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Design and development of a Soft Body-Actuated 3D printed prosthetic hand

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Design and development of a Soft Body-Actuated 3D printed prosthetic hand

Submitted in Partial Fulfilment of the Requirements for the Degree of Master in Mechanical Engineering in the speciality of Production and Project

Projeto e desenvolvimento de mão robótica protética por impressão 3D

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Abstract

The main objective of this work is design and development of a low cost soft 3D-printed body-actuated upper limb prosthesis. By integration of a soft silicone skin into the fingers and palms of the hand, we introduce a novel version of the prosthetic hand that adapts very well to various object shapes and sizes, and allows a better grasp of the objects due to a higher friction coefficient between the object and the elastic skin, when compared to a hand without the soft skin. In addition, the hand was tested by a volunteer with a congenital disorder as so, the fingers of his right hand are missing.

Over the last few years, advancements in additive manufacturing and rapid prototyping, led to new designs of upper limb prosthesis at low cost and light weight. The e-NABLE, a non-profit community, has largely contributed into this field over the last four years. This community develops new designs of upper limb prosthesis and places them online for replication as well as contribution on the design. The devices made by e-NABLE community don’t pose any actuator or sensors in the prosthesis, as so, the prosthesis are light weight and low-cost. The closing and opening of the prosthetic hand is based on the movement of flexion and extension of the wrist, which makes the device very intuitive to control.

The methodology of this work is to create a 3-D sketch of the prosthesis based on the hand of the person along with the concept of e-NABLE prosthesis. However, by taking advantage of a soft skin, we improve the hands functionality, i.e. the number of grasps it can perform. After each component is printed, an analysis of the component is made to see if there is any material that can be removed to decrease the weight of the prosthesis.

For each of the components of the body-actuated hand, we analysed the actual problems and proposed, designed, developed and tested a new solution. Afterwards, the final assembly was tested and validated through several iterations involving the volunteer in the decision making loop.

Keywords Prosthetics, Body-powered, 3D Printing, e-NABLE, Compliant mechanisms.

Resumo

O principal objetivo deste trabalho é a produção de uma prótese de uma mão, com baixo custo, através de impressão 3D. Através da utilização de um silicone dúctil nos dedos e na palma da mão, foi criada uma nova versão deste tipo de próteses, que se adapta muito bem às diferentes formas e tamanhos dos objetos, permitindo-nos ter um melhor coeficiente de atrito entre a prótese e os objetos, quando comparada com uma prótese sem este tipo de materiais. Depois da produção da prótese, esta foi testada por um voluntário com um transtorno congenital na mão direita e, como tal, os dedos desta mão estão em falta.

Os avanços nos últimos anos em fabricação aditiva levaram à produção de próteses de membros superiores a baixo custo e baixo peso. A e-NABLE é uma organização não lucrativa que tem contribuído em larga escala para esta área nos últimos quatro anos. Esta comunidade desenvolve novos desenhos de próteses da mão e coloca-os no seu website para que qualquer pessoa possa fazer o download sem qualquer custo. As próteses da e-NABLE não possuem nenhum atuador ou sensores, portanto apresentam um baixo peso e custo. O movimento de abrir e fechar a mão é feito através da flexão e extensão do pulso, o que faz com que prótese possua um controlo muito intuitivo.

A metodologia desta dissertação passou pelo uso de um programa CAD, para criar um desenho 3-D baseado na mão do voluntário e no conceito de prótese da e-NABLE. Contudo, a funcionalidade da prótese, foi melhorada graças aos materiais usados nos dedos e na palma da prótese. Para cada componente da mesma foi realizada uma análise com o intuito de remover partes desnecessárias e, consequentemente, diminuir o peso da prótese.

A prótese final foi então montada e testada pelo voluntário, e através de várias iterações, uma prótese final ótima foi produzida.

Palavras-chave: Próteses, Ativada por um movimento do corpo, Impressão 3D, e-NABLE, Mecanismo flexível

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ACRONYMS

Acronyms

ASTM – American Society for Testing and Materials

DEM – Departamento de Engenharia Mecânica

FCTUC – Faculdade de Ciências e Tecnologia da Universidade de Coimbra

MIT – Massachusetts Institute of Technology

FDM – Fused Deposition modeling

SLS – Selective laser sintering

SLA – Stereolithography

DOF – Degrees Of Freedom

PLA – Polylactic acid

MCP – Metacarpophalangeal

PIP – Interphalangeal

1. INTRODUCTION

A prosthesis is an artificial extension that replaces missing parts of the body. The purpose of prosthesis is to replace parts of the body and give them back the function of that body part in order to reduce the limitation created in the person's lifestyle, providing a higher quality of life. The prosthesis can replace a missing extremity like arms (upper limb prosthesis) or legs (lower limb prosthesis).

In a world where the technology advances at a high speed, the number of hand prosthesis rejection is high. The most common reasons for this rejection is the weight, high initial costs, and maintenance, as well as poor aesthetics. This work seeks to overcome some of these disadvantages by proposing the production of a 3D printed prosthesis and applying it to a volunteer.

The use of 3D printers has increased in the world of prosthesis and have come to provide a new range of prosthesis at low cost with a wide variety of designs. Some of the most used 3D printing processes are FDM (Fused Deposition modeling), SLS (Selective laser sintering) and SLA (Stereolithography). However, in this work the goal is to use the most accessible option, i.e. the FDM.

The volunteer who tests the prosthesis produced was born with a congenital disorder in the right hand. Despite having a high productivity in his professional life, daily tasks are difficult to perform. The device should help, not just to overcome the most common disadvantages of the prosthesis, but also giving it a more intuitive control to avoid the initial training.

1.1. Background

A functional prosthesis should provide an amputee as many limb functionalities as possible and, at the same time, should be light weight, affordable, easy to use and intuitive to control. In addition, it should provide the capacity to adapt to different object shapes and sizes, as well as, be able to exercise both power and precision grasps. Despite all the existing technology it is hard to find a prosthesis that has all these characteristics.

1.1.1. Light weight

The comfort of prosthesis is critical for its use. In order for it to be successful in this field, it is necessary to take into account the weight of the prosthesis, especially in children.

In a recent research it was concluded that the rates of rejection for myoelectric hands, passive hands, and body-powered hooks were 39%, 53%, and 50%, and the weight of prosthesis is the highest priority design concern of consumers [1]. In [2], 33.75% of the patients that used body-powered and passive devices rejected the prosthesis, being one of the reasons for the rejection the weight of the prosthesis. In another study at [3] some patients reported that the weight of prosthesis was excessive.

In conclusion, the prosthesis should be as light as possible to avoid rejection and discomfort.

1.1.2. Low cost

A prosthetic hand could have different prices depending on the type of device. Some prosthesis could range a price of thousands of Euros which is not affordable for people with financial difficulties. The high cost of some prosthesis can be explained because of the material used, the number of degrees of freedom (DOF) and quality of the sensors and actuators. Some of the most advanced myoelectric prosthetics hands could go from 33.000€ to 62.000€ [4].

The initial cost of prosthesis cannot be considered on its own, it is necessary to take into account other costs such as maintenance. In a study at [5], it was observed that the cost of hospital stay in the initial training, among others, are high and can be problematic even for people with health insurance. So, when a person decides to buy a prosthesis, they cannot just take into account the initial price, but also the cost of training and maintenance.

1.1.3. Intuitive control

The control of a prosthesis could be in most cases complex, as it requires some training to enjoy it to its full power. When someone has intensive training, acceptance of the prosthesis [6] and daily use of the prosthesis increases [5]. There is no clear consensus on the amount of prosthetic training upper limb amputees should have [7]. The time of training can be different for several patients and can depend on several factors, such as, according to [8], the level of amputation, learning ability of the amputee, complexity of the prosthesis, functional needs and motivation. To avoid initial training, the prosthesis should have a simple and intuitive control for a better usage.

1.2. Goal and Methodology

The objective of this work is to develop an upper limb body-actuated prosthesis at a low cost and at a low weight, with the least rigid material possible and apply it to a volunteer. More specifically, the goal is to use existing open source designs of the 3D printed body-actuated hands, and update them with the state of the art advances in the area of soft robotics and soft-matter hands. This study will show how integration of an elastic skin, in addition to design optimization, can benefit the functionality of simple body actuated hands, without necessarily increasing its costs and weight.

Iterative versions of the hand were designed, printed, assembled and tested by a volunteer and results were registered. The volunteer was born with a congenital right hand disorder as such, all his fingers of the right hand are missing but he still has the palm of the hand and therefore, he can perform the movement of extension and flexion of the wrist (Figure 1).

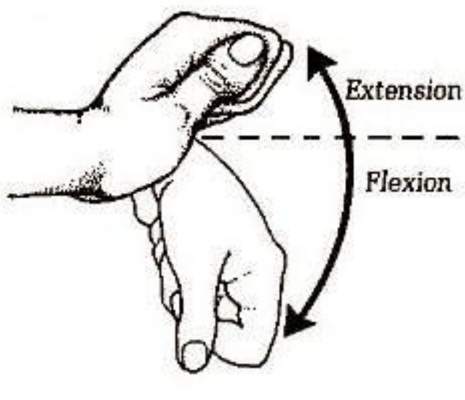

Figure 1 – Movement of flexion and extension of the wrist [9]

Volunteers with a congenital disorder spend all their lives with a big limitation on their life style and difficulties that affect their daily living. So it is imperative to give them back the functions of the hand and thus improve their life quality.

