prototype. This led to not being able to print and test the prosthesis in time, leaving it as a proposed design to, later on, print, assembly and carry out the tests mentioned throughout the document, thus allowing the functionality to be checked and, also, comparing this new prototype with previous projects carried out by the author of this document.

As possible design improvements that have occurred after the completion of the whole document, it should be mentioned that for the final UNIQUE-HAND project the AB/AD system of the thumb will have a flexible part in the palmar case that will allow to protect in a better way the mechanisms that it houses.

This has been an incredibly enriching and challenging experience. However, that is what the degree in which this project is framed, engineering, is all about, finding solutions to problems that arise as one progresses through the different stages, both in design and in life.

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II. ANNEXES

1. Spring calculations

In order to select the springs to maintain the extension of the phalanxes and guarantee the return of them to the initial position.

Here there are calculations for the thumb finger, which is the heaviest among the fingers. The calculations for the middle and ring finger are similar to the index ones.

1.1. Thumb

To calculate the needed spring load, first the weight of the proximal phalanx is used.

$$P = m \cdot g$$

$$P = \frac{25,48}{1000} \cdot 9,81$$

$$P = 0,25\ N$$

The distance considered in order to calculate the torque is half of the distance of the whole finger.

$$L_1 = 58\ mm$$

$$M_1 = d_1 \cdot P$$

$$M_1 = 58 \cdot 0,25$$

$$M_1 = 14,5\ N \cdot mm$$

The distance d_1 is the distance from the cable to the middle rotation axis of the finger.

$$d_1 = 9,25\ mm$$

Then the needed force to maintain the extension is obtaining by equalling the torques:

$$M_1 = M_2$$

$$P \cdot d_1 = F_2 \cdot d_2$$

$$F_2 = \frac{P \cdot d_1}{d_2}$$

$$F_2 = 1,56\ N$$

Thus, the selected spring for the thumb is a commercially available constant load spring with 1,6 N.

1.2. Little finger

To calculate the needed spring load, first the weight of the proximal phalanx is used.

$$P = m \cdot g$$

$$P = \frac{12{,}2}{1000} \cdot 9{,}81$$

$$P = 0{,}12\ N$$

The distance considered in order to calculate the torque is half of the distance of the whole finger.

$$L_1 = 44{,}15\ mm$$

$$M_1 = d_1 \cdot P$$

$$M_1 = 44{,}15 \cdot 0{,}12$$

$$M_1 = 5{,}3\ N \cdot mm$$

The distance d_1 is the distance from the cable to the middle rotation axis of the finger.

$$d_1 = 5{,}15\ mm$$

Then the needed force to maintain the extension is obtaining by equalling the torques:

$$M_1 = M_2$$

$$P \cdot d_1 = F_2 \cdot d_2$$

$$F_2 = (P \cdot d_1)/d_2$$

$$F_2 = 1{,}029\ N$$

Thus, the selected spring for the thumb is a commercially available constant load spring with 1,03 N.

1.3. Distal phalanxes

For the distal phalanx the spring needs to be able to withstand the stress generated by both the spring of the proximal phalanx and its own weight.

First the force that the weight of the distal phalanx produces is calculated.

$$P = m \cdot g$$

$$P = \frac{12{,}12}{1000} \cdot 9{,}81$$

$$P = 0{,}12\ N$$

Then the torque generated by this phalanx is calculated.

$$L_1 = 26\, mm$$

$$M_1 = L_1 \cdot P$$

$$M_1 = 26 \cdot 0{,}12$$

$$M_1 = 3{,}12\, N \cdot mm$$

The load that the spring for the proximal phalanx implies in the system is considered. F_1 being the load of the spring=1,61 N, multiplied by the distance to the axis of rotation D_1=9,25 mm.

Obtaining the second torque that influences the equation.

$$M_2 = F_1 \cdot D_1$$

$$M_2 = 14{,}89\, N \cdot mm$$

Then adding this two values and dividing by the distance from the position of the cable in the distal phalanx to the axis of rotation, the force of the distal phalanx spring is obtained.

$$M_2 + M_1 = 18{,}01\, N \cdot mm$$

$$F_2 = \frac{18{,}01}{11}$$

$$F_2 = 1{,}63\, N$$

The selected spring with constant force selected from the catalogue is the one with a force of 1,7 N.

2. Cable length excursion

Using the measure feature available in SolidWorks, the distance that the cable varies during the flexion and extension movements is obtained. The distance is obtained subtracting the length of the cable at maximum extension to the distance of the cable at its maximum flexion. These obtained distances are shown in Figure 110 and Figure 111.

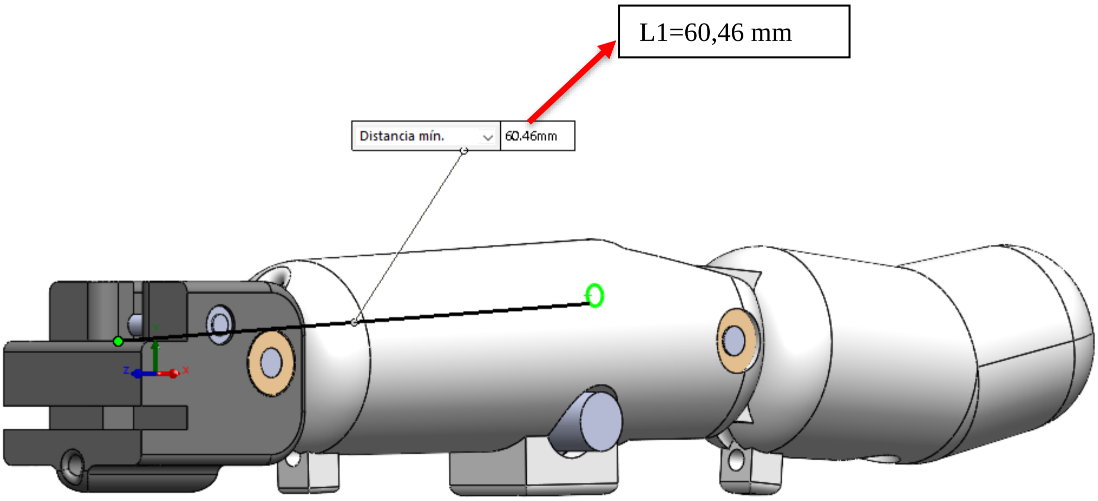


Figure 110 Distance at maximum extension

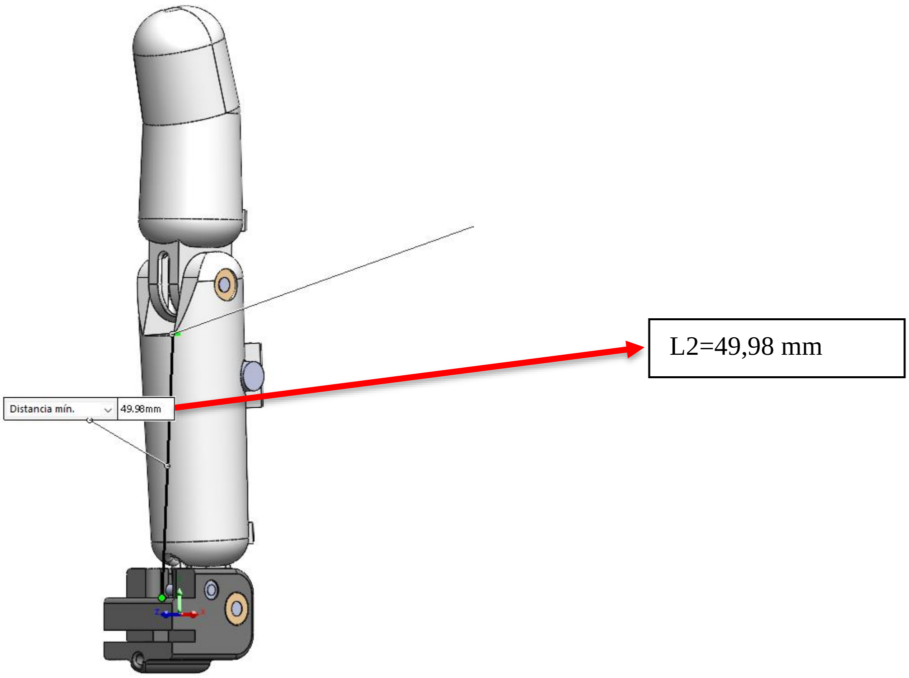


Figure 111 Distance at maximum flexion

Therefore, the variation in cable length is:

$$\Delta l = L_2 - L_1$$

$$L_1 = 60{,}46\ mm$$

$$L_2 = 49{,}98\ mm$$

$$\Delta l = 60{,}46 - 49{,}98$$

$$\Delta l = 10{,}48\ mm \sim 10{,}5\ mm$$

The selected distance for the slots has been deciding according to the previous section calculations. These obtained results about the length variation of the cable during the extension and flexion of the fingers led to designing the slots with enough distance to complete the movement and adding extra displacement as a security coefficient in case one of the fingers is blocked and the others need to rotate.

Finally, the selected distance was of 24,5 mm for the slots that guide the bolts of the underactuation system.

With the slots located in the sliders it is the same principle, the selected distance is the necessary to allow the slider to rotate and allow extra movement if one of the fingers is blocked.

3. Finite element analysis

Next sub-sections show the finite element analysis (FEA) of some selected parts of the hand in order to study the resistance and deformation of those components when having to bear the loads that the hand suffers when grasping an object.

3.1. Slider bar

In order to analyze the slider bar component, the most unfavorable situation was chosen. This case occurs at the moment of maximum flexion of the fingers, where this component supports the force of the tendons that are redirected towards the fingers, as well as the force of the tendon that pulls on this piece itself. The selected loads were extracted from previous work related to the subject matter of the project [58].

The load, which can be seen in pink color and has a value of 40N, that is considered for this analysis is the force that the tendon that is attached to the bolt in the middle of the component. The restrictions are also included in the model and can be seen in green and blue in Figure 112.

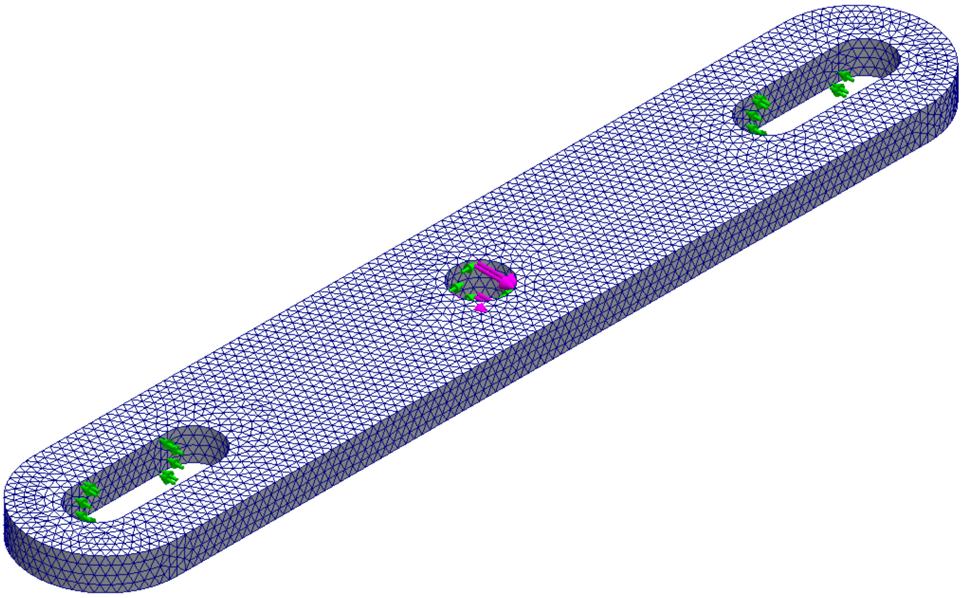


Figure 112 Slider bar, loads and restrictions

As it can be seen in Figure 113, the maximum stress is far below the elastic limit with a maximum value of 3,5 MPa.

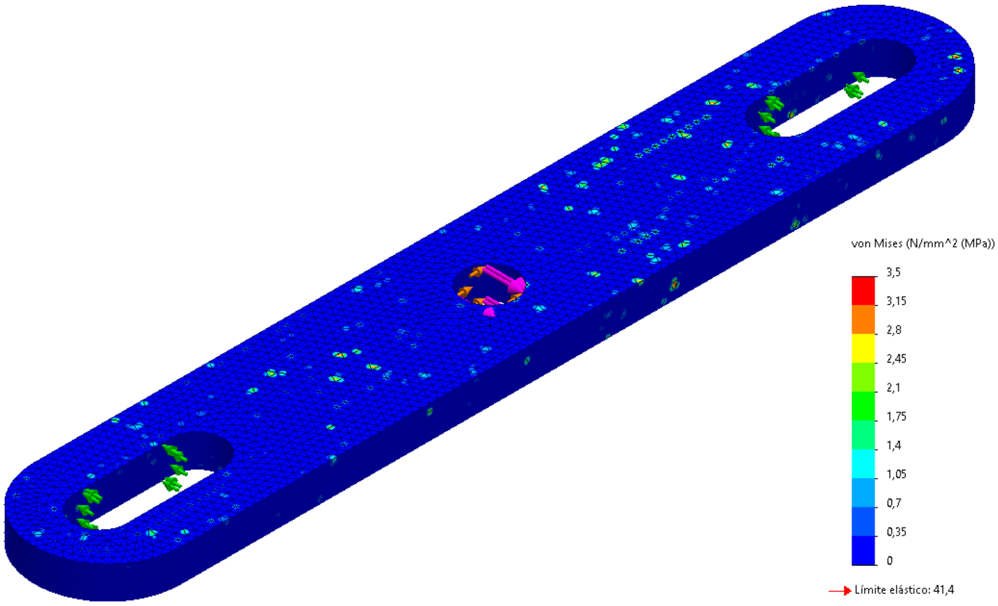


Figure 113 Slider bar FEA, stress

Figure 114 shows the displacements of the slider bar, giving values that are negligible due to their low value.

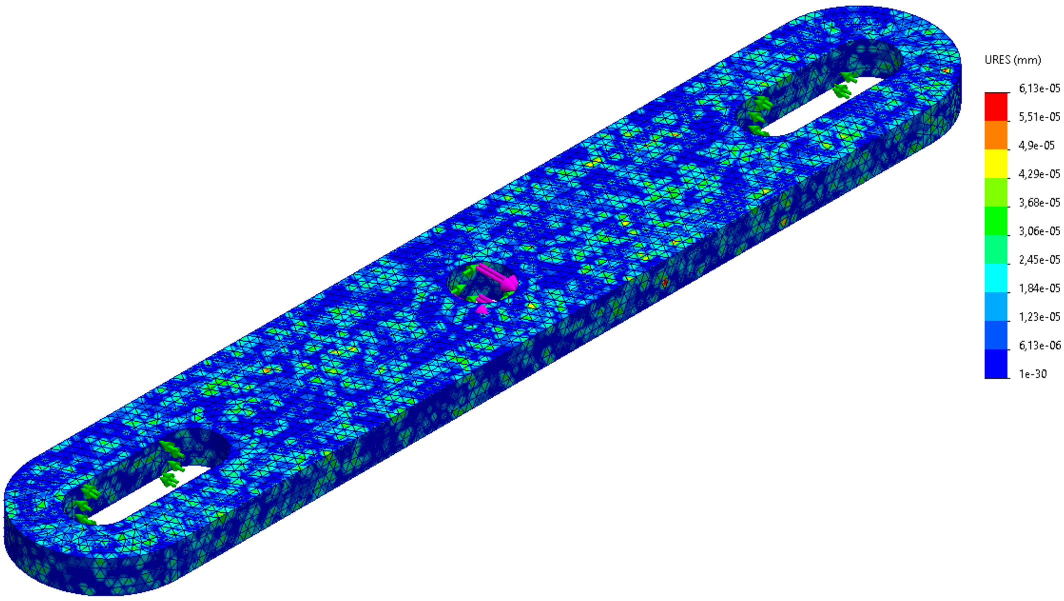


Figure 114 Slider bar FEA, displacements

These analysis confirm the viability and resistance of the component.

3.2. Pulling slider

The procedure for this component is very similar to that used for the slider bar. The applied force is meant to be that which the bowden cable applies to the component, as well as the opposite load that the tendon from the underactuation system adds.

The considered situation is that the part is in equilibrium in the maximum flexion of the fingers, thus it cannot move, so the bottom of the part is considered as a fixed geometry.

Figure 115 shows the applied loads (pink, 60N) and the movement restrictions (green) in order to simulate the moment of maximum flexion.

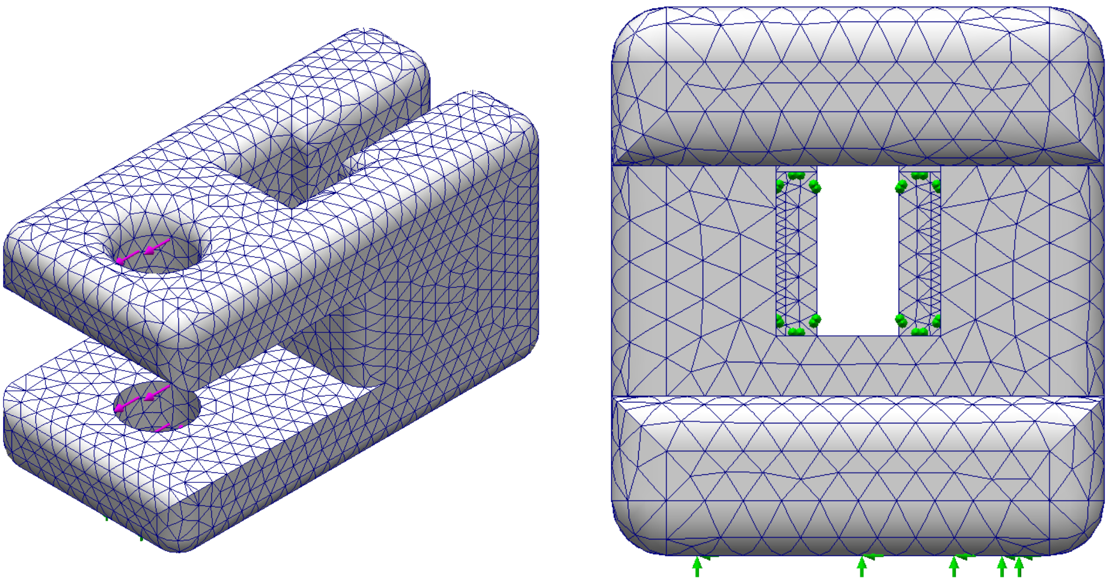


Figure 115 Pulling slider, loads and restrictions

Below, in Figure 116, the images show the stress that the component is subjected to, which is lower than the elastic limit of the material.