1.2.1. E-NABLE Group

The E-NABLE group [10] is a community of people, that already counts with more than 7000 people spread around the world, that use 3D printers to produce upper limb prosthesis for anyone who needs them. This community creates multiple files for 3D prints and makes them available on their website. So anyone can download the files without any cost and print the prosthesis with a 3D printer.

The first design was created in 2011 (Figure 2) by Ivan Owen and, after 3 years, with the collaboration of people from different countries, the e-NABLE group was created. After the creation of the website the e-NABLE group grew at a higher rate and currently has 11 prosthesis with different designs available for free download on the website.

Figure 2 - Frist design by Ivan Owen [11]

The e-NABLE prosthesis does not have actuators or any type of sensors. The movement of opening and closing of the fingers is made through the flexion and extension of the wrist or the elbow. As there is no actuator or sensor, these prosthesis have a low cost and are very light weight when compared with the prosthesis that are currently in the market. Nevertheless, their actual functionality is rarely evaluated against a grasp benchmark. While being low cost and intuitive to control are important factors, it is necessary to compare the functionality of these hands against a benchmark.

1.2.2. Methodology

The methodology we take in this dissertation includes updating one of the available open source designs as the starting point along with the previous experience of the group with soft hands (ISR-Softhand, UC-Softhand).

The improvements include mainly two aspects, better fitting of the prosthesis to the hand of volunteer by a moulding process, and utilization of state of the art soft fingers that are composed of a 3D printed bone, as well as an elastic skin. In addition, by creation of a soft palm, we even increased the number of the contact points and functionality of the hand.

We then compare the functionality of the hand with the help of a volunteer against a well-known grasp benchmark. This will show how well the hand performs against various prosthetic devices.

Figure 3 - Mould of the volunteer hand

In this first chapter it was introduced the main goal and the methodology used to accomplish the objectives of this work. Chapter 2 reveals an overview about upper-limb prosthetic devices and disadvantages of each one of them. Chapter 3 is responsible for describing the production of the prosthesis by explaining all the steps that were taken to produce the final prosthesis and, in each one of these steps, the problems that we faced and the solutions that we applied to solve those problems. Chapter 4 presents the test of the assembled devices and final results. Chapter 5 resumes the results and the conclusion that was taken.

2. STATE OF ART

2.1. Upper Limb Prosthetic Devices

Currently the upper-limb prosthetic devices can be classified based on functional capacity or by the energy source used to drive the functional components. As functional capacity we have passive devices or active devices. The passive devices don't have a mechanical function, but they have very good aesthetics and are light-weight. The active devices have mechanical functions which allow the person to grab objects. The active devices can be electric-powered or body powered.

2.1.1. Passive devices

A passive prosthesis serves mainly to recover the external appearance of the amputated limb, they have a very limited number of functions and are used mostly by people who have great difficulties in operating with active prosthesis. A passive prosthesis is actually a well implemented glove. It is mostly made of silicone and have a high aesthetic quality because their external appearance is very close to that of the amputated limb. In a study [12], 44% of the patients (kids and adolescents) selected a passive prosthesis as their primary choice.

Figure 4 – Passive prosthesis [13]

2.1.2. Electric-powered (Myoelectric) devices

The myoelectric prosthesis are devices in which the movement of opening and closing of the prosthesis fingers are activated through the muscular contraction. Each muscle contraction produces an electrical voltage that is picked up by the prosthesis. Then the signal is amplified and sent to the controller of the prosthesis which will, through motors, open and close the fingers.

Currently the most common myoelectric prosthesis are the be-bionic [14] (Figure 5 (a)) and the I-limb [15] (Figure 5 (b)). Both prosthesis have sensors in each finger and each finger has a motor connected to the sensor. The motors are controlled by myoelectric and by the sensors and in this way the hand can be adapted to the shape of the objects. These prosthesis have different sizes, for different people. The smaller prosthesis made by be-bionic weigh around 309g and the smaller one made by I-limb weighs around 410 g. The prices of these prosthesis could go from around 9.000€ to 30.000€ for the be-bionic and around 14.000€ to 34.000€ for the I-limb.

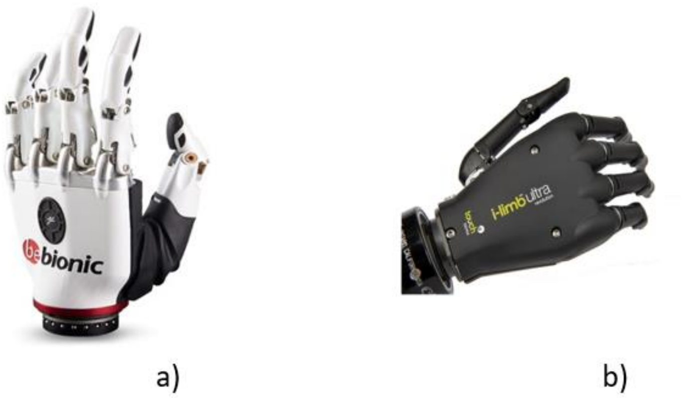

Figure 5 – a) Be-bionic hand [14]; b) I-limb ultra [15]

Another myoelectric hand currently in the market is the Michelangelo-Hand [16] (Figure 6 (a)). This prosthesis weighs 380g and has two drives to control the gripping, one to control the gripping action of the fingers and another to control the position the thumb. On this prosthesis only 3 fingers are activated (thumb, index and middle finger), and the other two only follow the others. Vincent Evolution 2 [17] (Figure 6 (b)) is a myoelectric hand that gives the person the touch sense by stimulation of the receptors on the arm. This prosthesis also has 6 motors, one for each finger and two to close and control the position of the thumb. For the Michelangelo-Hand the prices could range from 50.000 € to 60.000€.

a) b)

Figure 6- a) Michelangelo-Hand [16]; b) Vincent Evolution 2 [17]

2.1.3. Body-powered devices

This type of prosthesis are devices activated by a certain movement of the body. Normally the body-powered devices only have one function, like opening and closing the prosthesis. So a person by making a certain movement of the body closes the prosthesis and by making the counter movement opens it.

The most common body-powered device in the market is the split-hook. This device is sold by Hosmer® that has several products of this type [18]. After a quick look on the website, we can see that these prosthesis are fabricated in several materials such as aluminium, stainless steel and titanium, then the fingers may be coated with nitrile rubber.

Figure 7 – Split-hook from Hosmer® [18]

In the same website we can also see that are several devices more aesthetic and with a similar function to the split-hook like the UCLA CAPP Terminal device and the Dorrance 400 Mechanical Hand. The UCLA CAPP Terminal Device was initially developed in the Child Ampute Prothetics Project (UCLA) and this device allows the hand to grab several objects even when these have a very low stiffness. The Dorrance 400 Mechanical Hand presents the same mechanism that the split-hook but this prosthesis is coated with PVC or silicone giving it a texture and design more similar to the human hand.

Figure 8 - a) UCLA CAPP Terminal Device [18]; b) Dorrance 400 Mechanical Hand [18]

Other devices in the market are the Grip PREHENSORS made by TRS Prosthetic [19]. These prosthesis are made with several materials, like titanium, aluminum, stainless steel, and some foams. These devices allow the person to pick an object with very low stiffness.

Figure 9 – Grip PREHENSOR

2.2. Additive Manufacturing role in evolution of low cost bionic hands

The major advantage of the additive manufacturing (AM) processes is the ability of building any form that is able to be created in a 3D CAD program [20]. When using a 3D CAD program, a designer can make several prototypes with different designs and, with an additive manufacturing process, it's possible to make several iteration of the prototype to reach a final design. There are several open source examples of prototypes made with AM process such as the Rehand [20], the 6 DOF Hand [21], the iCub hand [22] and the Tact Hand [23].

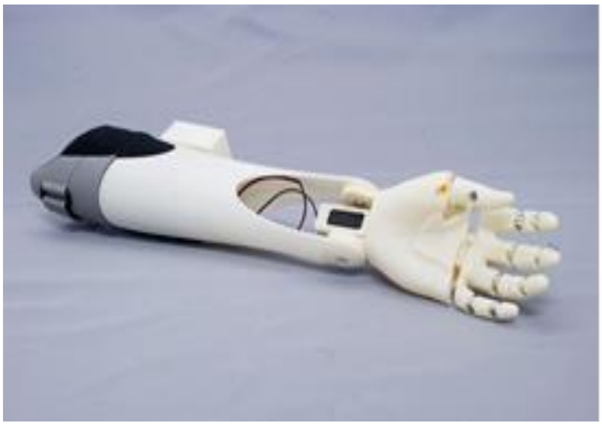

Figure 10 – Rehand [20]

There are also body-powered devices that are built with AM process like the Raptor Reloaded, the most recent 3-D print prosthetic hand. This hand is more useful for children and if the device breaks it is easy to replace the parts with a 3-D printer [24]. This model was built by the e-NABLE community which has several devices similar to that one like the K1-Hand and the cyborg-beast.

Figure 11 - a) Raptor Reloaded; b) Cyborg Beast; c) K1-Hand

2.3. Compliance Integration

Integration of compliance into prosthetics has been explored over the last few years by the robotic community. A compliance mechanism is important because it increases the safety and therefore it has been integrated into several robotic systems. It can be integrated in the control loop, in the actuator, or in the joints.

The Hit-Hand [25] is a biometric prosthetic hand that integrates the compliance into the control loop using an impedance controller. The impedance controller uses a single control law which attempts to regulate both position and force by specifying a dynamic relationship between them[25].

The series elastic actuator (SEA) incorporates an elastic element (springs) in serial with the actuator. The SEA protects the gearbox and allows the manipulator to make contact with objects in the world without damaging itself or the object [26]. The Meka 2 Hand [27] uses a SEA to control its fingers. This robotic hand has a spring between the motor and the tendon which gives the hand a higher control of the tendon force and more robustness to impacts [27].