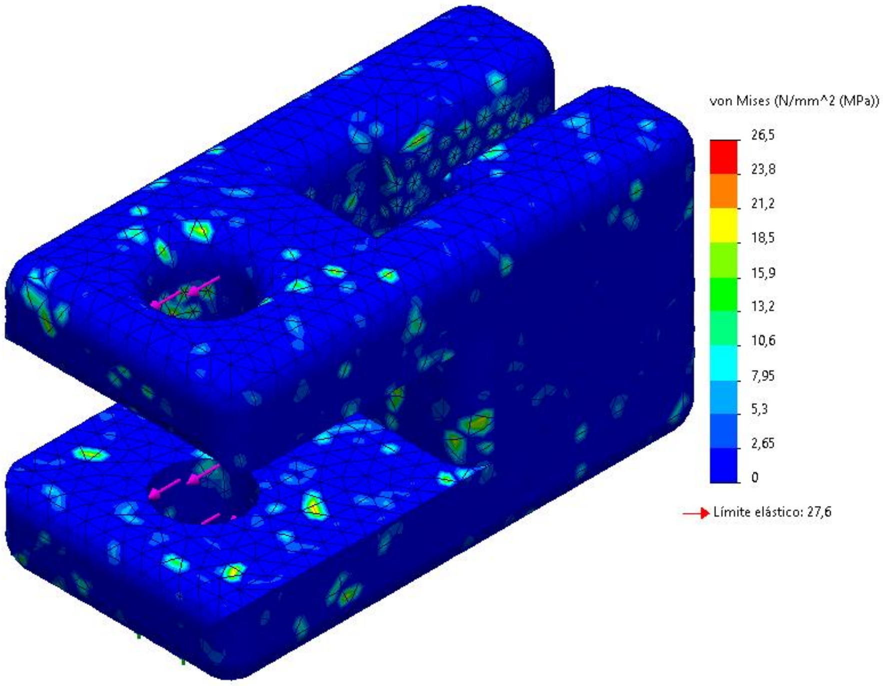


Figure 116 Pulling slider FEA, stress

In addition, in Figure 117, the displacements are shown, giving also negligible values, meaning this that the component is resistant enough.

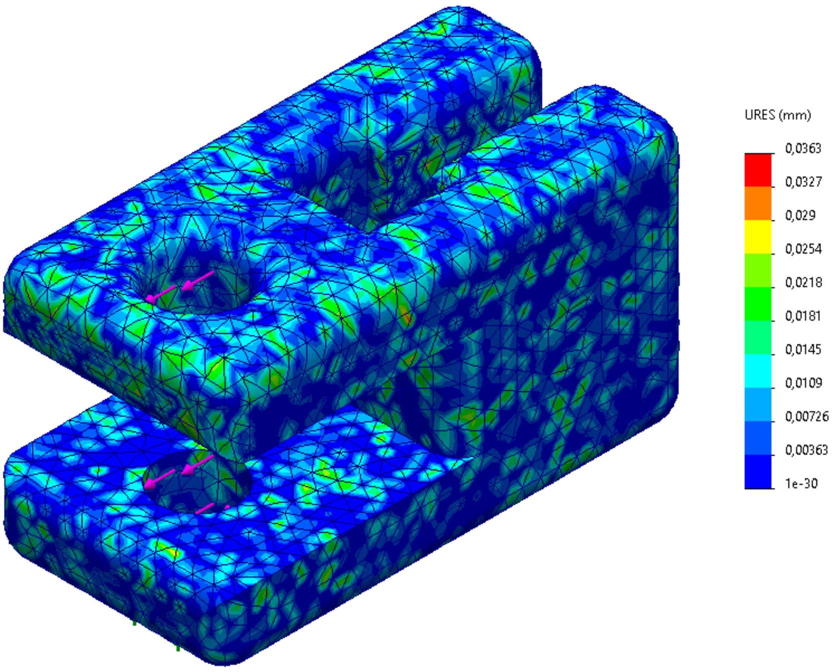


Figure 117 Pulling slider FEA, displacements

3.3. Index finger

The followed procedure with the index finger is a bit more complex than in previous components.

First of all, the distal phalanx is analyzed. This is made by applying loads, as shown in a section view in order to see the restrictions that are in the holes inside of the component (Figure 118), to the last segment of the phalanx (5N), where the spring's cable is attached (1,7N) and applying a roller restriction where the cable is attached. A roller is placed where the knot of the tendon is made, simulating the DOF that it has. A fixed hinge is located in the rotation axis of the distal phalanx with respect to the proximal phalanx and a roller is located where the extension cable from the spring is attached.

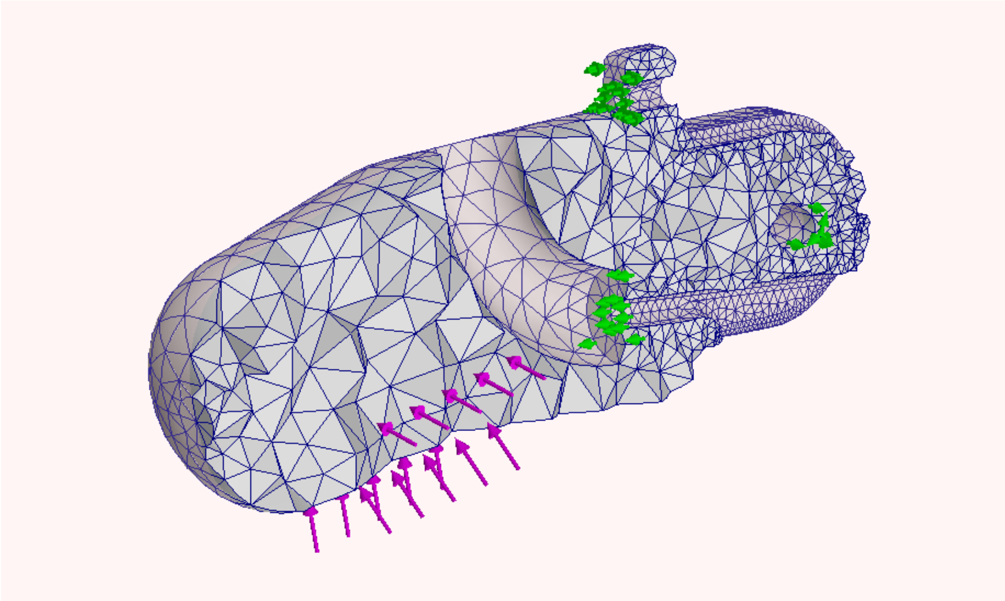


Figure 118 Index's distal phalanx, loads and restriction

Figure 119 shows the results of the finite element analysis of the distal phalanx, also in a section view due to the fact that the maximum stress is located in the cable housing hole.

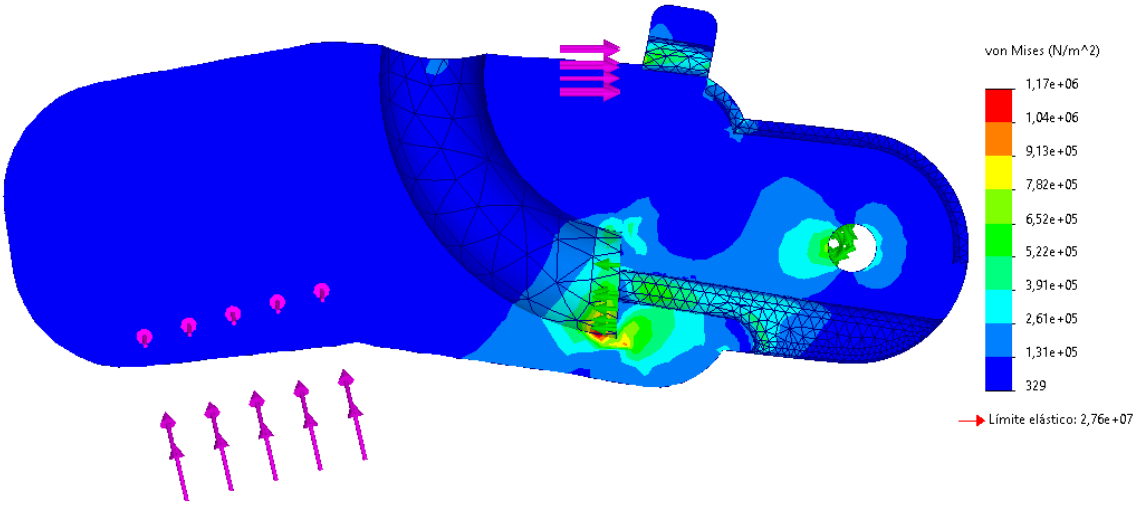


Figure 119 Index's distal phalanx FEA, stress

The obtained values in the stress analysis are below the elastic limit of the material.

Next images show the analysis for the displacements in the component, shown in Figure 120.

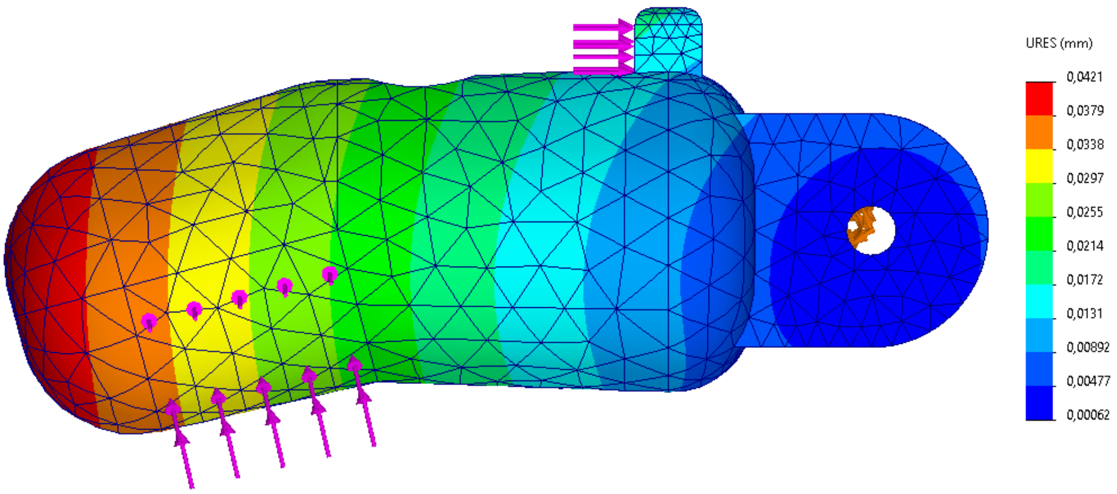


Figure 120 Index's distal phalanx FEA, displacements

The obtained values mean negligible deformations in the component, which added to the resistance verification, makes the component viable and resistant enough.

The next step is to obtain the resultant forces obtained in the joint between the distal and proximal phalanx. This is an option that SolidWorks provides its users with. This resultant load (18,2N) can be seen in Figure 121.

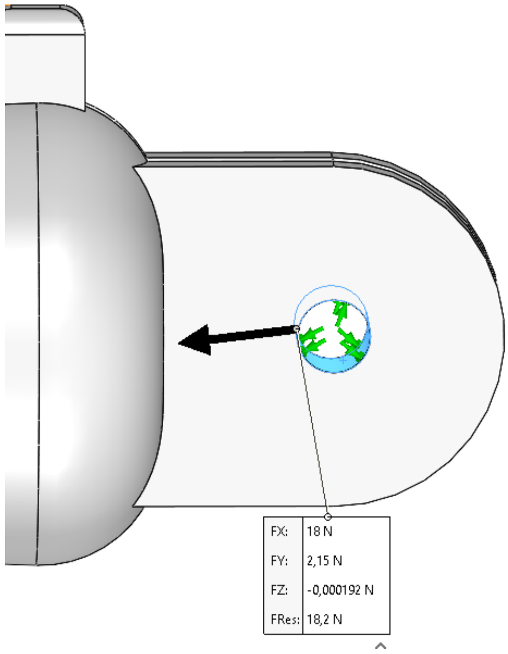


Figure 121 Index's distal phalanx, resultant forces

Once the load is obtained, the procedure is very similar to the distal phalanx one. The forces are applied in the previously mentioned joint (see Figure 122) and the load that the spring applies (1,6N) is also applied where the spring's cable is attached, as shown in Figure 123 together with the stress values, then the fixed hinge is applied to the joint that connects with the metacarpophalangeal joint.

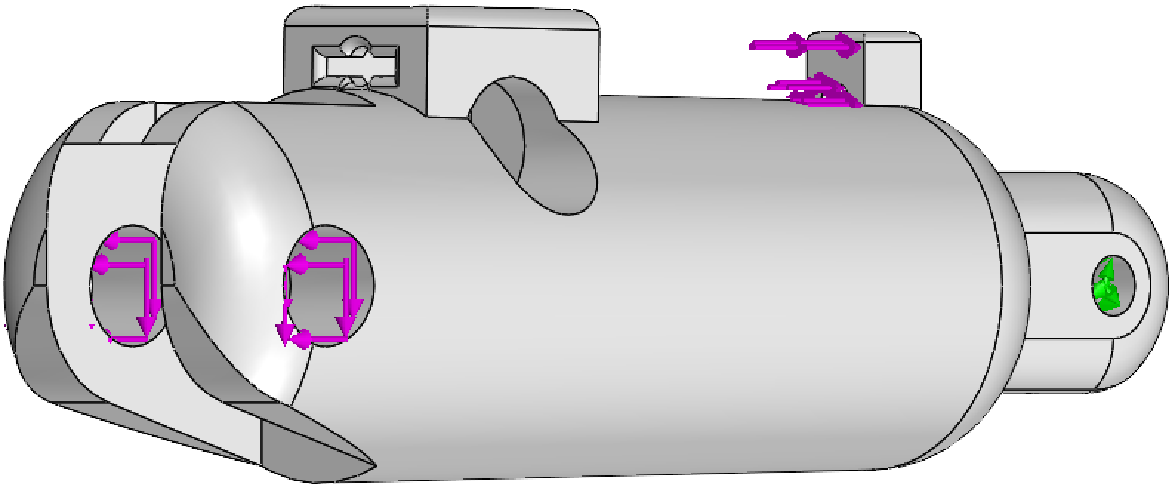


Figure 122 Index's proximal phalanx loads and restrictions

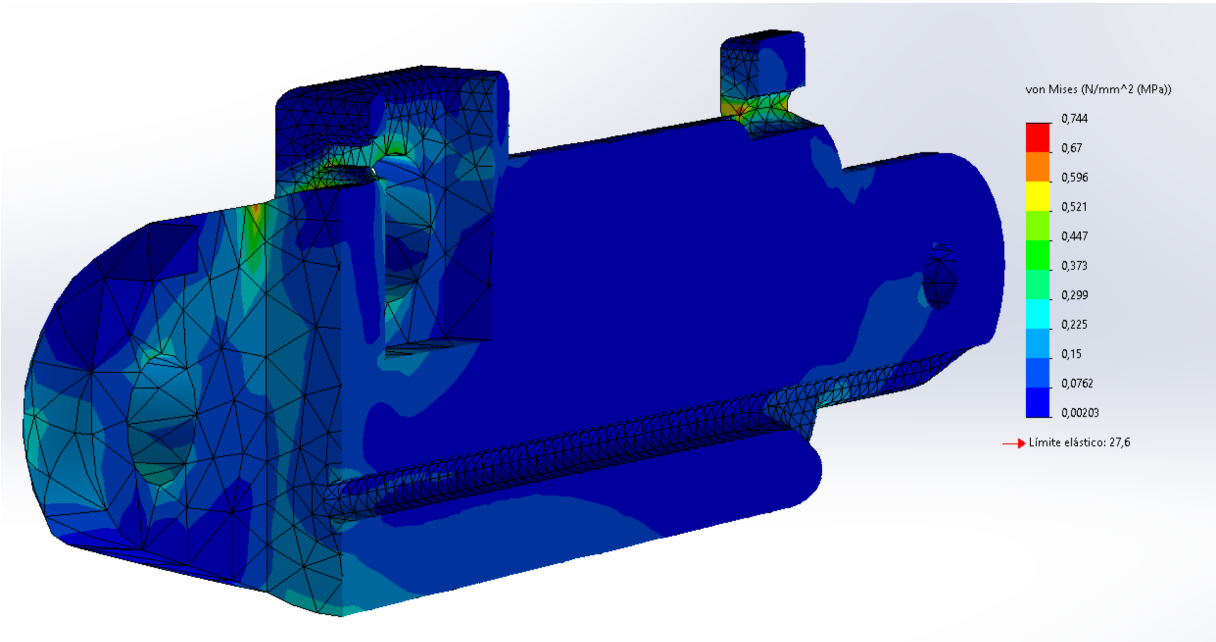


Figure 123 Index finger's proximal phalanx FEA, stress

Below, in Figure 124, the displacements analysis is shown.

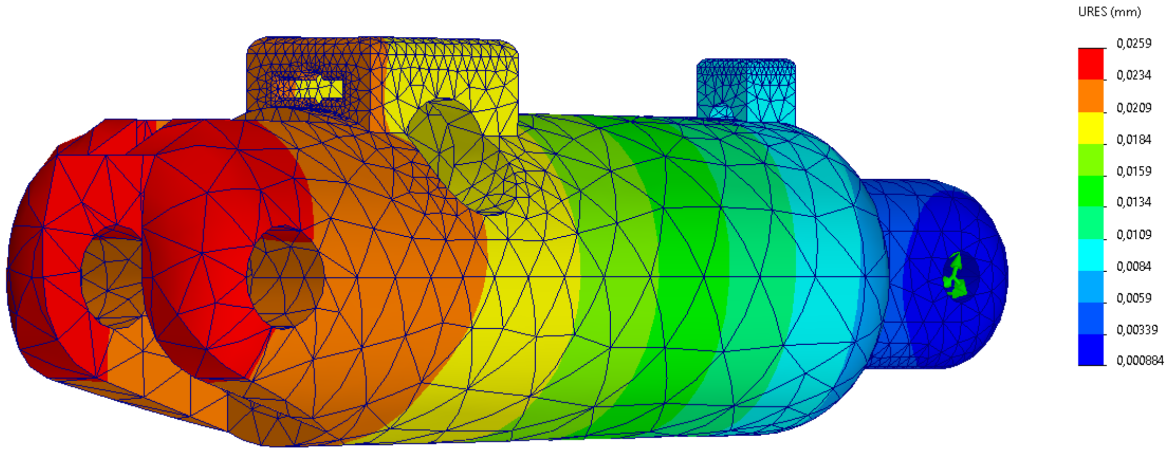


Figure 124 Index finger's proximal phalanx FEA, displacements

3.4. Thumb

The procedure for the thumb is very similar to the one carried out with the index finger. The most critical situation is selected, which in this case is the maximum flexion while grasping an object, then the resultant forces are applied to their respective places in the 3D component, and the analysis is carried out. The force is applied in the estimated contact point of the distal phalanx with an object and the value for this load is 7N.