The compliance mechanism into the joint of the finger could be accomplished using springs or elastic materials. The ISR-Softhand [28], The UC-Softhand [29], the SDM Hand [30], and the Flexirigid [31] are robotic hands that use elastic material in the joints. In the ISR-Softhand and the SMD Hand, the elastic joints are made in polyurethane which has a significant viscoelastic behaviour. The Flexirigid uses an elastomer to connect the rigid parts. The Pisa-IIT [32] and the UB hand [33] are also robotic hands that have a compliance mechanism into the joints but are different from each other. While the Pisa-IIT uses rolling contact joints with elastic ligaments, the UB hand uses springs into the joints.

Figure 12 - a) The UC-Softhand [29]; b) The ISR-Softhand [28] ; c) The SDM Hand [30]

3. DEVELOPMENT PROCESS

This chapter deals with an analysis of the cyborg beast from e-NABLE community so that it is possible to understand the concept of this type of prosthesis as well as its advantages and disadvantages. There are several iterations of the different components of the prosthesis and their associated problems. For each problem, a new solution is proposed, implemented and tested. The final design is achieved through several iterations and tests in the lab for each of the components and with the help of the volunteer.

3.1. E-NABLE prosthesis concept

3.1.1. Mechanism, components and fabrication methods

The e-NABLE prosthesis are prosthesis fabricated by a 3-D printer and powered by the movement of the extension and flexion of the wrist. The e-NABLE prosthesis are constituted by 4 components: hand part (1), arm part (2), finger (3) and cables (3) (Figure 13).

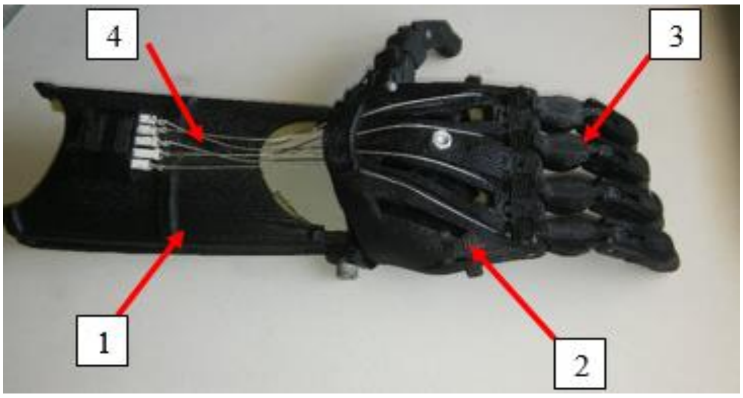

Figure 13 - Cyborg Beast prosthesis

The arm part is fixed to the person's arm with velcro and the hand part is attached to the palm of hand, and these two components are connected with two straight shafts. The cables are fixated on top of the arm part, passing through the top of the hand part, then they pass through the down side of the hand part and are attached to the tip of the fingers. In this way when a person does the movement of flexion of the wrist, the fingers close and when he does the movement of extension of the wrist, the fingers open.

The components for the arm part, hand part and fingers were fabricated on a 3-D printer in polylactic acid (PLA) and the cables can be bought in a normal store. These last ones can be made from several types of materials but they can't be made by elastic material otherwise the prosthesis will not work.

The first step was to ask the volunteer to come to our lab to make a mould of his hand. After having the mould, it was possible to have an approximation of the dimension of the hand of the volunteer. The mold was then drawn in 2-D on a paper, so as to be easier to take some measurements.

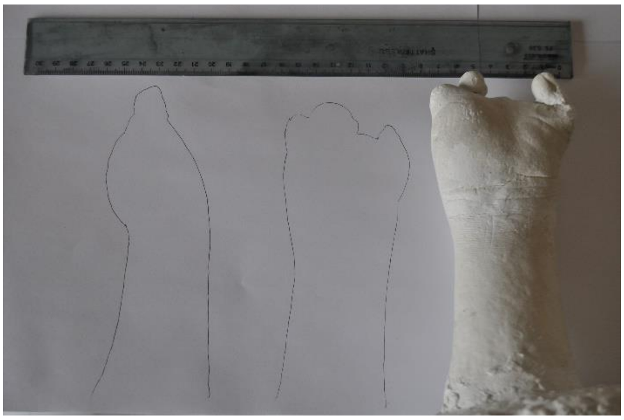

Figure 14 – 2-D drawing of the mould

3.1.2. Performance analysis of the cyborg beast prosthesis

In the last few years, ISR researchers have been producing prosthesis and applying them to people that need it. The prosthesis from e-NABLE already has been analyzed in this institute, and it was concluded that there are some improvements to be made. To analyze the performance of the prosthesis from e-NABLE, the cyborg beast was tested by performing several grasps.

Figure 15 – Testing the cyborg beast prosthesis

After the test, it was concluded that the prosthesis can´t grab some objects without the help of a healthy hand. They also verify that, besides the two contact points (thumb and the 4 fingers), a third contact point (Figure 16), in the palm of the prosthesis, helps a lot to grab an object and prevent it from slippage.

Figure 16 – Contact points between the prosthesis and the object

Another thing to take into account is the position and orientation of the thumb. The thumb could take two positions: thumb abducted or thumb adducted (Figure 17). The prosthesis from e-NABLE community have the thumb in adducted position which could be prejudicial to the performance of the prosthesis. According to Thomas Feix [34], with the thumb in abducted position more grasps are possible to perform (23 of 33) when compared to the thumb in the adducted position. According to [35], the cyborg beast can only perform 5 of the 33 grasps possible.

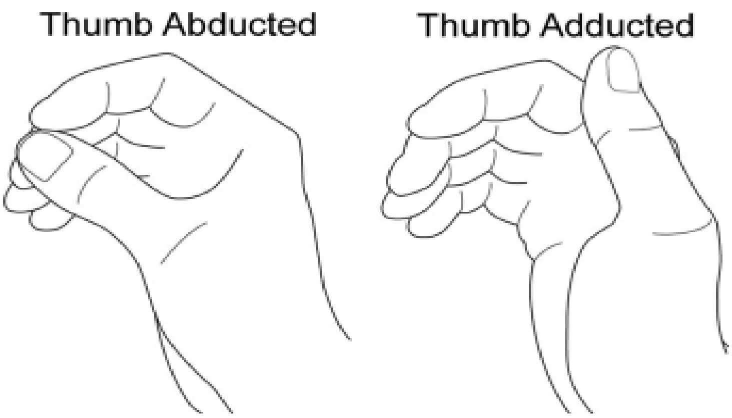

Figure 17 - Thumb abducted and Thumb Adducted

3.2. Components

3.2.1. Hand part

3.2.1.1. First prototype

This prototype of the hand part component was drawn with a 3-D CAD program and it is based on the prosthesis from e-NABLE and prototypes made in ISR. After finishing the first 3-D drawing, the prototype was produced in a 3-D printer.

Figure 18 - Hand part component: First iteration

The first prototype of the hand part was built with the intention to put two bands of velcro to attach the hand of the person to this component. However, on the hands fabricated in the ISR labs it was verified that without a rigid part on the palm, the movement of the wrist is not transmitted to the fingers. This happens because the velcro bands are too elastic as so, when a person does the flexion of the wrist, the fingers don’t bend.

Figure 19 – Deformation process of the velcro

This component was analyzed with an objective to reduce the weight and remove parts that were unnecessary. After looking at the device, it was concluded that some parts could probably be removed. The parts that could be removed are described on Table 1 and the zones described in the table 1 are referring to Figure 20.

Table 1 – Problems and solutions

Zone	Problem	Solution
1	Probably an unnecessary zone	Remove the zone
2	Stiffness to high compared to rest of the hand	Reduce the finger groove
3	Uncomfortable to the person	Remove the zone, or change the material

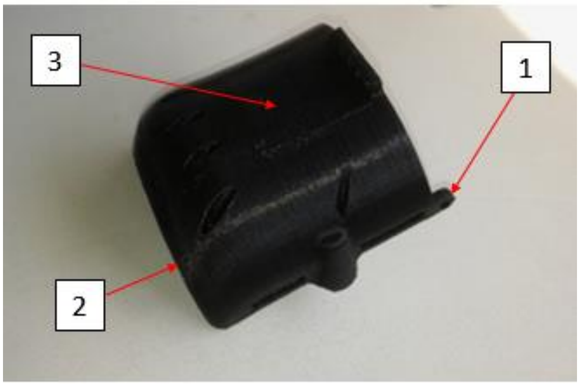

Figure 20 – Zones of the prototype

3.2.1.2. Second prototype

The second prototype made of the hand part component contains the solutions presented on Table 1. In this prototype, the zone 3 was changed to a more flexible and soft material (filaflex) in order to be more comfortable to the person. On the bottom of the prototype it was also put a band of this flexible material. The filaflex was attached to the PLA by heating the two materials at melting temperature and then mixing them. After mixing the two materials were cooled until they reached room temperature.

Figure 21 - Hand part component: second iteration

This prototype is very comfortable to the person, but this idea had to be abandoned because it was not very aesthetic, especially in points that were reheated, and because the filaflex has a higher density than PLA which increased the weight of the prosthesis [36].

3.2.1.3. Third prototype

On the third prototype, all the flexible material was removed from the top of the component and it was decided not to put any material. Instead of the flexible material in the bottom of the component, it was decided to just put two band of velcro and then, later, remove one of bands and put a rigid material with the shape of the hand of the person, so as to be possible a better transmission of the movement of flexion and extension of the wrist to the component.

Figure 22 - Hand part component: Second iteration

After printing, the component was tested on the mould, to see if it is well dimensioned to the hand of the volunteer.

Figure 23 – Hand part on the mould

3.2.2. Arm part

3.2.2.1. First prototype

Many amputees have mastered using their hand for many years in spite of the missing fingers. For some tasks they even prefer to use their hand instead of the prosthetic device. Therefore, an easy release mechanism was implemented that separates the actual prosthetic from the forearm fitting. That means there will not be a connection between the arm part and the hand part. The cables will attach the arm part and can be disconnected and connected to this component. In this way the person can remove the hand part by disconnecting the cables. By making these two components independent from each other the person can make simple tasks, such as cleaning the hand, without removing the entire prosthesis, which is an important factor for amputees.

The system used to connect and disconnect the cables to the arm part consists on a plastic buckle, a very common system used mostly in backpacks and waist bags. This system is composed by two components: male and female. The female component was already attached to the arm part and the male component was attached to the cables with screws.

Despite being a promising system, the 3D-printed components started to lose their functionality after a few cycles. Therefore, we gave up continuing this idea, for this specific prosthesis. Nevertheless, if the part is made with a SLS printer, or if an injected plastic is used, one can yet use this idea.

Figure 24 – Lock and unlock system

3.2.2.2. Second prototype

On this second prototype of arm part the lock and unlock system was removed. Instead of lock and unlock system, it was chosen to make 5 holes to insert the screws, where the cables were attached.

Figure 25 – Arm part: Second Iteration

As the hand part, this component was also tested on the mould to check for any dimensional problem.

Figure 26 – Hand part on the mould

3.2.3. Fingers

An initial version of the fingers have already been designed by ISR researchers. These fingers have a 3D printed rigid endoskeleton (Figure 27) and then are coated with soft matter [35]. In the older versions of robotic hands made in ISR it was used a compliant mechanism, but just in one joint, and the finger was connected to the robotic hand with a straight shaft.

Figure 27 - 3D printed rigid endoskeleton [35]

The fingers that were used are a new version of fingers that have two compliant mechanisms in two joints and have a simple mechanism to attach to the robotics hands. This way the complexity of the fingers assembly and the number of components were reduced.

In the previous version, the finger metacarpophalangeal (MCP) (Figure 28) joint was a normal mechanical joint. This implies utilization of a rotational spring, often difficult to replace by a normal user.

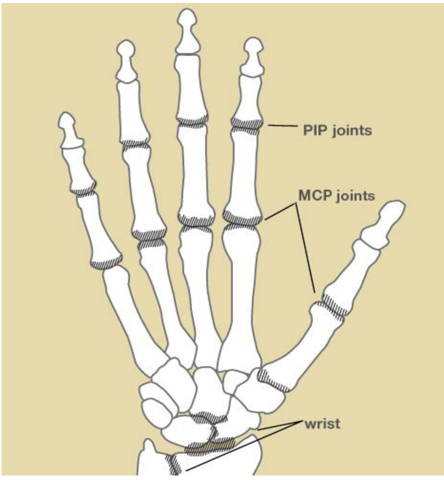

Figure 28 – MCP and PIP joints [37]

In the new version, both joints, MCP and proximal interphalangeal joint (PIP) (Figure 28), are integrated into the finger core, thus making it easier to assemble, disassemble and replace the fingers.

Figure 29 - 3D printed rigid endoskeleton with two joints

The 3D printed endoskeleton is then placed in a mould for integration of the skin (Figure 30). The skin is made of two polymers, one highly elastic silicone for the joints and overall skin, and another high-friction polymer at the finger tip. Overall, this finger should provide better results compared to the previous version, considering the design optimization.

The integration of the skin is made in three steps. The first step is to inject the highly elastic silicone into the mould (Figure 30 (a)) which is then removed, after around 24 hours, and left at room temperature to cure. The second step is to remove the highly elastic silicone on the finger tip. The third step is to place the finger in another mould and inject a high-friction polymer at the fingertip (Figure 30 (b)).

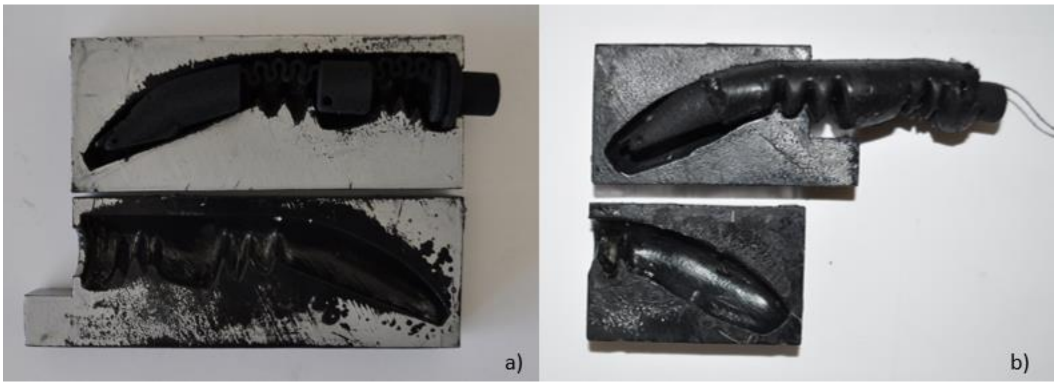

Figure 30 - a) First step: 3D endoskeleton in the mould; b) Third step: Fingertip in the mould

After around 12 hours the final finger is removed from the mould. The final finger is then composed by two different materials (Figure 31). The polymers used are Ecoflex® 30 to the highly elastic silicone and Vytaflex® 30 to the high-friction polymer and both their characteristic are described in Table 2 .

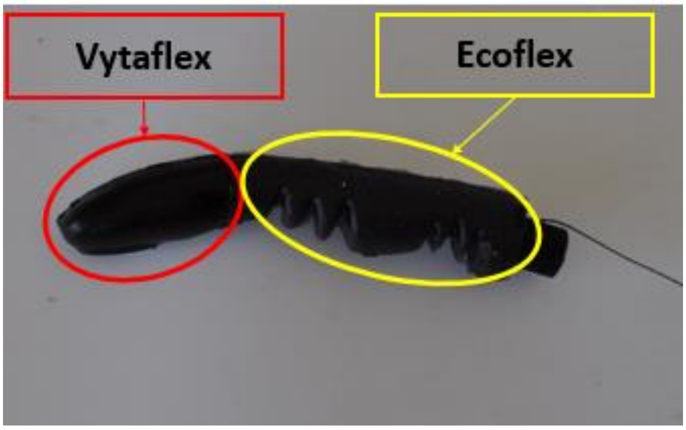

Figure 31 – Final Finger

Table 2 – Ecoflex and vytaflex characteristics [38]

Characteristics/materials	Ecoflex 30	Vytaflex 30
Tensile Strength [psi]	200	500
Elongation Break [%]	900	1
100% modulus [psi]	10	65

3.2.4. Tension system

The tension system is composed of a screw and two nuts. On the top of the arm part it has 5 holes for the screws to pass. One of the nuts is attached onto the arm part and the other one is glued to the tip of the screw. The cables are tied with a knot in the nut which is connected to the screw, in this way we can adapt the flexion of the finger by screwing and unscrewing.

Figure 32 – Tension system

4. TESTS AND RESULTS

4.1. Assembly

After analyzing the components and correcting the problems, the prototype was assembled and tested by grasping several objects to see if there was any problem.

4.1.1. First assembly of the device

After printing all the components and the fingers were manufactured, the prosthesis was ready to be assembled (Figure 33).

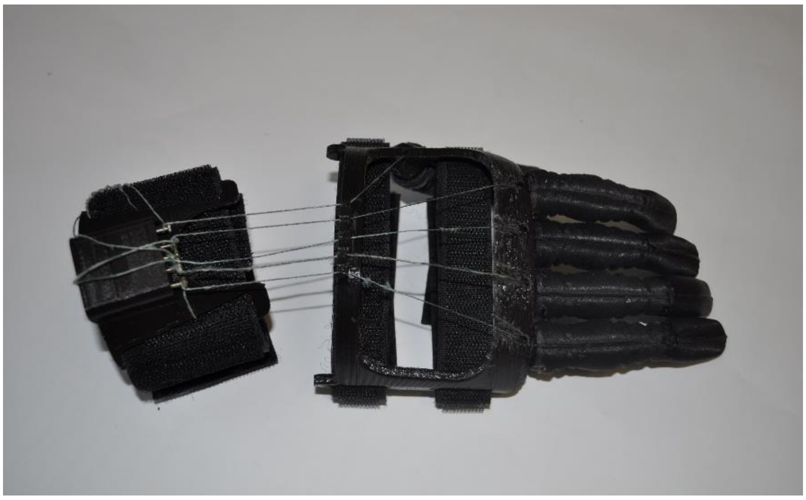

Figure 33 – First prototype assembled

The prototype was tested by grabbing several objects with the purpose to see if there is any problem. According to [39], cylindrical objects are the most used by humans during their daily tasks as so, most of the objects tested were cylindrical or spherical.