The different considerations are considering fixed hinge located in the joint between the distal and proximal phalanges, torque applied in that joint and an external force caused by the grasping of the object (see Figure 125).

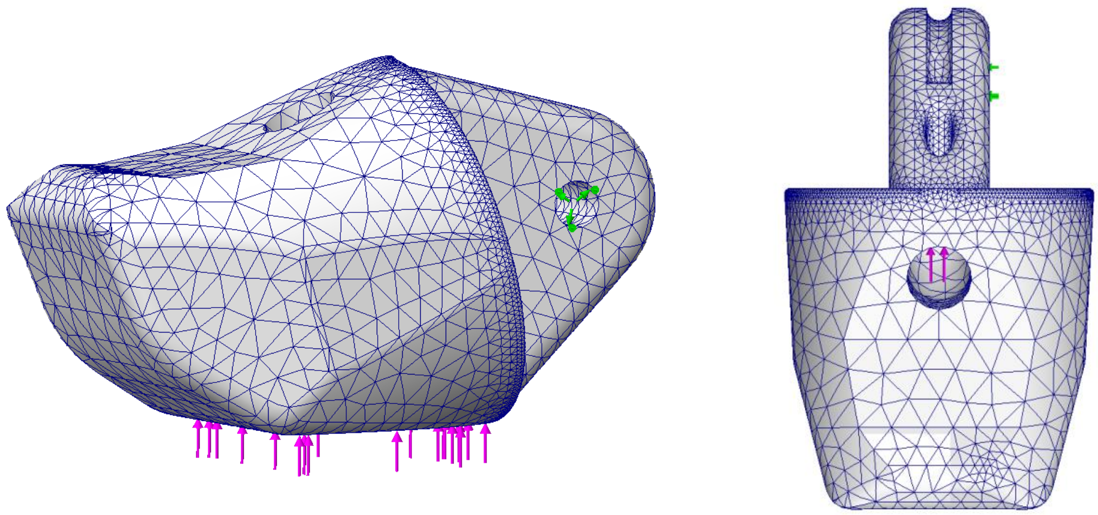


Figure 125 Thumb's distal phalanx, loads and restrictions

The stress analysis is shown in Figure 126.

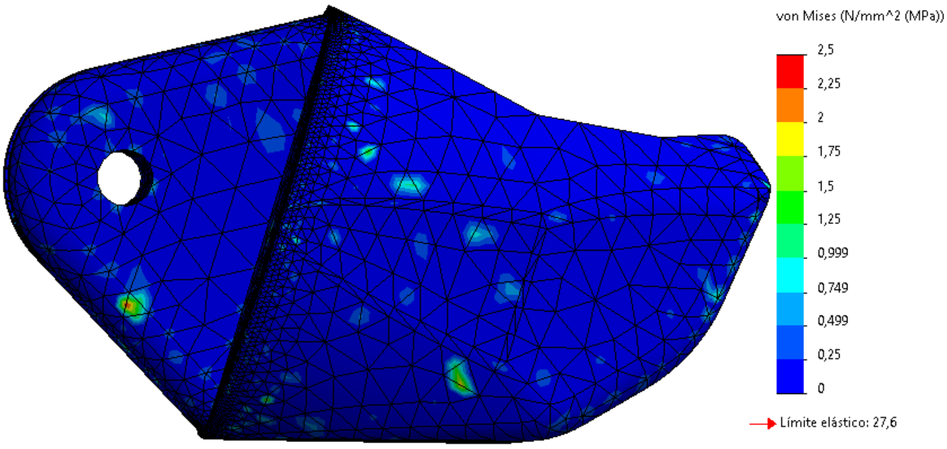


Figure 126 Thumb's distal phalanx FEA, stress

Below, the displacements results of the FEA are shown in Figure 127.

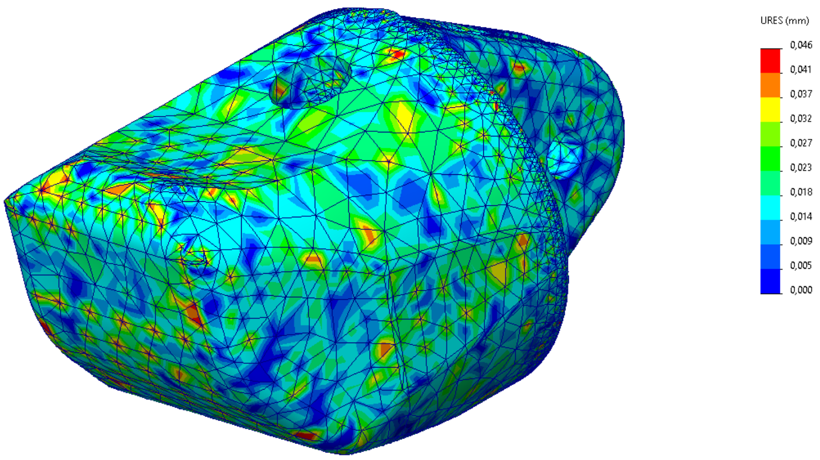


Figure 127 Thumb's distal phalanx FEA, displacements

As previously made above in the index finger, the resultant forces are obtained in the joint. Then, those forces are transferred to the analysis of the proximal phalanx. The resultant forces obtained in the distal phalanx can be seen below in Figure 128.

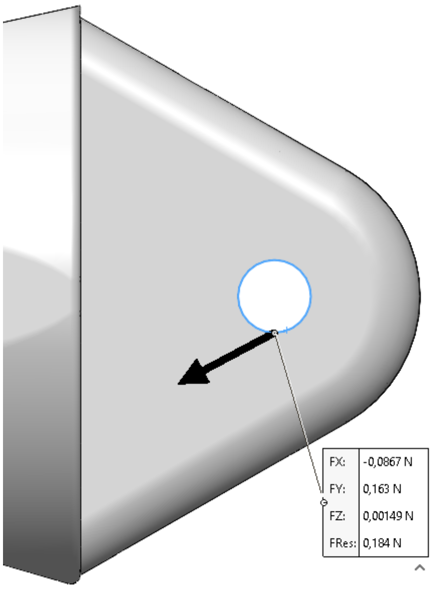


Figure 128 Resultant forces in the distal phalanx of the thumb

Figure 129 shows the loads and restrictions of the thumb's proximal phalanx.

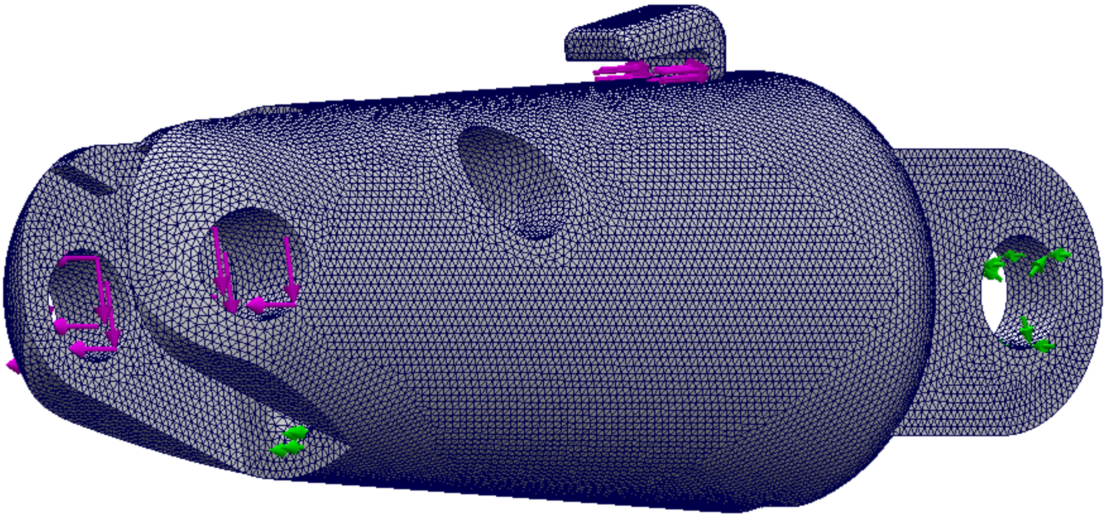


Figure 129 Thumb's loads and restrictions

Following this previous step, the resultant forces are introduced in the proximal phalanx, the boundary conditions are stablished (in this case 1 fixed hinge) and the analysis are made. The stress results are shown below in Figure 130, showing values far below the elastic limit of the material. A section view is shown in order to see better the results.

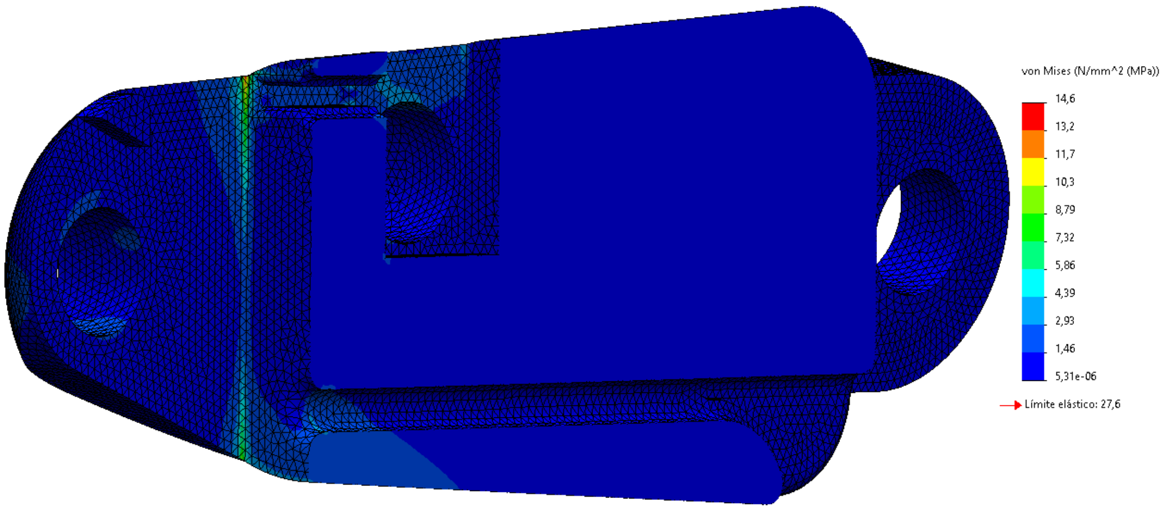


Figure 130 Thumb's proximal phalanx FEA, stress

Following the stress results, the displacements results are also obtained, shown in Figure 131, which also show negligible values.

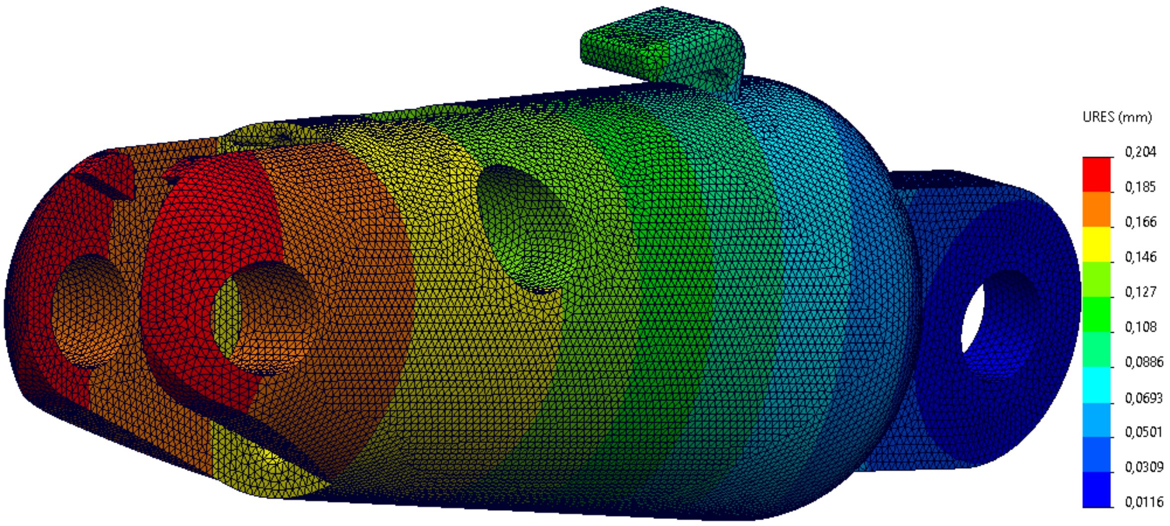


Figure 131 Thumb's proximal phalanx FEA, displacements

III. BUDGET

The budget considers the engineer and laboratory technician fees, the software amortizations, the hardware amortizations and the cost of the components.

1. Working staff

The next calculations are estimations about the salary that the author of this document had obtained, due to the fact that, this project being involved in the FDP development, the student hasn't obtained monetary remuneration, and there are also calculations made for the fee of the laboratory technician. These calculations are shown in Table 5.

Employee	Cost per hour (€/h)	Time (h)	Cost (€)	Total cost (€)
Mechanical Engineer	25	200	5000	6500
Technician	15	100	1500	

Table 5 Working staff fees

2. Software and hardware amortization

This section is used to estimate the cost of the hardware and software used during the development of this project. These calculations are shown in Table 6.

The equation which is used to calculate this amortization is:

$$Amortization = Cost \cdot \frac{Time\ of\ usage\ (months)}{12\,\frac{months}{year}} \cdot \frac{1}{Lifespan(years)}$$

Component	Time of usage (months)	Cost (€)	Lifespan	Cost of amortization
Laptop	4	1379	5	91,93
3D printer	0,25	500	6	1,73
SolidWorks	4	4000	1	1333,33

Table 6 Hardware and software amortization

The total cost of amortization is obtained by adding all the values obtained in the last column of the previous table, being this a total of 1426,99 €.

3. Industrial components

The commercially available components and its unitary cost, as well as the cost estimation for the PLA and FilaFlex printed components and the aluminium components, are shown in Table 7 and Table 8. It must be pointed out that the PLA and FilaFlex materials are sold in packs of 1kg and 500g respectively, so that is the quantity considered to do the calculations, even thought that is not the total quantity used in the design. With the aluminium components the same happens, an aluminium plate is bought and the components are cut from that initial plate.

Component	Unitary cost (€)	Number of units	Total cost (€)
Constant load spring	11,93	5	59,65
Constant load spring	11,93	4	47,72
			107,37

Table 7 Commercially available components cost

Material	Kilograms (kg)	Cost (€/kg)	Total (€)
PLA	1	25	25
FilaFlex	0,5	33,76	33,76
			58,76

Table 8 3D printing materials cost

4. Summarized budget

The total cost is shown in Table 9.

Concept	Cost (€)
Working staff fees	6500
Software and hardware amortization	1426,99
Industrial components	107,37
Materials	58,76
Total	8093,12

Table 9 Summarized budget

5. Cost of execution per contract

The cost of execution per contract (CEC) involves general fees, industrial benefit and taxes. The result of 8093,12€ obtained above is the cost of execution per material, as shown in Table 10, some extra values have to be added.

Concept	**Cost (€)**
Budget	8093,12
20% General fees and benefit	1618,62
Sub-total	9711,74
6% Industrial benefit	582,70
Parcial CEC	10294,44
21% Taxes	2161,83
Total CEC	12456,27

Table 10 Cost of execution per contract

IV. BID SPECIFICATIONS

1. Facultative conditions

The involved legal people in the development of this FDP are:

- The author of the document, which takes the part of responsibility for the idea, study and development of the document.
- The Universitat Jaume I, which is considered the promoter of the project, that is to say the legal person who gets the rights of deployment of the mentioned project.

2. Standards

The development of the project has been made following the UNE and ISO standards, being this related with the components that are bought and not designed, e.g., bolts, hex nuts or springs.

3. Software

The development of this project and document has been possible thanks to the usage of the following softwares:

- SolidWorks 2022 used for the modelling and designing of the different components, for the simulation of finite element analysis and for the obtainment process of the drawings.
- SolidWorks PDM to share and organize the different SolidWorks files.
- Google Drive to share text files.
- UJI VPN which allows to work from distance, simulating being in the university facilities.
- Microsoft Office, used for writing and formatting the document.
- Mendeley, used for organizing, managing and citing the external references to papers, books or websites.

4. Materials

Materials must be of high quality and meet the standards mentioned above. Commercially procured components, i.e., those not designed by the author of the project, are shown below. The aluminium alloy that has been considered is the 3003 alloy, which is the most commonly used in the industry. The temperature for the PLA extrusion must be made between 230ºC and 250ºC. *

*With the exception of the bolts and nuts which were already available in the laboratory where this project has been developed

Table 11 shows the different acquired components.

Name of the component	Reference	Supplier	Nominal load (N)	Quantity
Constant load spring	CF012-0038	SODEMANN	1,7	5
Constant load spring	CF018-0036	SODEMANN	1,61	4

Table 11 Acquired components

Table 12 shows the PLA material properties.