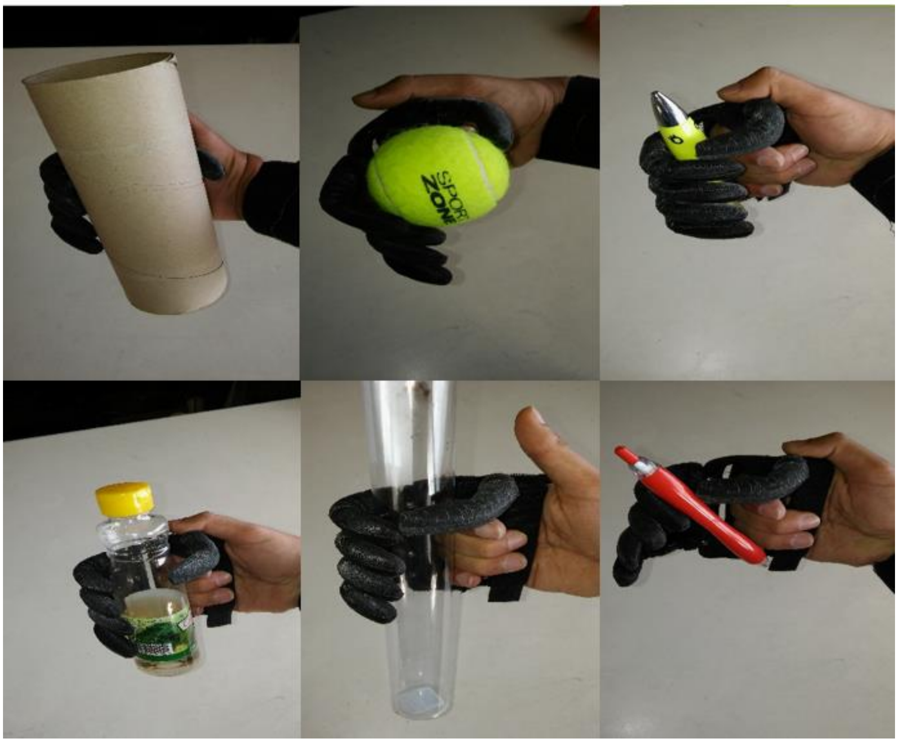

Figure 34 - A variety of objects possible to hold with a prototype

On Figure 34 it’s possible to see that the prototype can grab several objects but there were two problems.

The first problem was the position of the thumb, the tip of the thumb needed to be in same direction as the tip of the index finger (Figure 35). As we can see in some objects of Figure 34, the thumb and the index finger are not in the same direction which makes it harder to do a palmar pinch.

Figure 35 – Thumb and index finger not in the same direction

The second problem was with the ulnar deviation and radial deviation movement (Figure 36) of the hand.

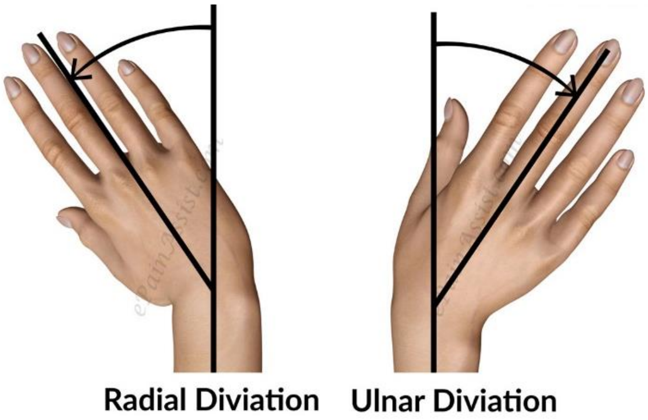

Figure 36 - Ulnar and radial deviation movement [40]

If the fingers were closed when the movement of radial deviation was made, the cables that were more to the right would no longer pull the tip of the finger, as so the fingers more to the right opened (Figure 37).

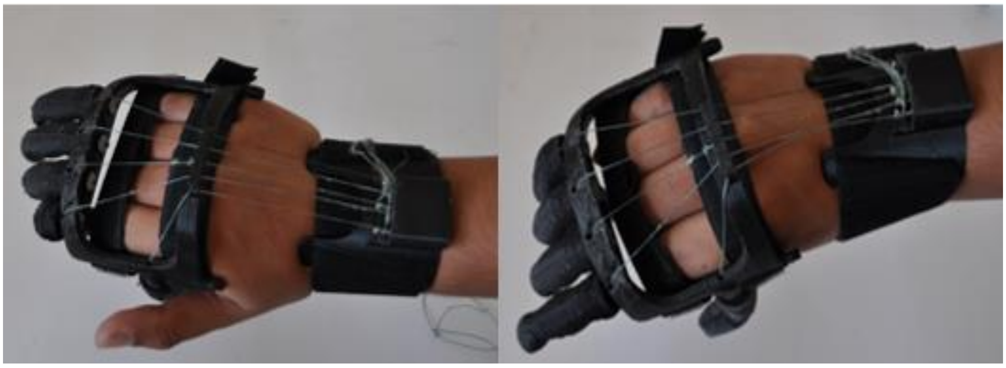

Figure 37 – Radial and Ulnar Deviation problem

The same would happen in opposite side of the hand, when it was made the ulnar deviation. This last problem was critical because if the device was holding an object, a small ulnar or radial deviation movement could lead to its fall.

4.1.2. Second assembly of the device

To correct the problem of ulnar and radial deviation it was clear that the hand part and the arm part should have a more rigid type connection, instead of what was originally proposed. Three joints with a straight shaft were used to make the connection between the hand part and the arm part (Figure 38 (a)).

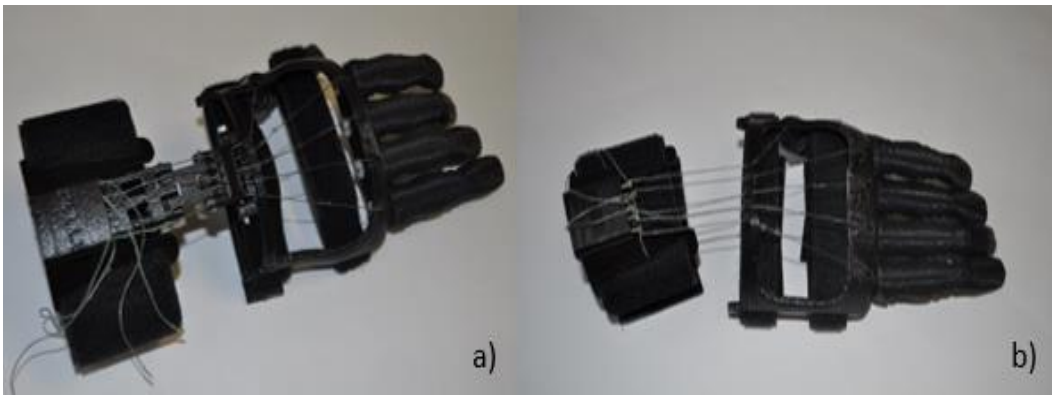

Figure 38 – (a) Second prototype vs. (b) First prototype

In the same way as the prototype presented in 3.3.1, this one was also tested with several objects (Figure 39).

Figure 39 - A variety of objects possible to hold with a prototype

After testing the prototype, the problem with radial and ulnar deviation was corrected, and it can now perform several grasps. Despite the problems of the first prototype assembled were corrected, a second problem was found. The connection system between the hand part and the arm part is subjected to compression as so, there is no control of the movement of this system. As there is no control, the joints could go against the skin and hurt the person. So, this type of connection had to be abandoned.

4.1.3. Third assemble of the device

To solve the problem of the last prototype, only one joint with a straight shaft was used. To increase the flexion of the fingers, the cables on the arm part were raised, this way increasing the distance travelled by the cables.

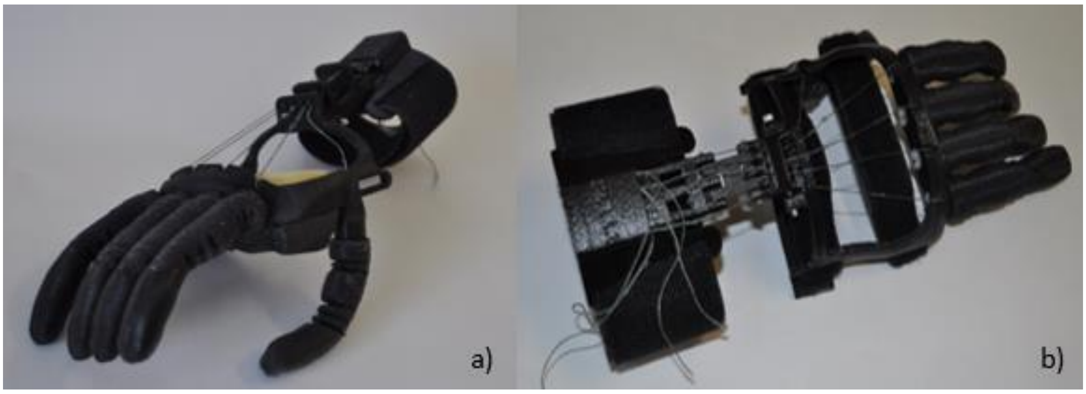

Figure 40 – (a) Third prototype vs. (b) second prototype

Also at the palm of the prototype a third contact point was added in order to increase the stability of the grasp.

This is an important improvement compared to the e-NABLE hands. A palm made out of soft materials, not only provides additional contact points that contribute to the stabilization of the grasp, it can also adapt to the shape of the object, thus increasing the overall size of the contact area.

To accomplish this, a mould was 3D printed (Figure 41 (a)) and placed over the palm (Figure 41 (b)). Then a high friction polymer (Vytaflex® 30) was casted in the mould at its liquid form, which, after curing, turned into the elastic palm (Figure 41 (c)). With this third contact point we have a better flexion and extension movement of the prosthesis as well as a better grasp between the prosthesis and the objects.