Property	Value
Printing Temperature	230-250ºC
Density	1,24 g/cm^3
Tensile Strength	50 MPa
Flexural Strength	80 MPa

Table 12 PLA properties

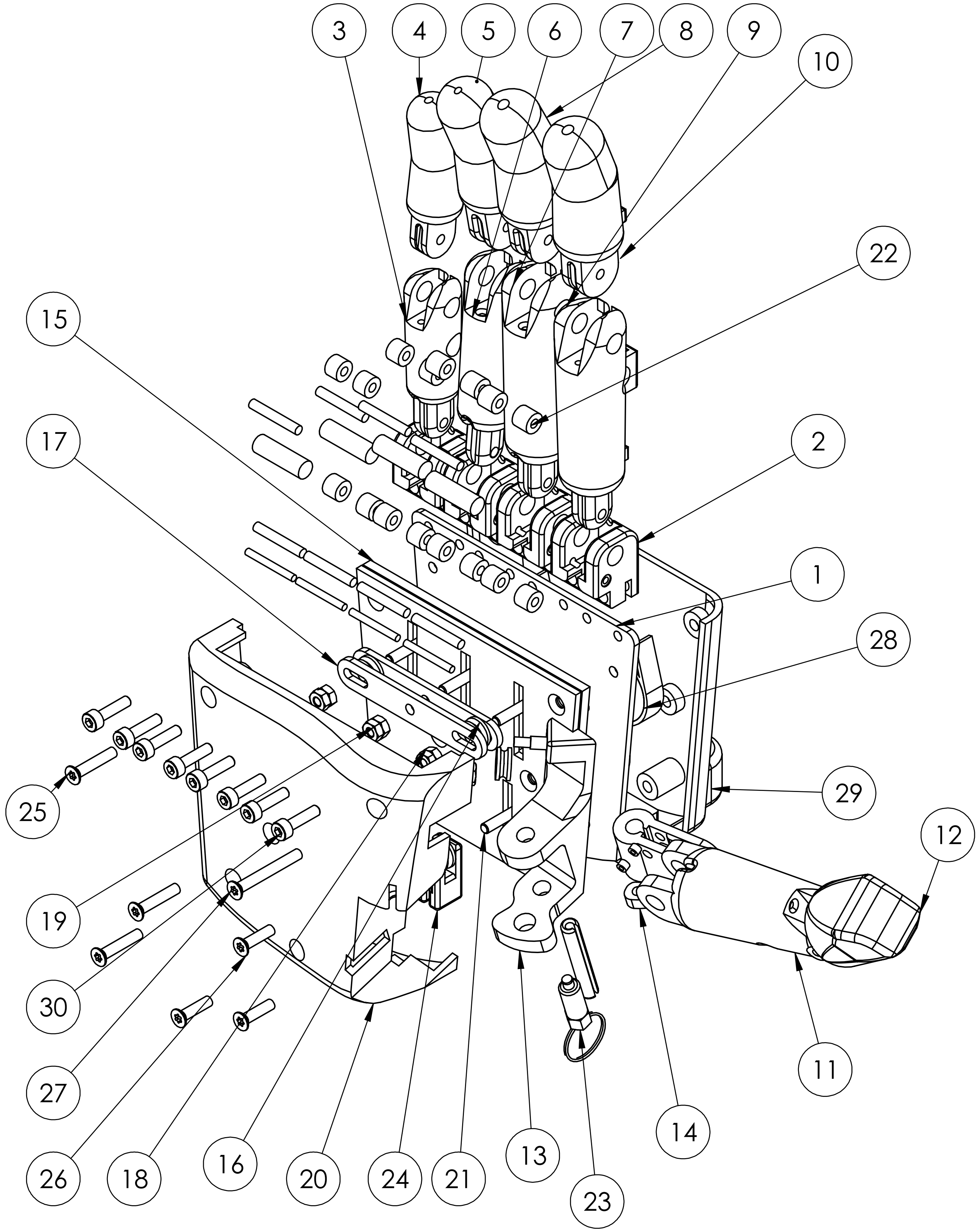
Table 13 shows the FilaFlex material properties.

Property	Value
Printing Temperature	215-250ºC
Density	1,12 g/cm^3
Tensile Strength	45 MPa
Flexural Strength	-

Table 13 FilaFlex properties

V. DRAWINGS

N.º DE ELEMENTO	N.º DE PIEZA	DESCRIPCIÓN	CANTIDAD
30	Bolts	ISO 4762 M3 x 12 - 12C	8
29	Dorsal case	PLA	1
28	Springs support	PLA	4
27	BOLTS	ISO 14581 M3x25x25-N	1
26	BOLTS	ISO 14581 M3x12x12-N	3
25	BOLTS	ISO 14581 M3x16x16-N	3
24	Pulling slider	PLA	1
23	Indexing plungers	GN 717-3-M6-A-ST	1
22	Finger joint support	FILAFLEX	18
21	Bolts	ISO 4762 M3 x 16 - 16C	4
20	Palmar case	PLA	1
19	Hex nut	ISO - 4032 - M3 - D - N	5
18	Hex nut	ISO - 4032 - M3 - D - C	4
17	Slider bar	ALUMINIUM	2
16	Pulley	PLA	4
15	Guidance bottom plate	PLA	1
14	Thumb AB/AD	PLA	1
13	Guidance top plate	PLA	1
12	Thumb distal phalanx	PLA	1
11	Thumb proximal phalanx	PLA	1
10	Index distal phalanx	PLA	1
9	Index proximal phalanx	PLA	1
8	Middle distal phalanx	PLA	1
7	Middle proximal phalanx	PLA	1
6	Ring proximal phalanx	PLA	1
5	Ring distal phalanx	PLA	1
4	Little distal phalanx	PLA	1
3	Little proximal phalanx	PLA	1
2	Metacarpophalangeal joints	PLA	4
1	Structural base plate	ALUMINIUM	1



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Propietario legal: Escuela Superior de Tecnología

Biomechanics and ergonomics

Document type:	Made by:	Date:
Design drawing	Joaquín Ibáñez	2022/11/07

Title:	Number:
Hand's Assembly	1

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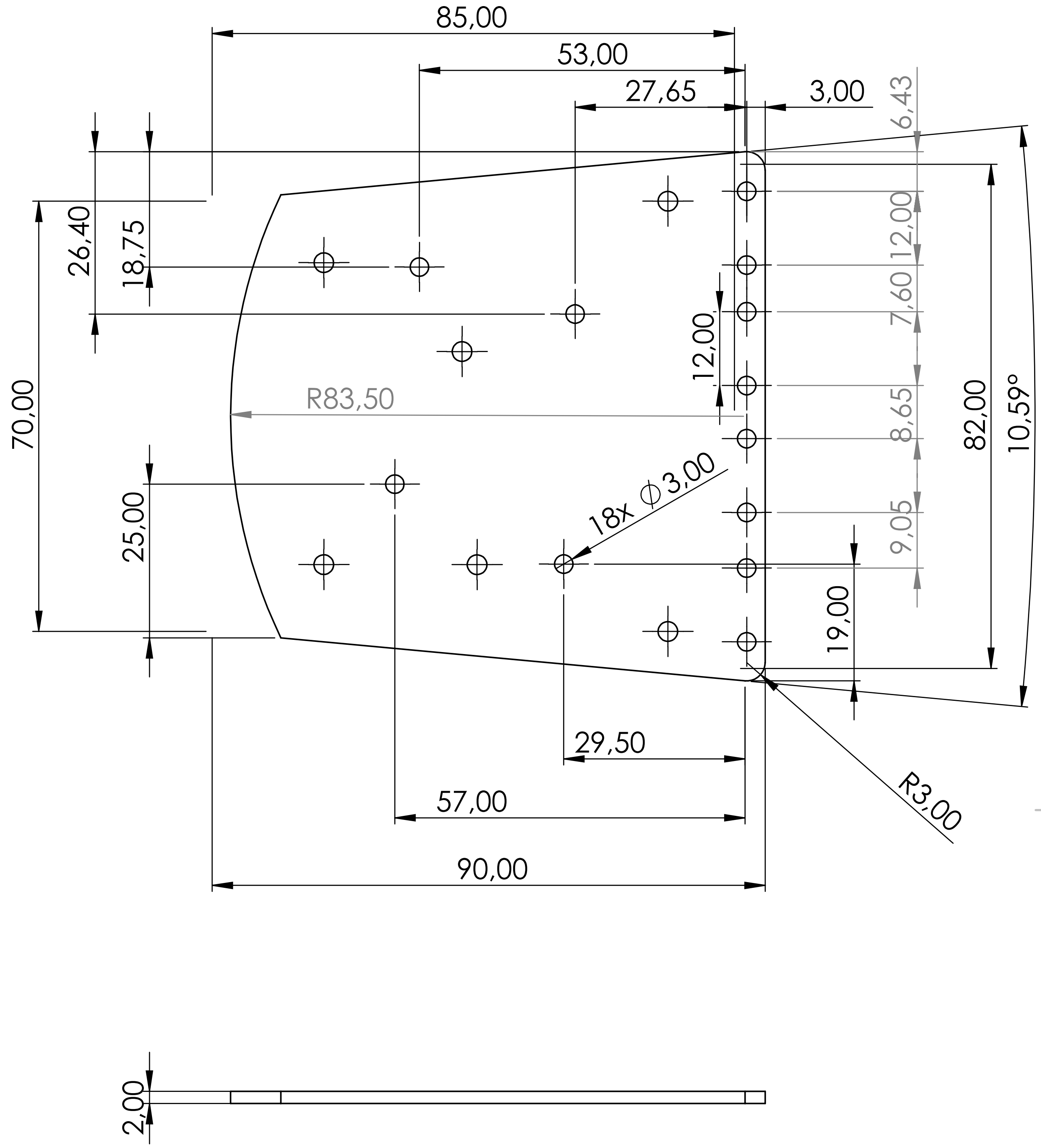

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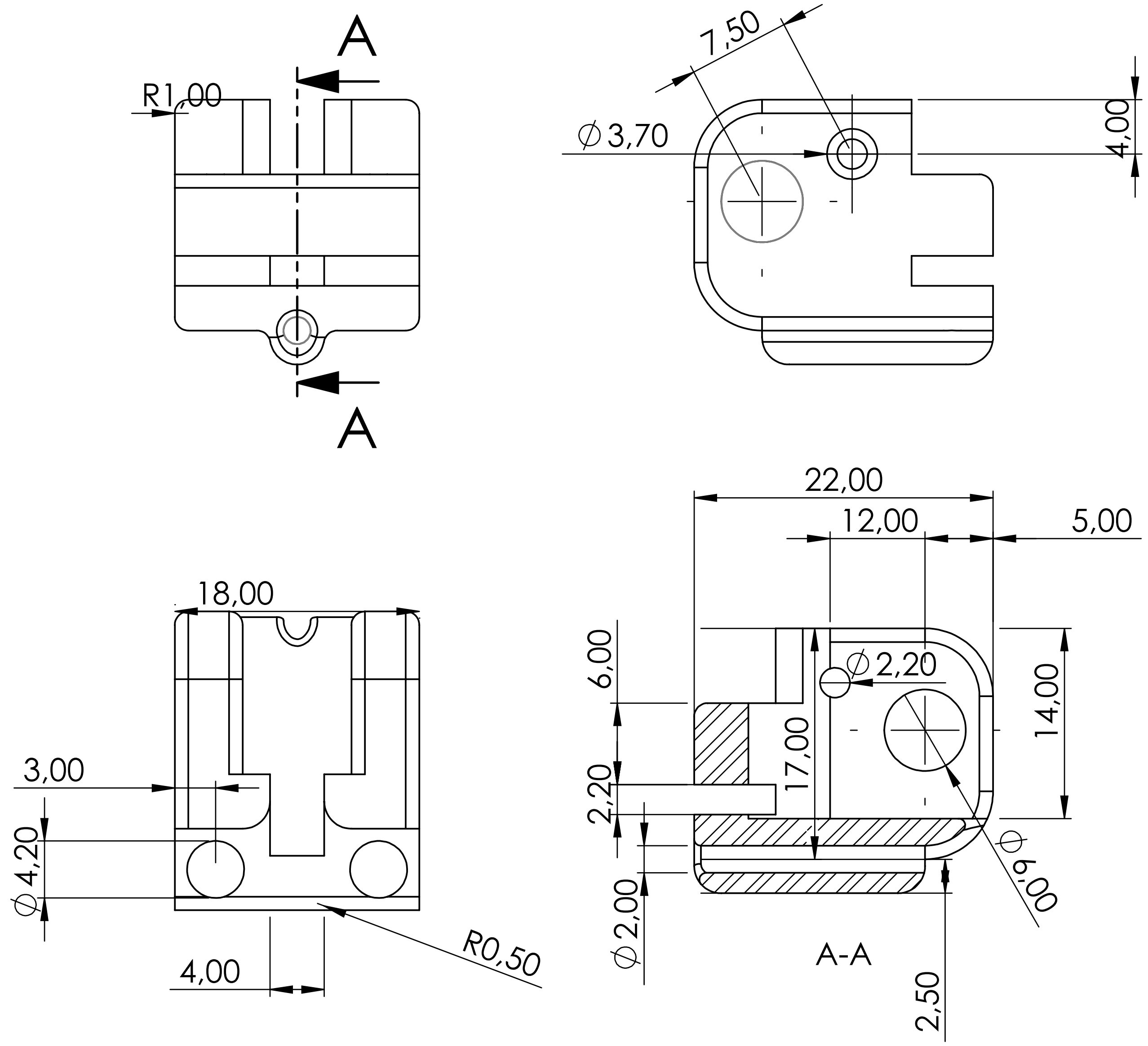

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Biomechanics and ergonomics

Document type: Design drawing

Made by: Joaquín Ibáñez

Date: 2022/11/07

Title: Metacarpophalangeal joints

Number: 3

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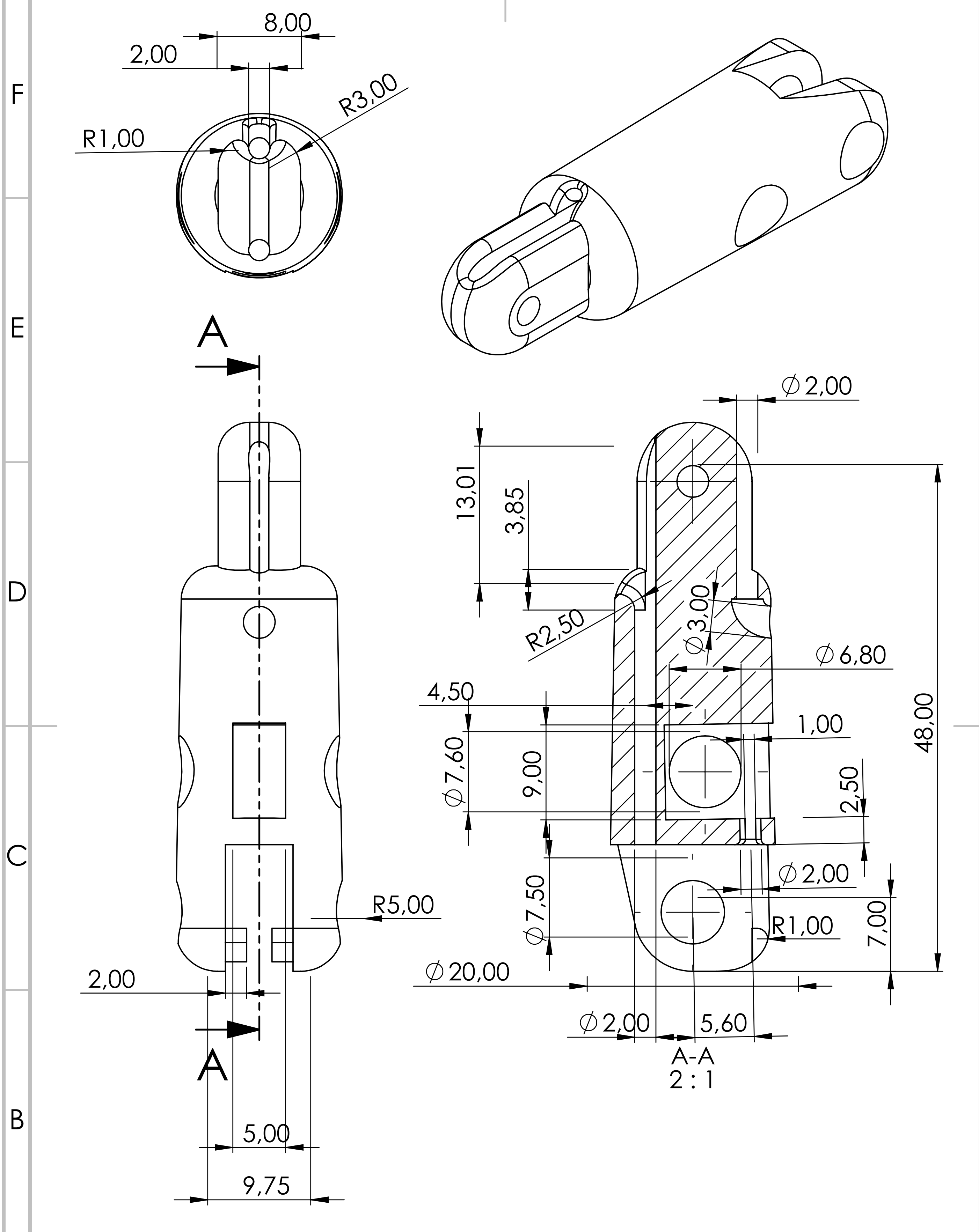

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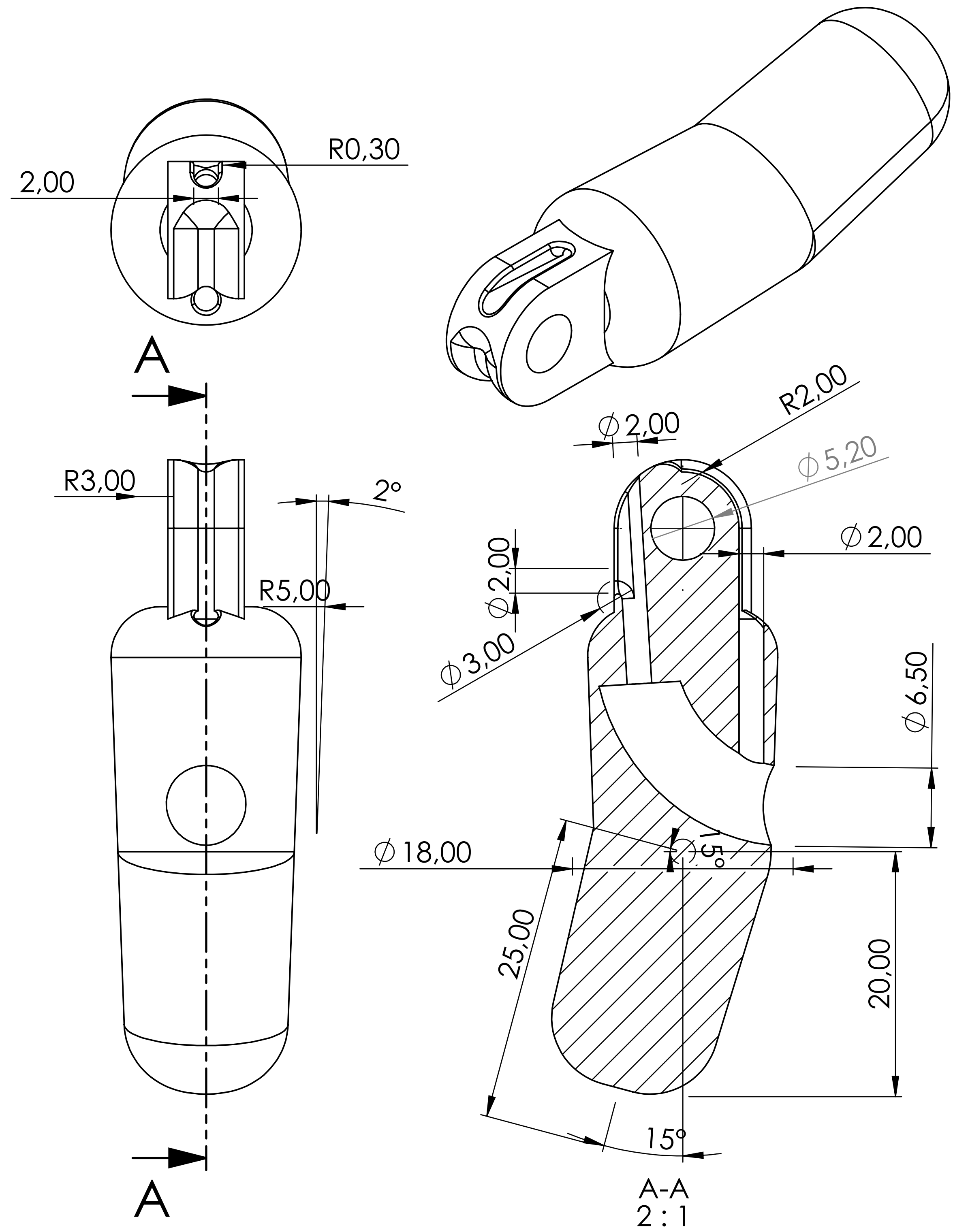