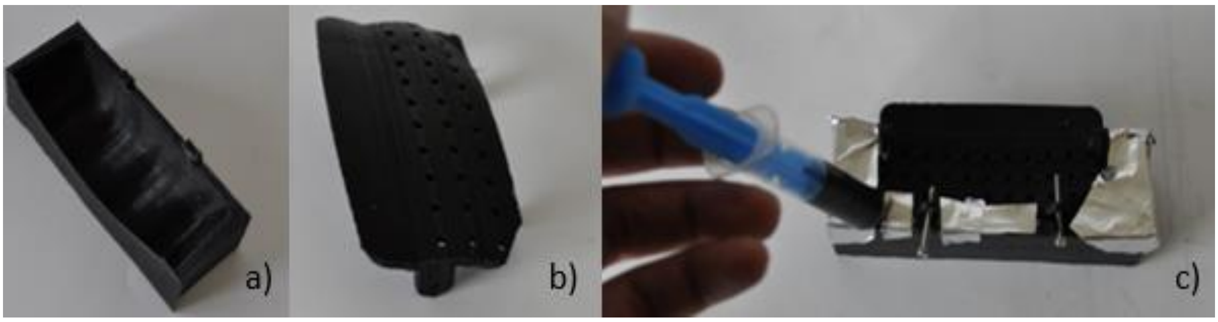

Figure 41 – a) 3-D printed mould; b) rigid part with the shape of the palm of the volunteer; c) cast process

After the prototype was assembled, several grasps were tested (Figure 42).

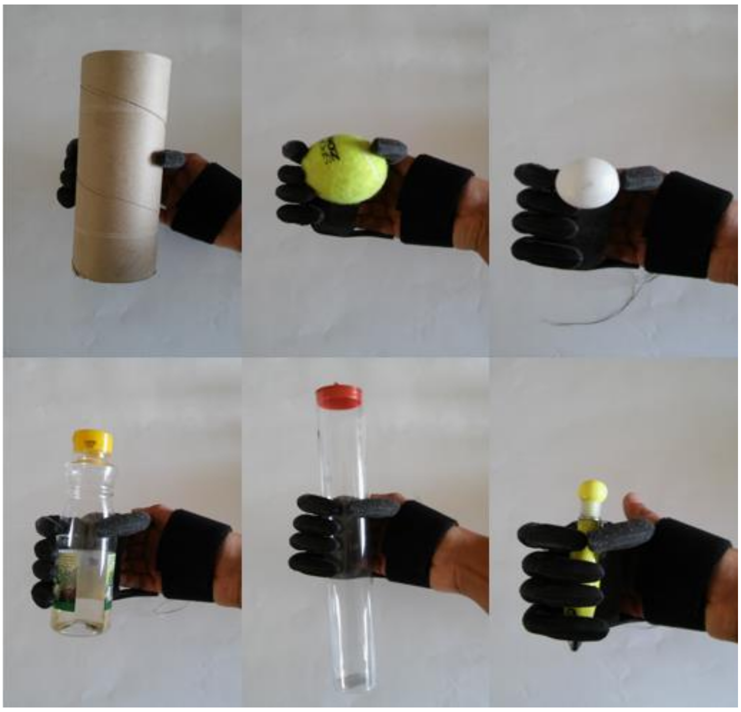

Figure 42 - A variety of objects possible to hold with a prototype

This prototype did not present any problems and was ready to be tested on the person.

4.2. Test with the volunteer

4.2.1. First tests

On the first tests made, the person was not capable of grabbing any objects because the movement of extension of the wrist wasn't being transmitted to the hand part. When the volunteer made the extension of the wrist his hand came out of the hand part.

Figure 43 – Test results: First problem

A second problem was also found on the arm part. During the movement of flexion of the wrist, the arm part was being pulled by the cables. So, after two or three grasps, it slipped from the initial position on the arm of the volunteer because the velcro was not tied properly to the arm (Figure 44).

Figure 44 – Arm part on the arm

In the first problem it was clear that the top of the hand part needed to have a rigid material, to be able to transmit the movement. It was then decided to add PLA to the top of the hand part and then add another material more aesthetic. For the second problem it was decided to change the arm part by putting two holes for the velcro to pass and in this way have a better grip between the arm part and the arm of the volunteer.

4.2.2. Final tests

After solving the problems found after the first tests on the person, a final version of the prosthesis was assembled and it was ready to be tested. The overall mass of this hand was 215 g.

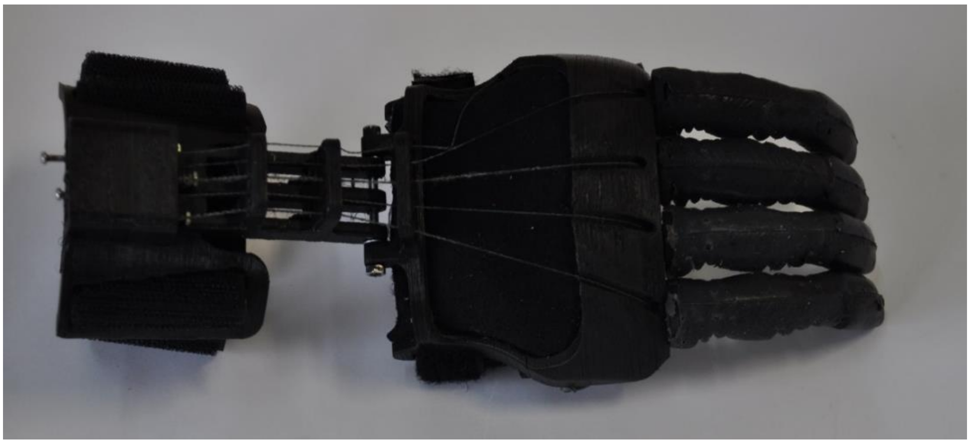

Figure 45 - A fully assembled final version of the prosthetic device

The final version was then tested by the volunteer, by performing several grasps with various objects with different weights and forms. As we can see on the (Figure 46), the volunteer can handle with some ease different types of objects.

Figure 46 - A variety of objects possible to hold by the volunteer

During the tests the volunteer stated that the final version of the prosthesis was very comfortable and a good fit to his hand. Also, the problems found in the previous versions were corrected. The volunteer did the movements of extension of the wrist which were very well transmitted to the prosthesis. The second problem found in the last version was also corrected. The velcro on the arm part tightened very well on the volunteer's arm and no longer slipped.

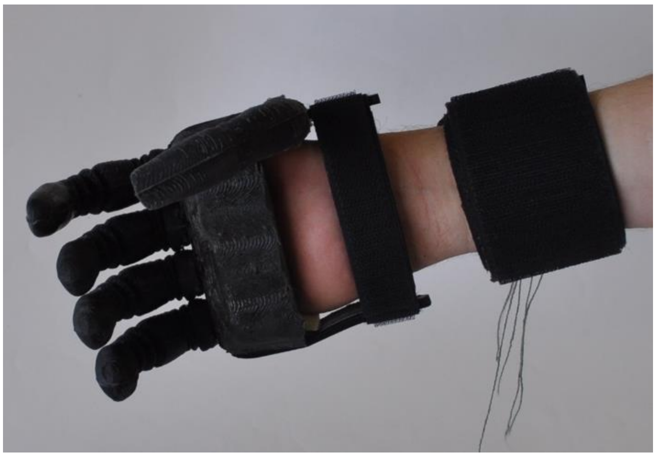

Figure 47 – A final prosthetic device worn by the recipient

4.3. Results

The final version was then tested in lab conditions. Different grasps were tested to understand the capacity and efficiency of the prosthesis. As we can see in Figure 48, the prosthesis can handle several objects. Operations like drinking water or throwing a ball are possible to perform without any need of previous training with the prosthesis. And, with some training, more complex operations are possible to perform like catching a ball in the air or even riding a bicycle. Despite that, the final version has weight limitations. Objects heavier than 800 g are impossible to lift, and objects heavier than 500 g are difficult to hold for long periods.

Figure 48 - Several objects possible to hold with a hand

However, there are some operations that are not possible to perform by the volunteer, as for instance, writing. The volunteer has a limited movement of extension and flexion of the wrist as such, he cannot close the fingers of the prosthesis enough to grab a pen. To solve this problem, the initial thought was to increase the initial flexion of the finger, but then the majority of the objects wouldn’t fit in the prosthesis. As his hand didn’t have much activity over the years, the muscles may have become dormant. Probably, with some physiotherapy, the volunteer could increase his flexion and extension movement of the wrist, and then be able to write with the prosthesis.

As been said, the device has an overall mass of 215 g so, this device has had a weight reduction of 7% when compared to the 230 g of the soft-enabled hand and also, a reduction of 8,6 %, when compared to cyborg beast (235g).

4.4. Performance comparison

As a means to compare the performance of this prototype with the "Cyborg beast" and "The soft enabled-hand", the prosthesis was tested by trying to perform each one of the 33 grasps from Grasp Taxonomy table by Felix et al. [41] (Figure 49).