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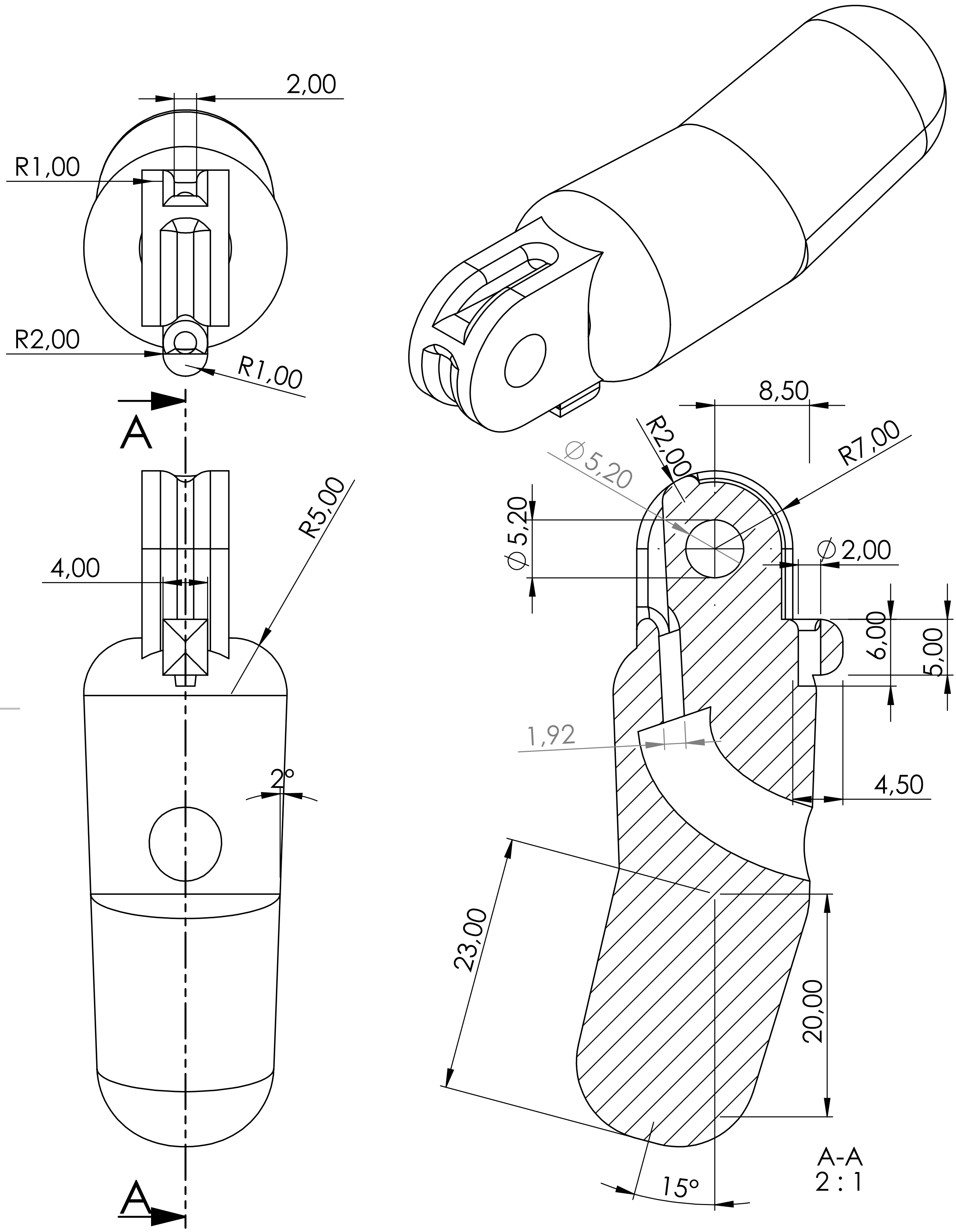

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Propietario legal: UNIVERSITAT JAUME I Escuela Superior de Tecnología

Biomechanics and ergonomics

Document type:	Made by:	Date:
Design drawing	Joaquín Ibáñez	2022/11/07

Title:	Number:
Ring distal phalanx	6

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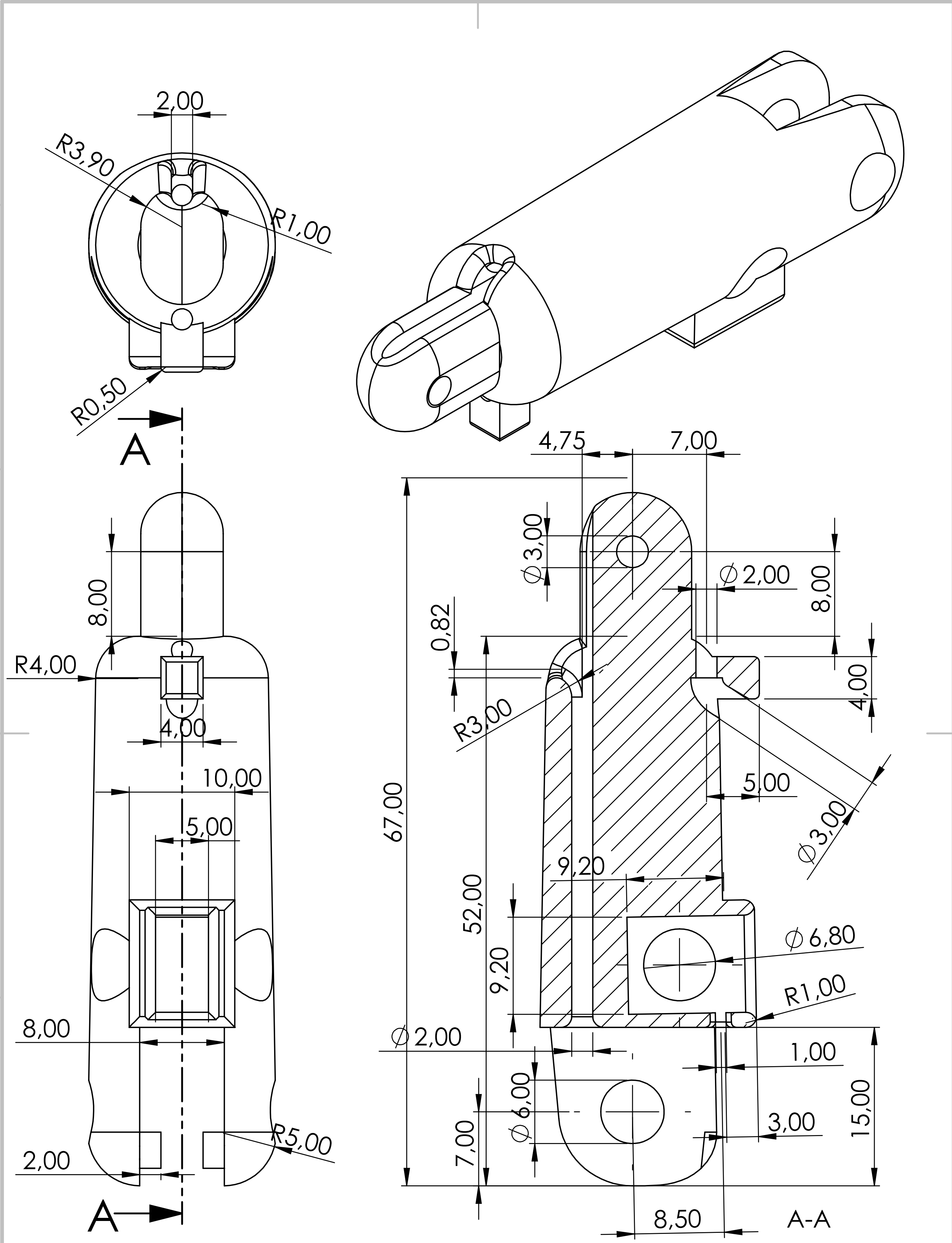

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Title:	Number:
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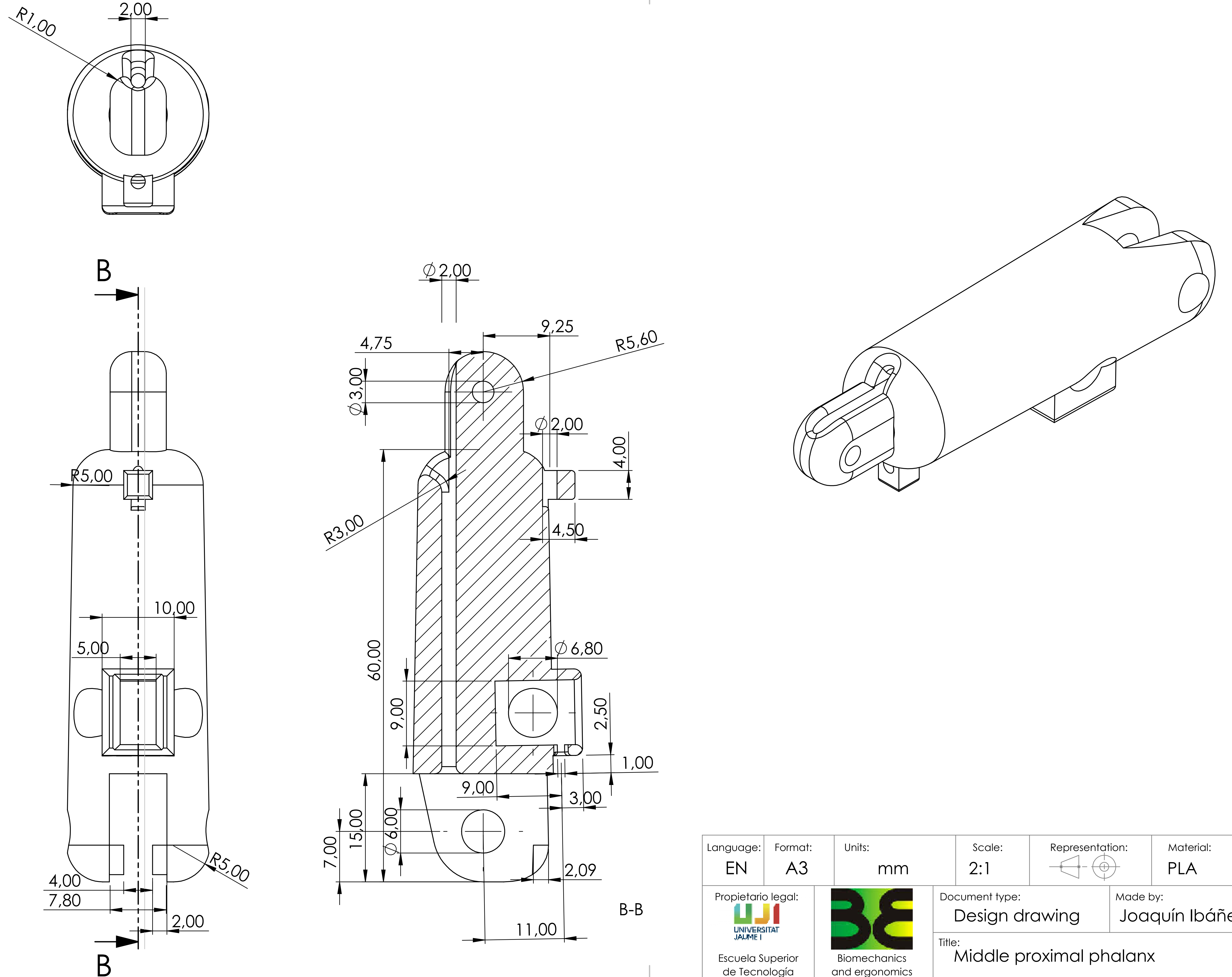

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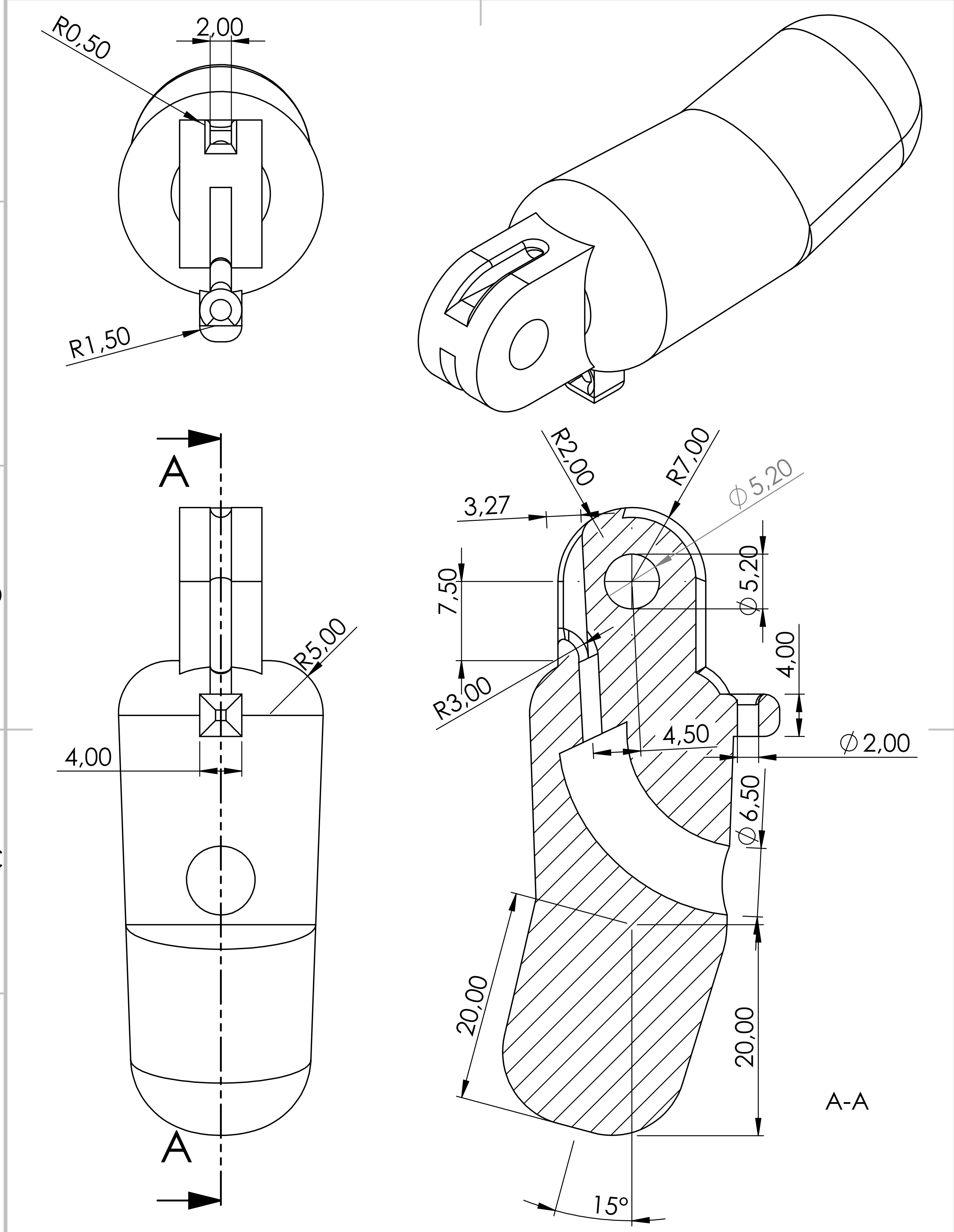

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Biomechanics and ergonomics

Document type:	Made by:	Date:
Design drawing	Joaquín Ibáñez	2022/11/07

Title:	Number:
Middle distal phalanx	9

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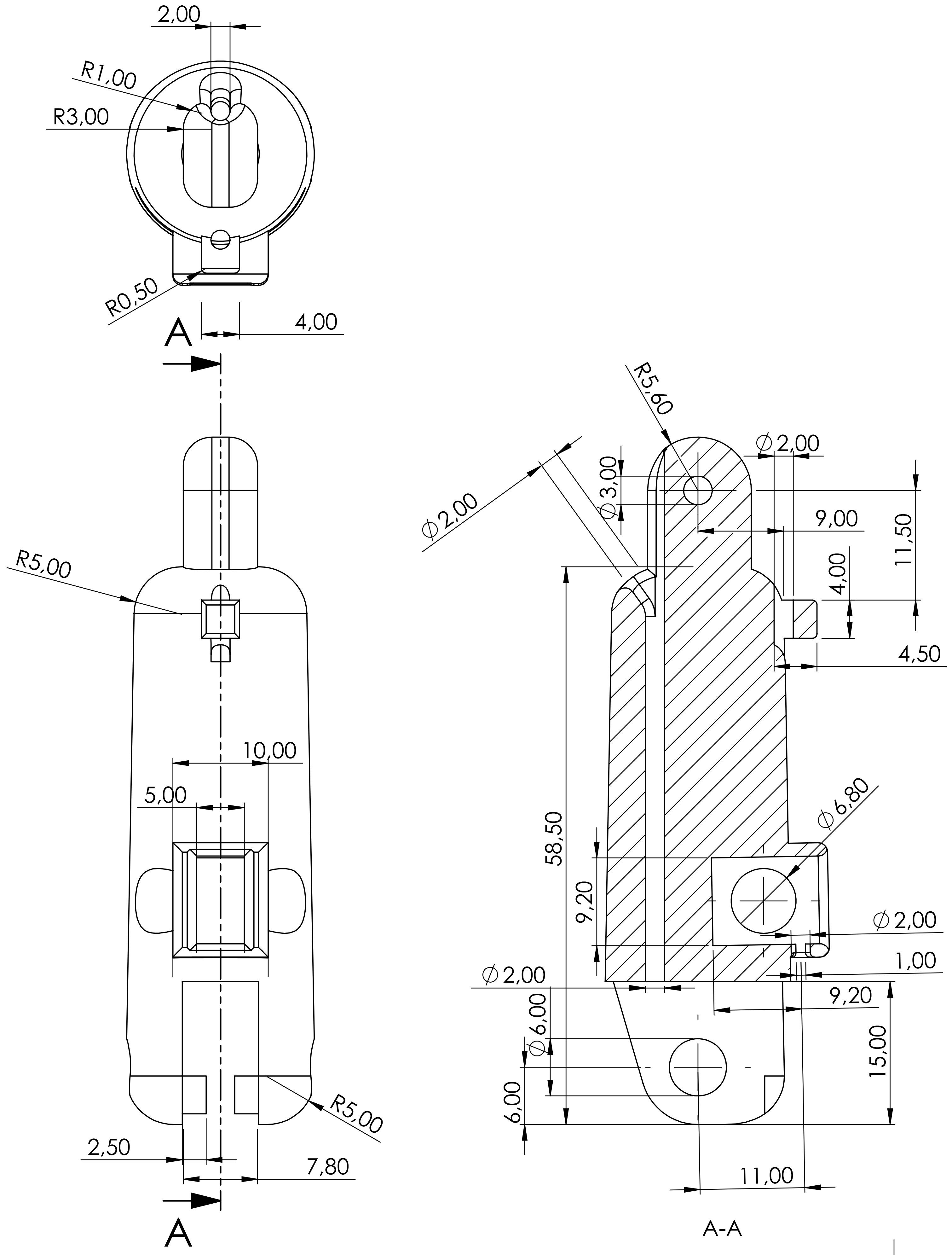

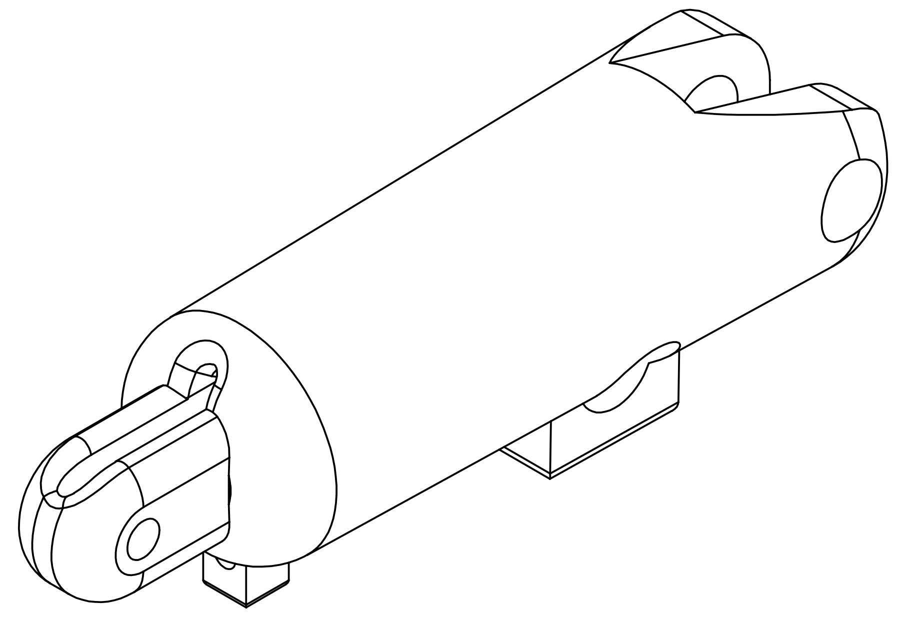

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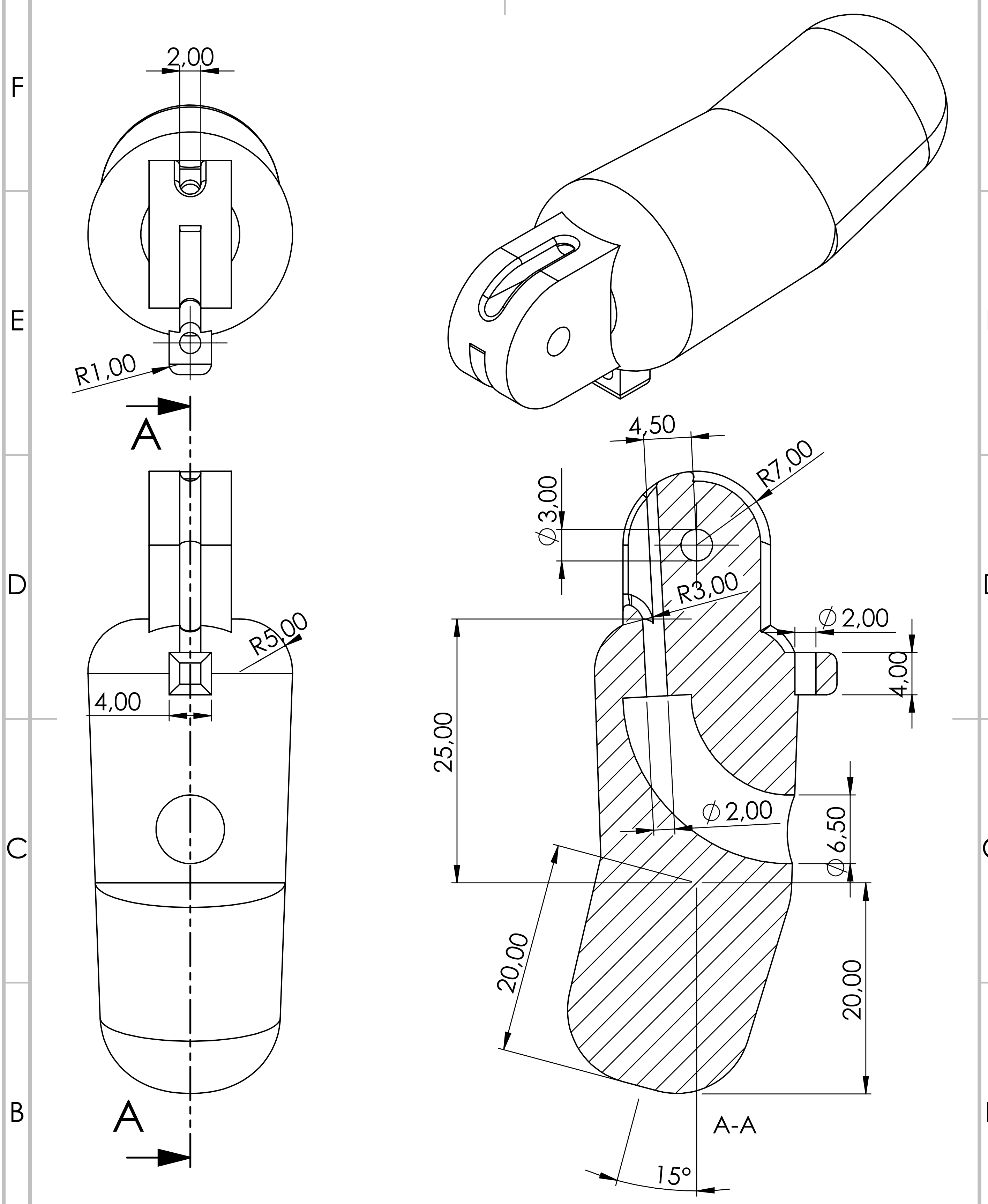

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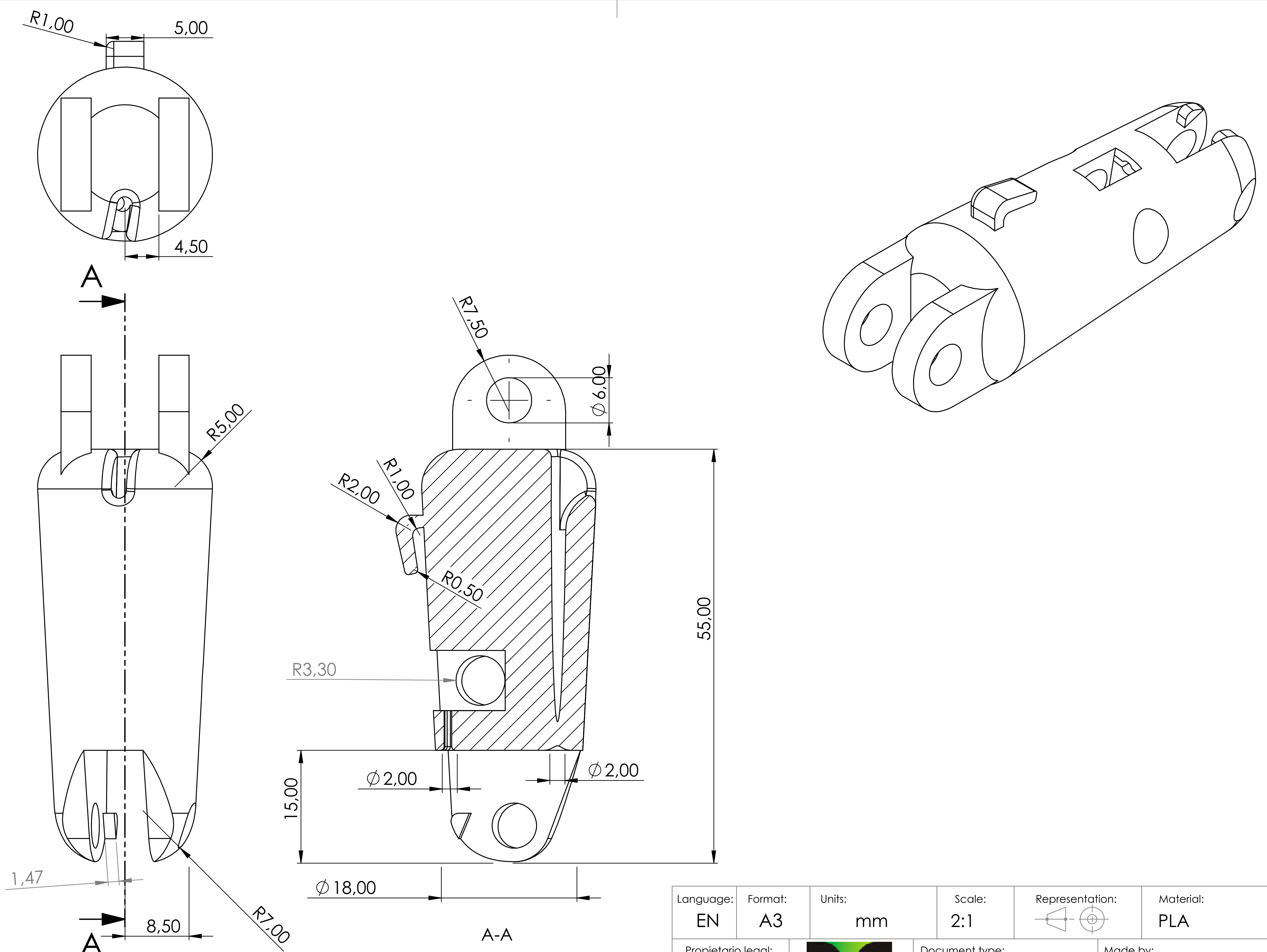

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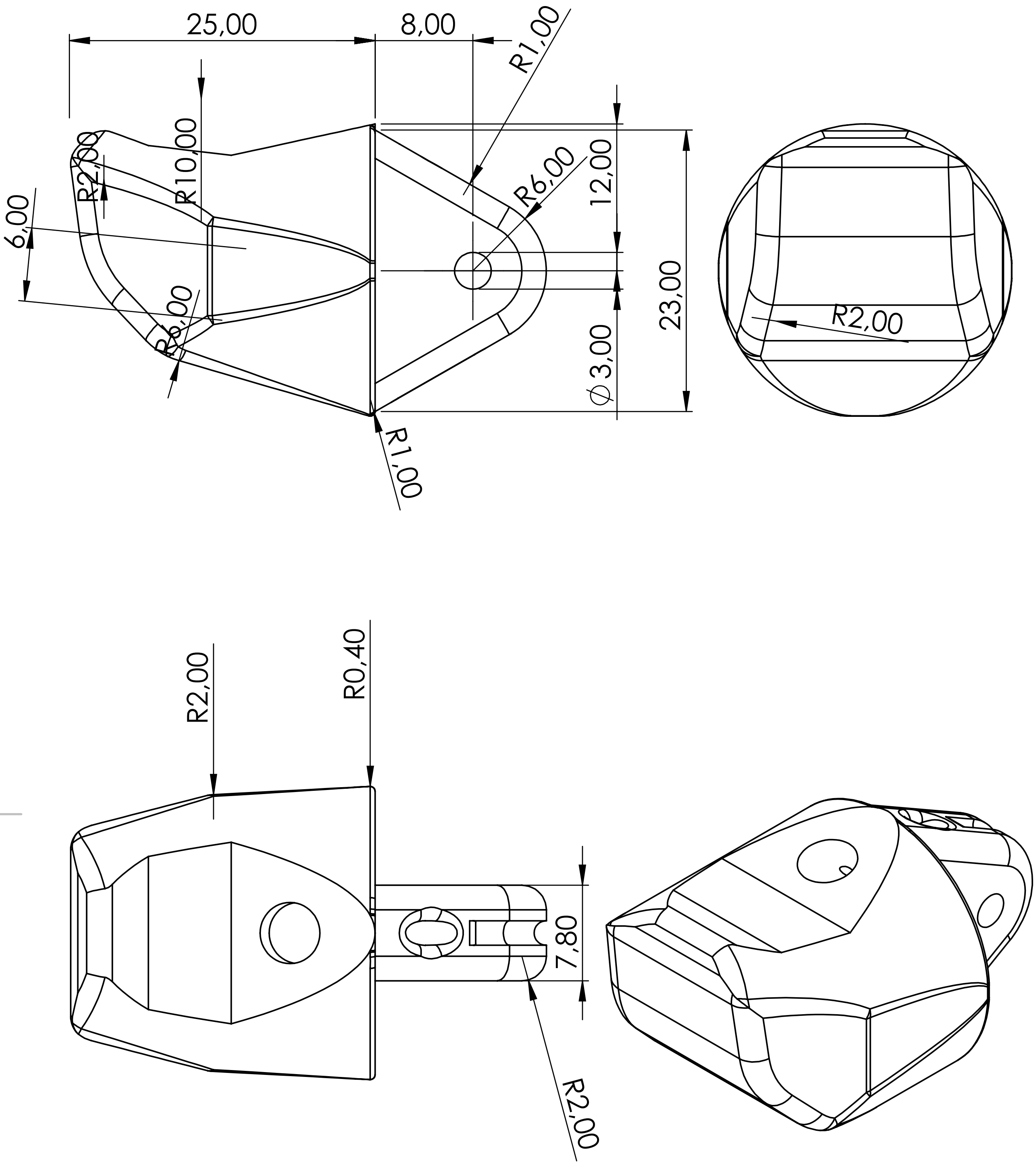

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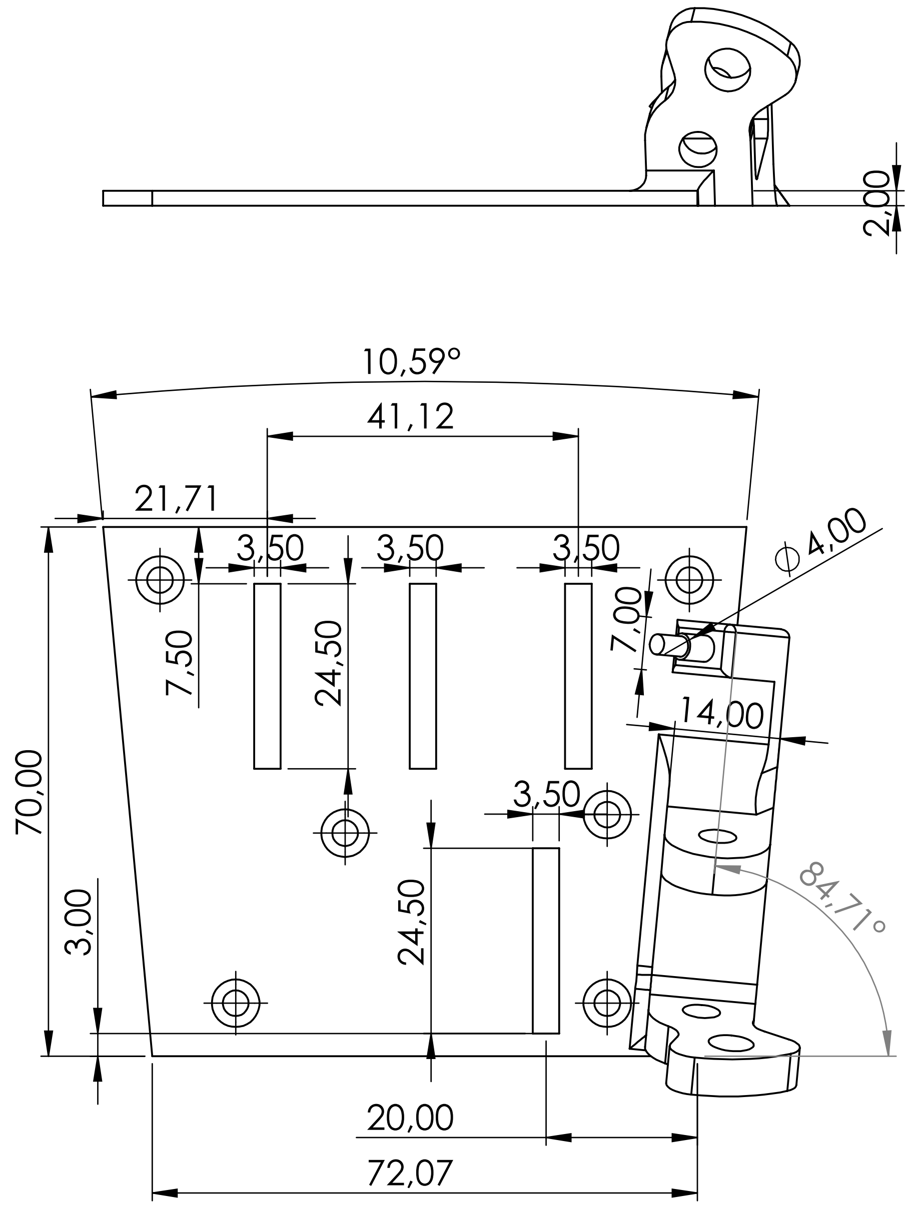
		Title: Thumb distal phalanx		Number: 13

Producto SOLIDWORKS Educational. Solo para uso en la enseñanza.