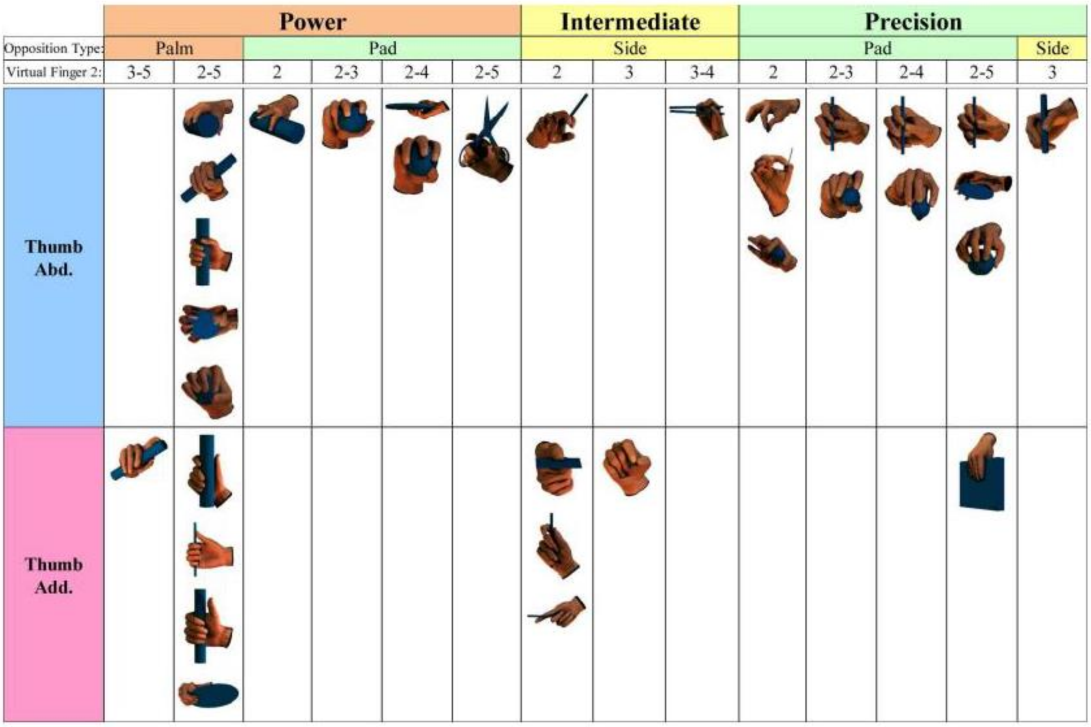

Figure 49 - Grasp Taxonomy table by Felix et al. [41]

To classify all the performed grasps, the same method was used as in [35] which classified the grasps in 3 categories: possible, approximate and impossible. By approximate are perceived grasps that make it possible to hold an object, but still can't reproduce perfectly the grasps [35].

The results of the 33 grasps performed by the "Cyborg beast" and the "Soft-Enabled Hand" are shown in Table 3.

Table 3 - Test results: quantity of possible, approximate and impossible grasps performed by the Cyborg Beast hand and the Soft-enabled hand [35]

Model	Imitation	Number of performed grasps	Grasp type
Cyborg Beast	Possible	2	15, 28
	Approximate	3	5, 9, 30
	Impossible	28	rest
Soft-Enabled Hand	Possible	17	1, 2, 3, 7, 8, 10, 11, 12, 13, 14, 18, 24, 25, 26, 27, 28, 33
	Approximate	6	5, 6, 15, 17, 19, 31
	Impossible	9	4, 16, 20, 21, 22, 23, 29, 30, 32

To test the prosthesis development in this work, different objects were used to perform the 33 grasp types. Some of the characteristics of the objects are shown on Table 4.

Table 4 – Characteristics of the objects used in tests

Objects	Diameter (mm)	Mass (g)
Tennis ball	65	61
Tube	40	18
Tube 2	80	41
Ping-Pong ball	40	2
Pen	15	20
Scissors	-	118
CD	120	15
Battery	14	24
Plate	-	11
Glass	58	115

The Table 5 shows the results of the 33 grasps performed by the prosthesis developed in this work.

Table 5 – Test results: Quantity of possible, approximate and impossible grasps performed by the prosthesis

Model	Imitation	Number of performed grasps	Grasp type
Prosthesis developed in this work.	Possible	18	1, 2, 3, 7, 8, 9, 10, 11, 12, 13, 14, 18, 24, 25, 26, 27, 28, 33
	Approximate	5	6, 15, 17, 19, 31
	Impossible	10	4, 5, 16, 20, 21, 22, 23, 29, 30, 32

It is clear that this prosthetic device outperforms the Cyborg Beast. In the Cyborg Beast only 5 out of the 33 Grasp possible were well performed, while the prosthesis developed in this work performed a total of 23 grasps. However, when we compared the device with the soft-enabled hand they both had the same performance.

5. CONCLUSION

5.1. General conclusion

In this work, an upper-limb device was designed, fabricated and tested in order to give a better quality of life to a person with a right hand disorder. Several characteristics were taken into consideration like low cost, intuitive control and light-weight. These characteristics are a great advantage because they allow the person to have a better use and to feel more comfortable with a low cost device. The advancements in additive manufacturing technologies and soft robotics played an important role in achieving the final design and the proposed aims.

The prosthesis produced was based on a concept created by the worldwide community e-NABLE Group. However major modifications were made in order to increase the hands functionality. This includes changes on the design of the finger, palm, chassis, and the thumb. Rather than a fully 3D printed finger, we used a finger composed of a 3D printed endoskeleton covered by a silicone soft skin, which was moulded around the endoskeleton. The position of the thumb was also corrected and a soft palm was added to increase the contact area. Also we took advantage of two different silicones, Ecoflex® 00-30 and Vytaflex® 00-30, in the hand implementation. The former one, as a reference for a highly elastic material, mainly used in the joint of the hand, and the latter a silicone elastomer which has good friction properties for contact zones, such as the palm and the finger tips. The desired colour was also added to the resins prior to casting.

Some designs in the e-NABLE website are very good aesthetically but their functionality is limited. The thumb position is a very important factor in the performance of the prosthesis. In e-NABLE community all the prosthesis have the thumb in the adducted position while, on the prosthesis built, the thumb is in abducted position. Since it's in a different position, the performance of the prosthesis outcomes, by far, the cyborg beast. Another factor that makes this prosthesis better than the Cyborg Beast is the third contact point on the palm. This third point allows a better stability when the prosthesis grabs the objects.

However, when compared with the Soft-enabled Hand, the prosthesis doesn't outcome nor fall behind its performance. These two hands presented the same performance, but the new version has improved stability when compared to the previous version (elastic palm and better finger tips made out of high friction elastomer). It also offers a better fitting to the volunteer hand, since the design of the main chassis of the prosthetic device was made based on casting of the volunteer hand. Finally by asking a volunteer to test the device we were able to find the actual problems which could not be understood without the volunteer's collaboration. It should be noted that, since the hand does not have actuators and all movements are based on the single DOF of the wrist, in our opinion, we cannot improve the hand further in terms of number of achievable grasps (23). However, there is still room for improvement in the hands fitting and aesthetics.

Also, it's difficult to perform more than the 23 grasps achieved by the prosthesis. Without the thumb in adducted position, most of the impossible grasps are not possible to perform.

In summary, the performance of the prosthesis produced in this work outcomes the cyborg beast. Three factors have contributed to this conclusion: the third contact point on the palm, the position of the thumb and the materials used on the fingers. As none of the prosthesis from e-Nable group present any of these factors, the prosthesis produced will probably outcome the performance of all devices from e-Nable group.

5.2. Future work

This work reports fabrication methods, assembly and the performance of a 3D prosthetic device. Over the last years, the use of 3-D printers has increased in several fields as so, it is very common to see these materials in prosthetic devices. Despite the fact that we have produced a functional prosthetic device, there is still work to be done.

As it has been said, the position of the thumb is a very important factor for the performance of the prosthesis. In future work, a system that allows the patient to change manually between abducted and adducted positions could increase the performance of the prosthesis.

Another future work could be a mechanism to increase the flexion of the fingers. With a better flexion of the finger, heavier objects could be lifted and we could have more stability in the grasp.

Future works should not just be about the functionality, but also about improving the comfort and the aesthetical appearance of the device by making it more like the human hand and through the utilization of soft materials on the points that are in contact with the body.