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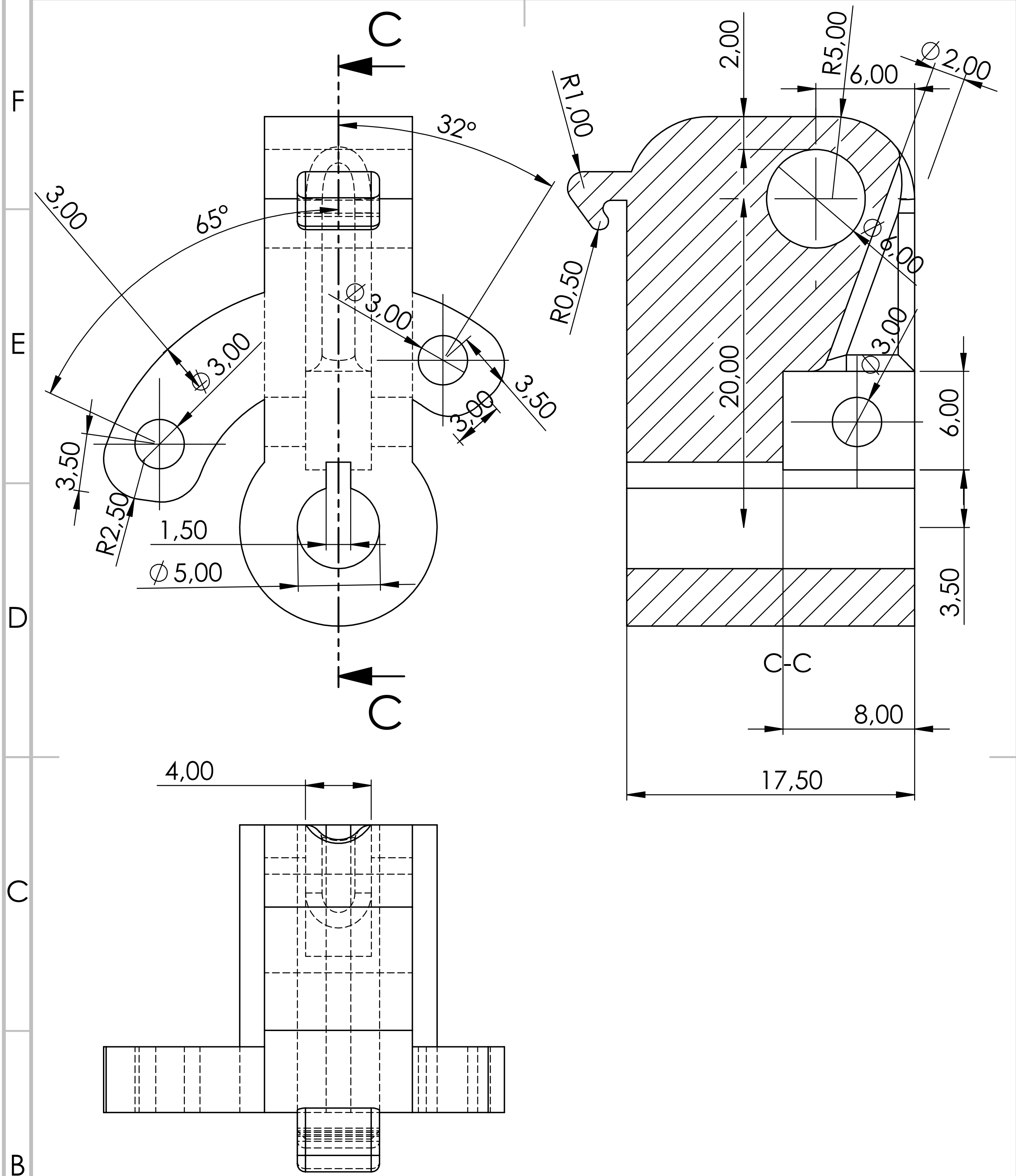
		Title: Guidance top plate		Number: 14

Producto SOLIDWORKS Educational. Solo para uso en la enseñanza.



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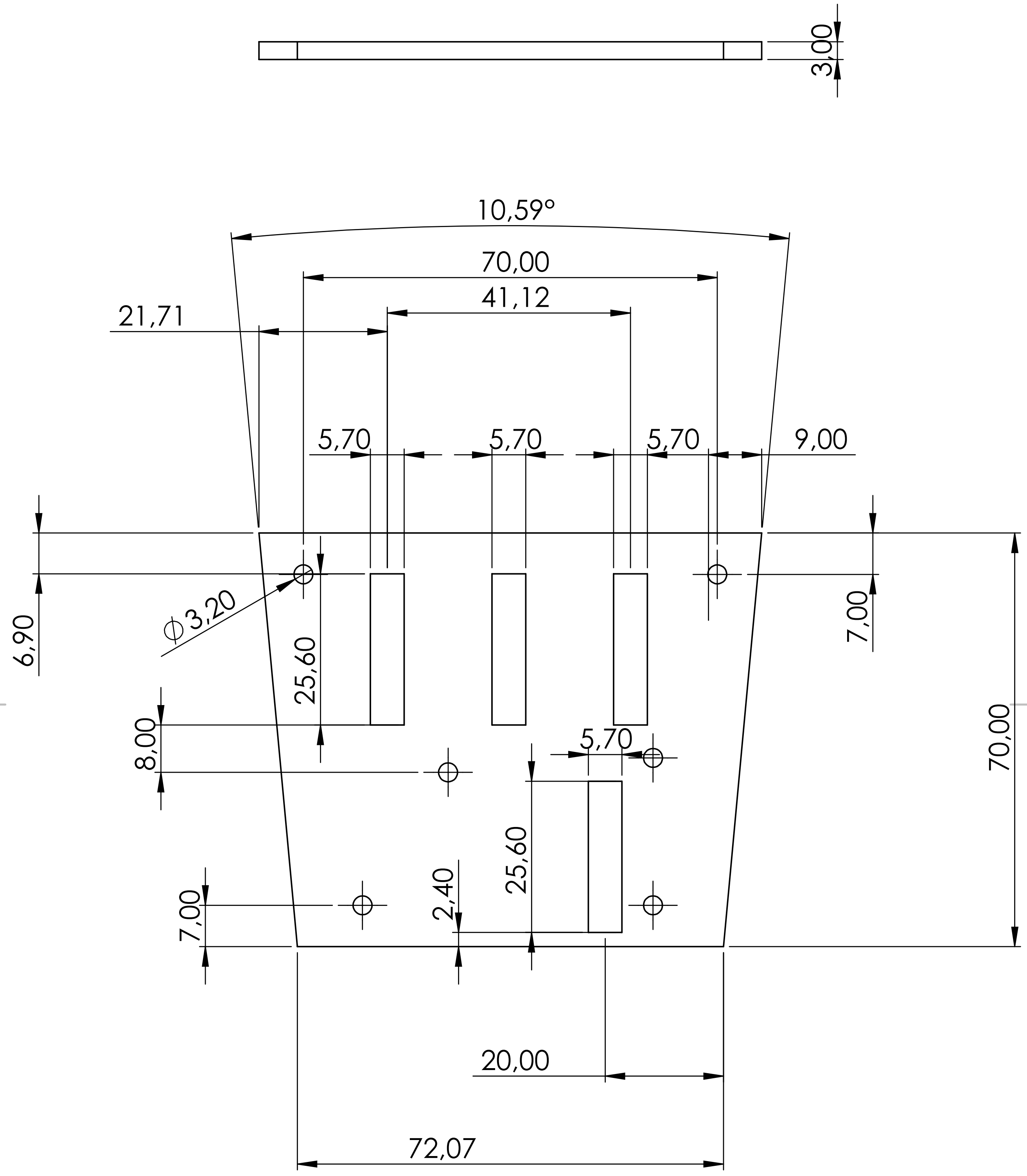
		Title: Thumb AB/AD		Number: 15

Producto SOLIDWORKS Educational. Solo para uso en la enseñanza.



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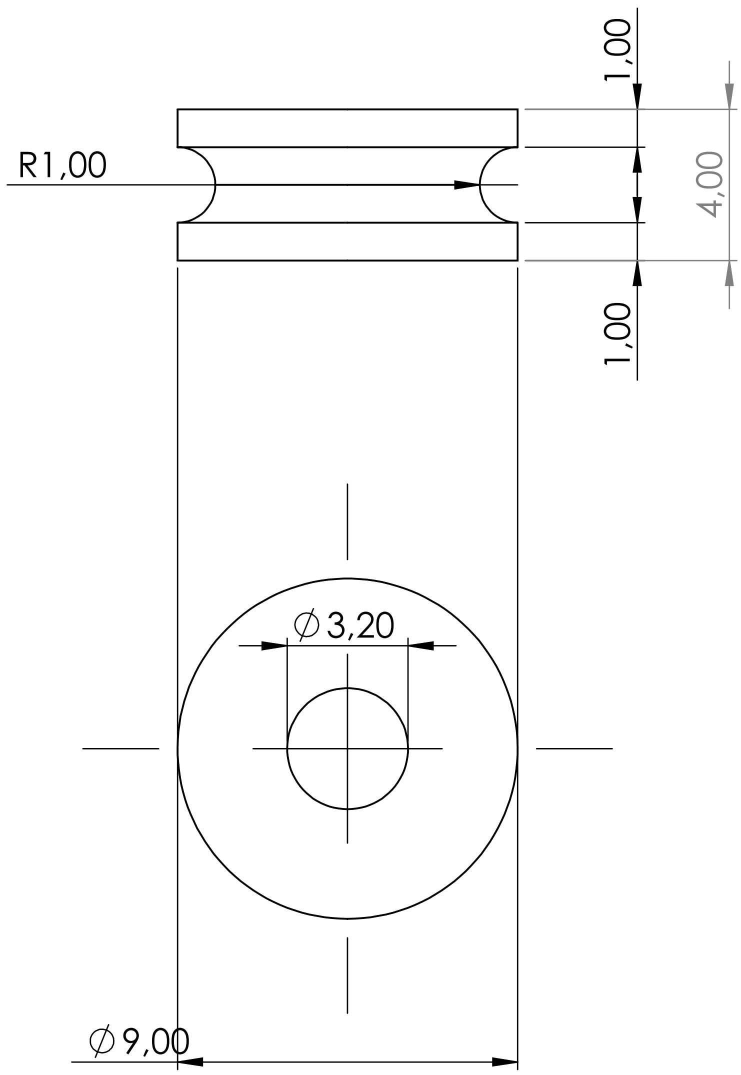
Producto SOLIDWORKS Educational. Solo para uso en la enseñanza.



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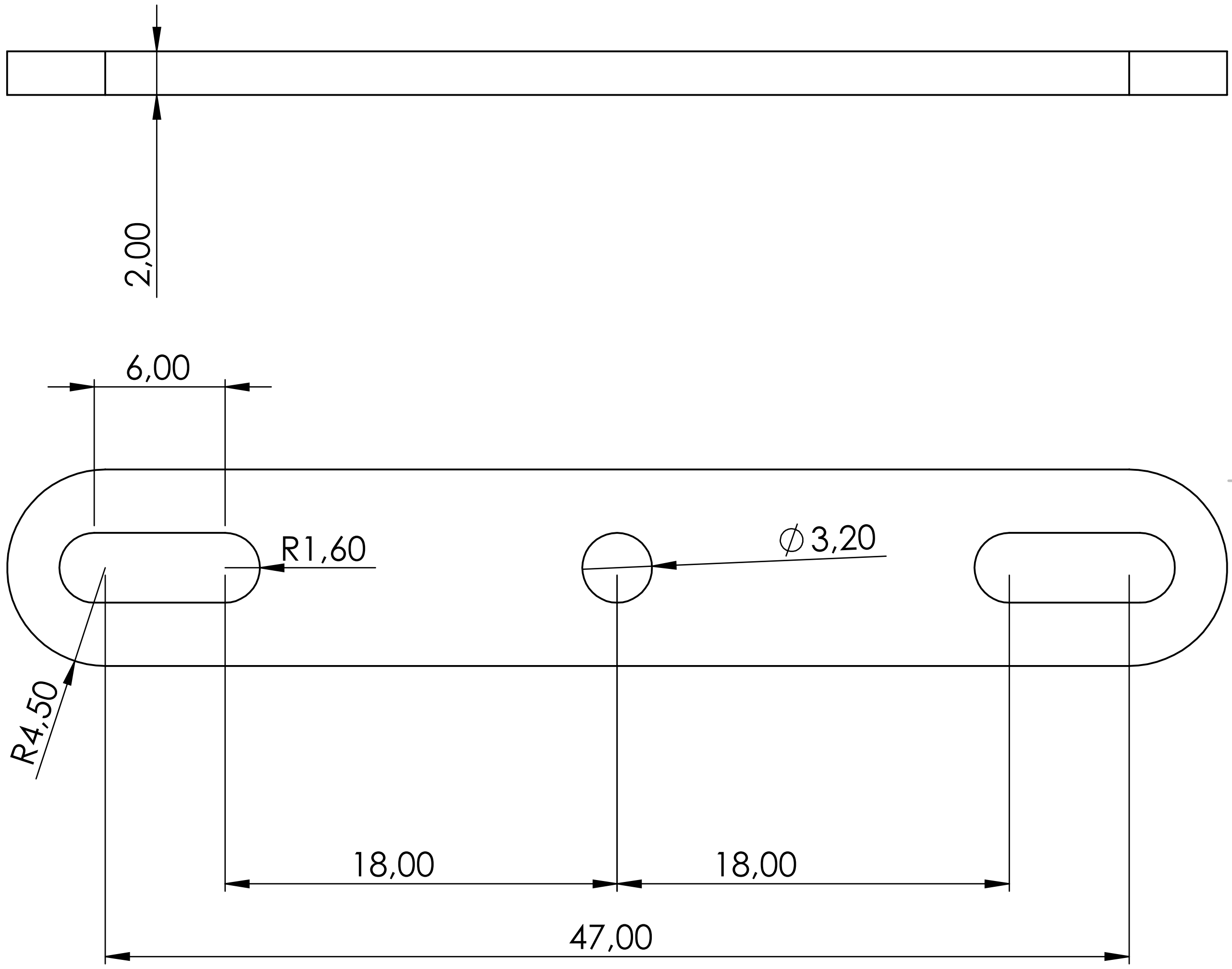
Producto SOLIDWORKS Educational. Solo para uso en la enseñanza.



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UNIVERSITAT JAUME I Escuela Superior de Tecnología	Biomechanics and ergonomics	Design drawing	Joaquín Ibáñez	2022/11/07
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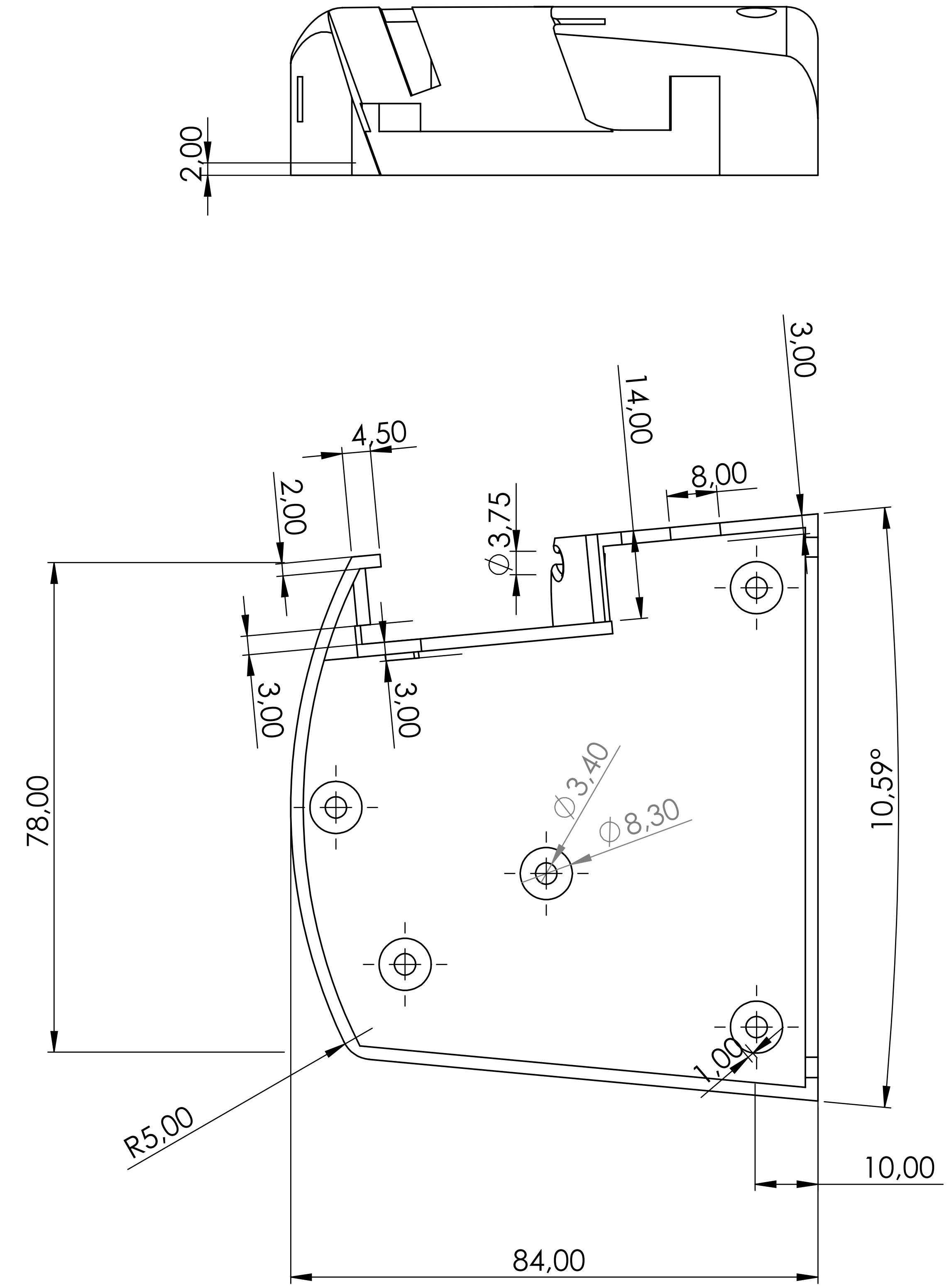
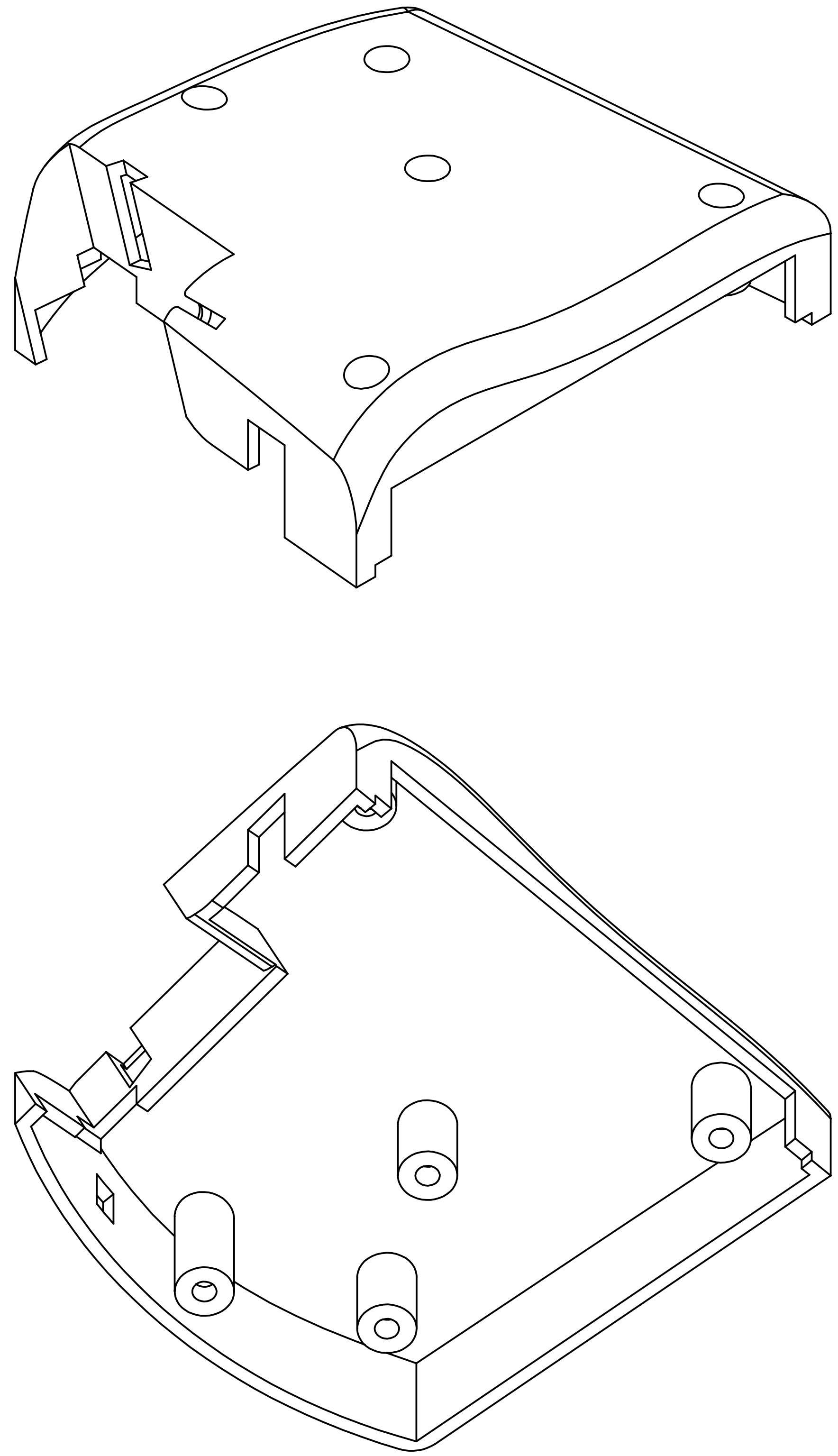
Producto SOLIDWORKS Educational. Solo para uso en la enseñanza.





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		Title: Palmar case		Number: 19

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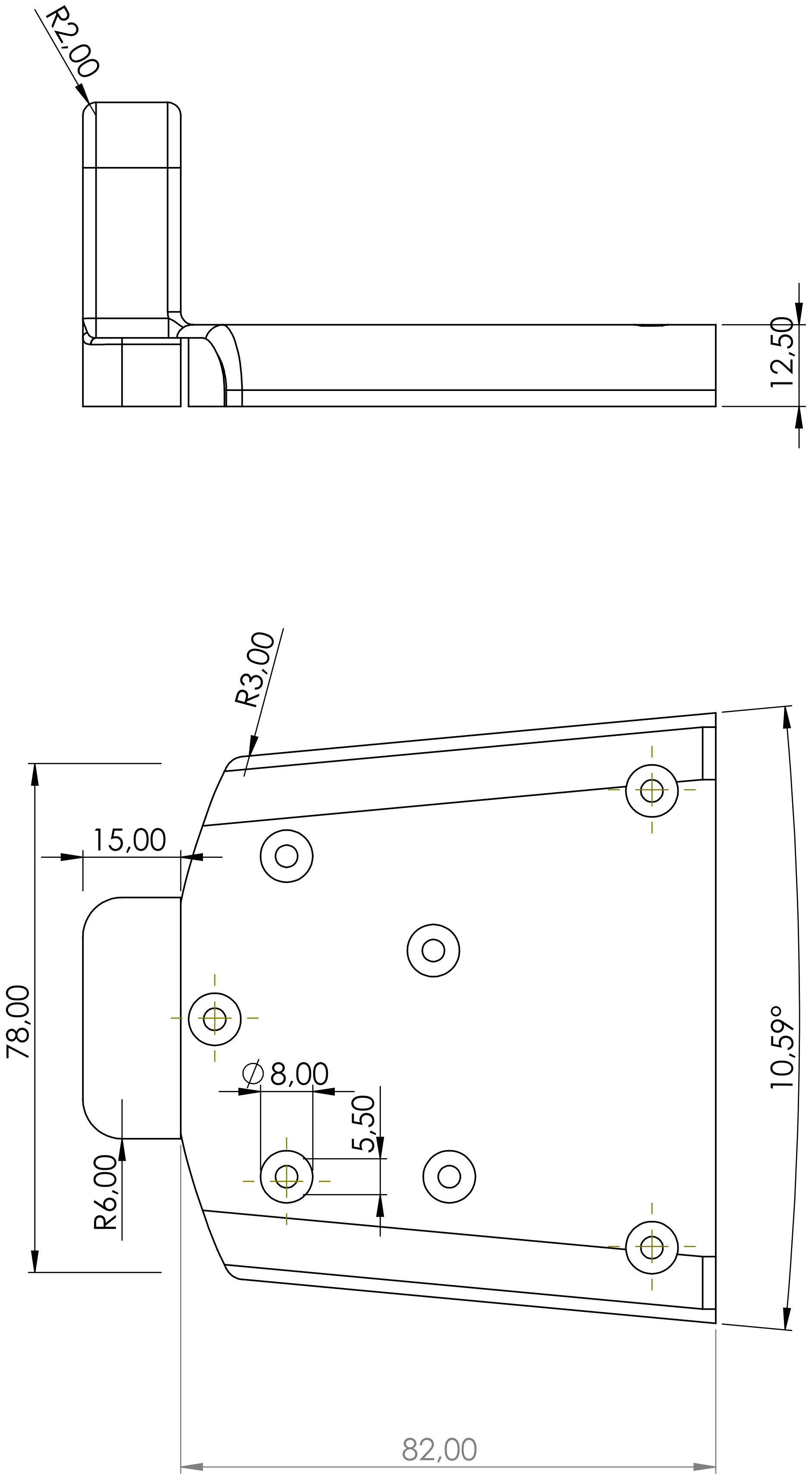

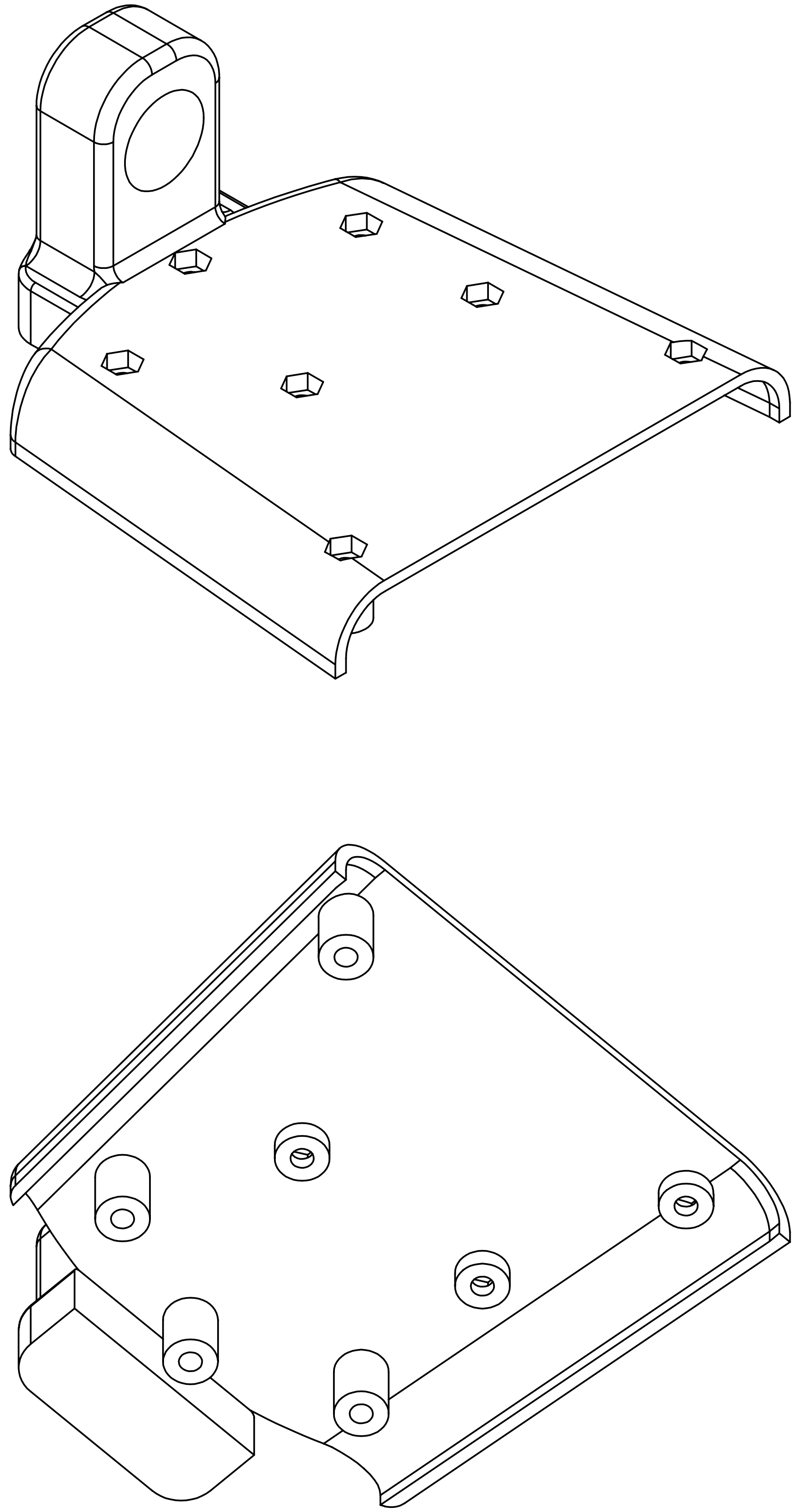

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Propietario legal:		Document type:	Made by:	Date:
UJI UNIVERSITAT JAUME I Escuela Superior de Tecnología	Biomechanics and ergonomics	Design drawing	Joaquín Ibáñez	2022/11/07
		Title: Dorsal case		Number: 20

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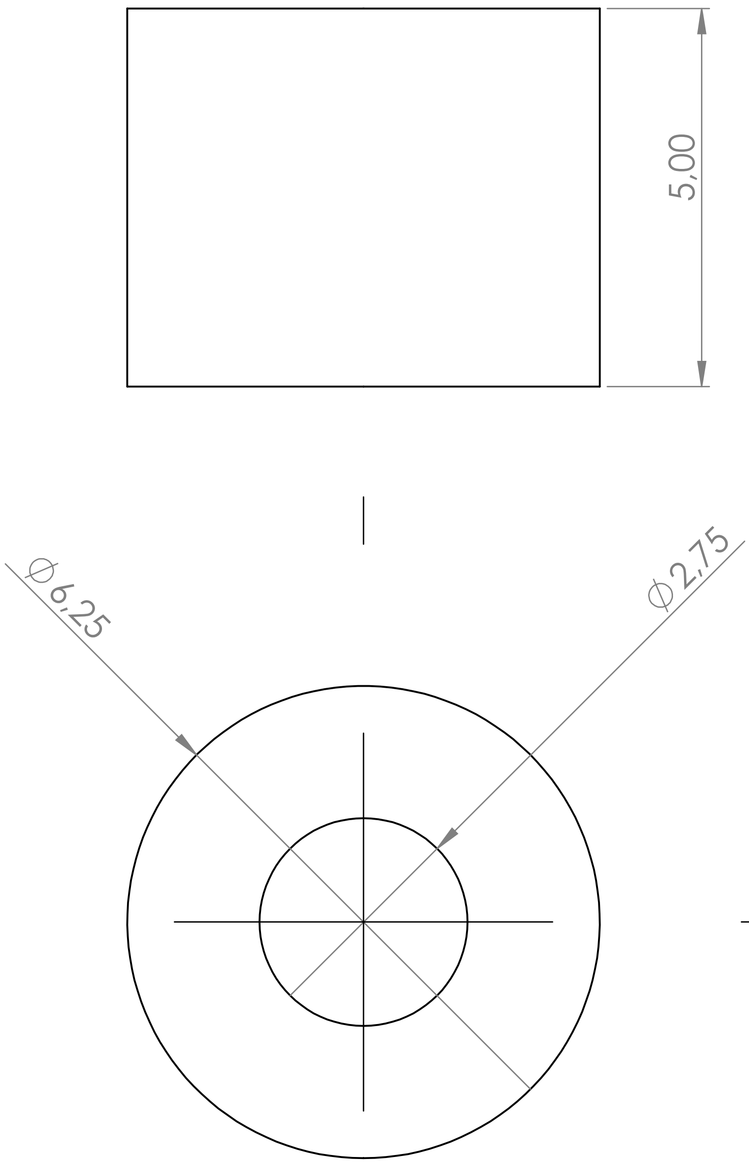

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UNIVERSITAT JAUME I Escuela Superior de Tecnología	Biomechanics and ergonomics	Design drawing	Joaquín Ibáñez	2022/11/07
		Title: Finger joint support		Number: 21

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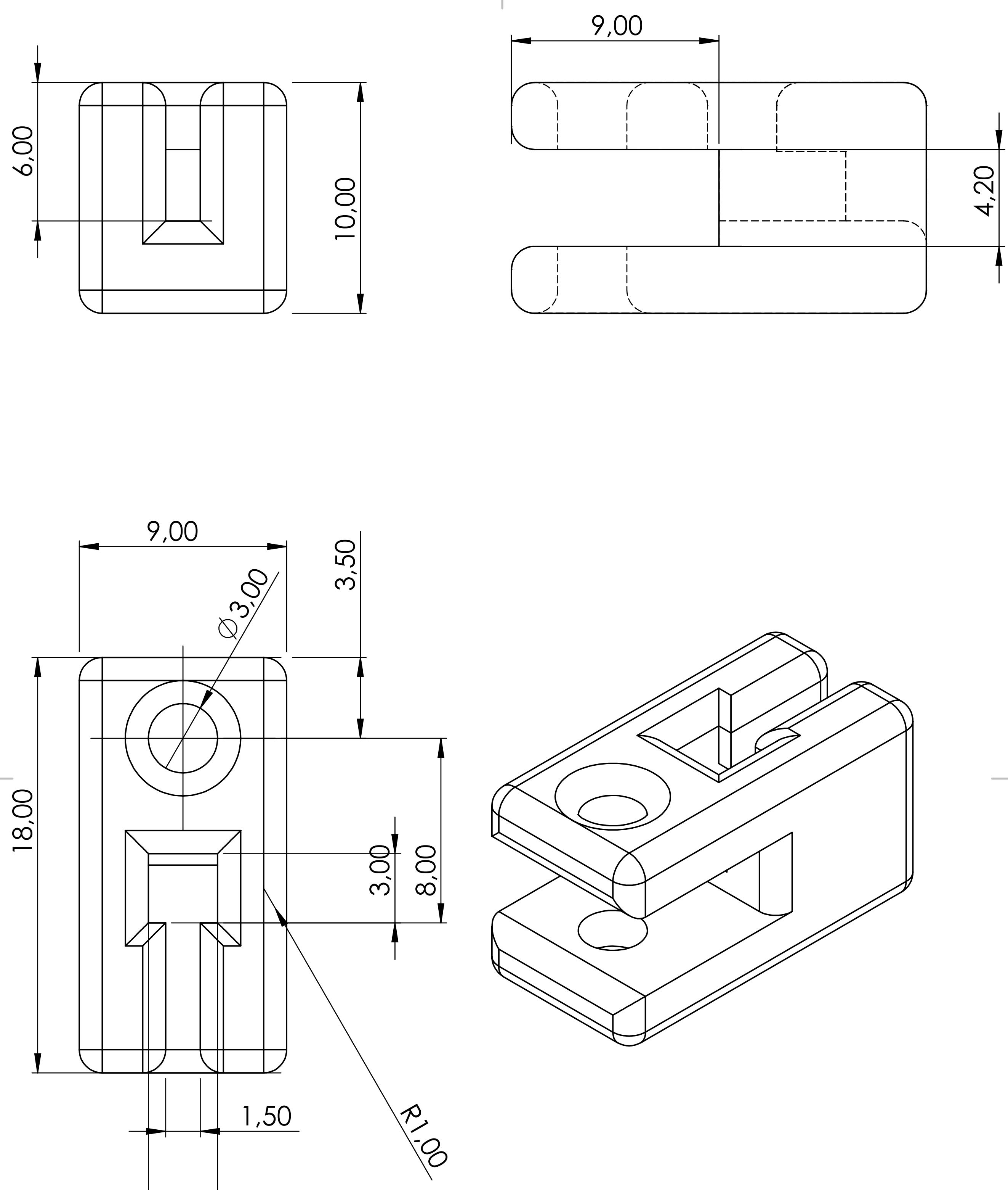

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Propietario legal: UNIVERSITAT JAUME I Escuela Superior de Tecnología

Biomechanics and ergonomics

Document type:	Made by:	Date:
Design drawing	Joaquín Ibáñez	2022/11/07

Title:	Number:
Pulling slider	22

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