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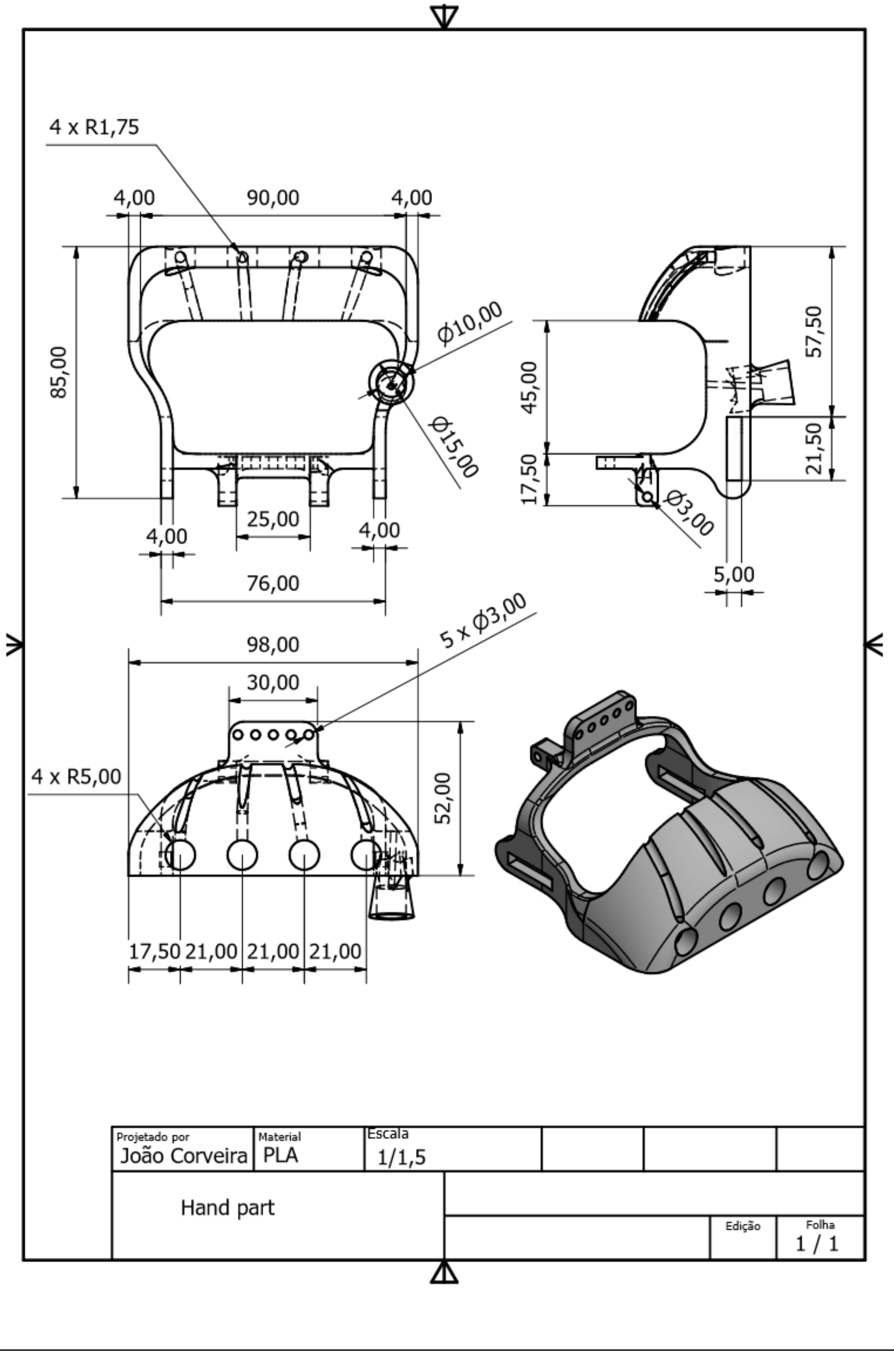
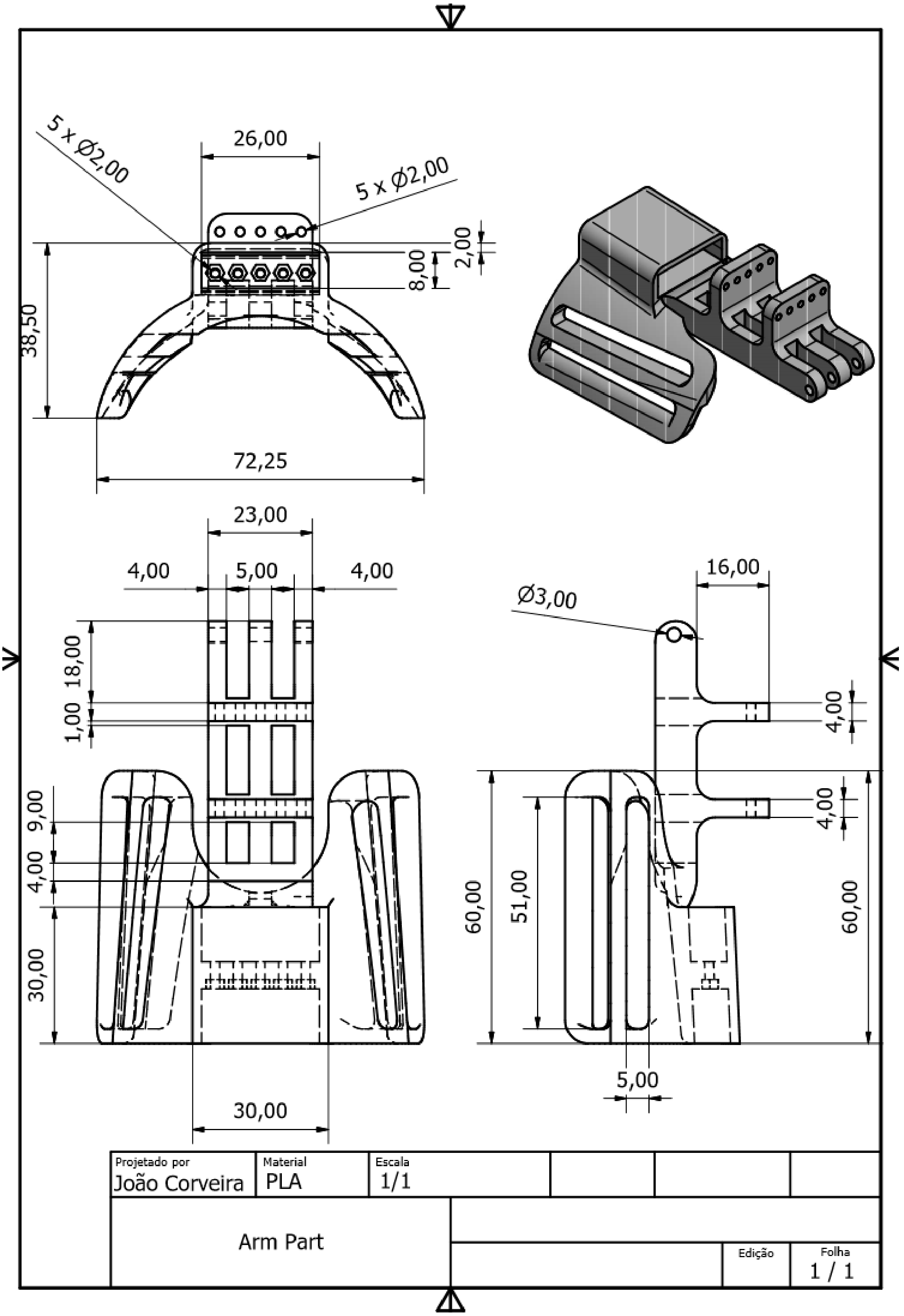
APPENDIX A

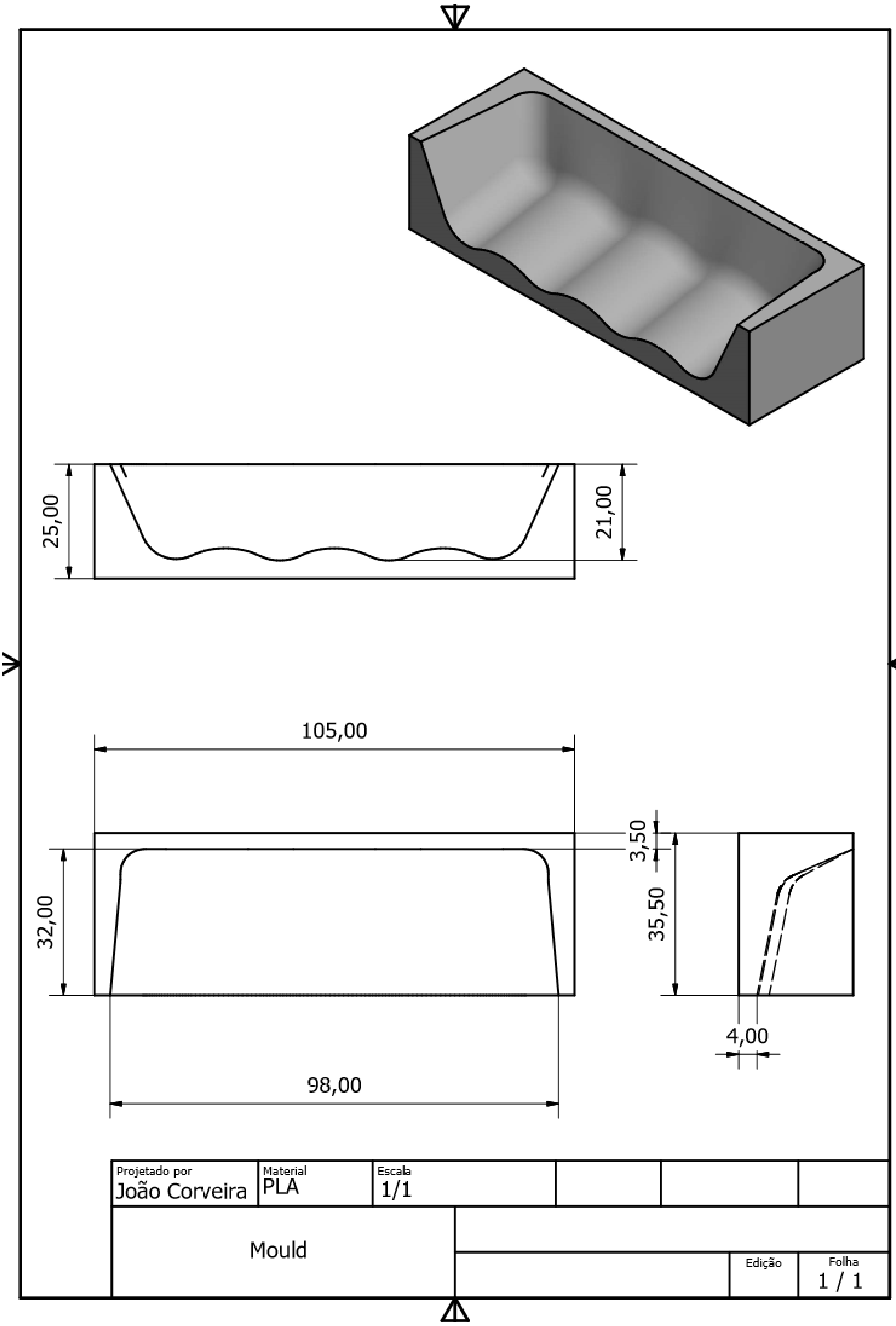
A1 . Hand part drawing



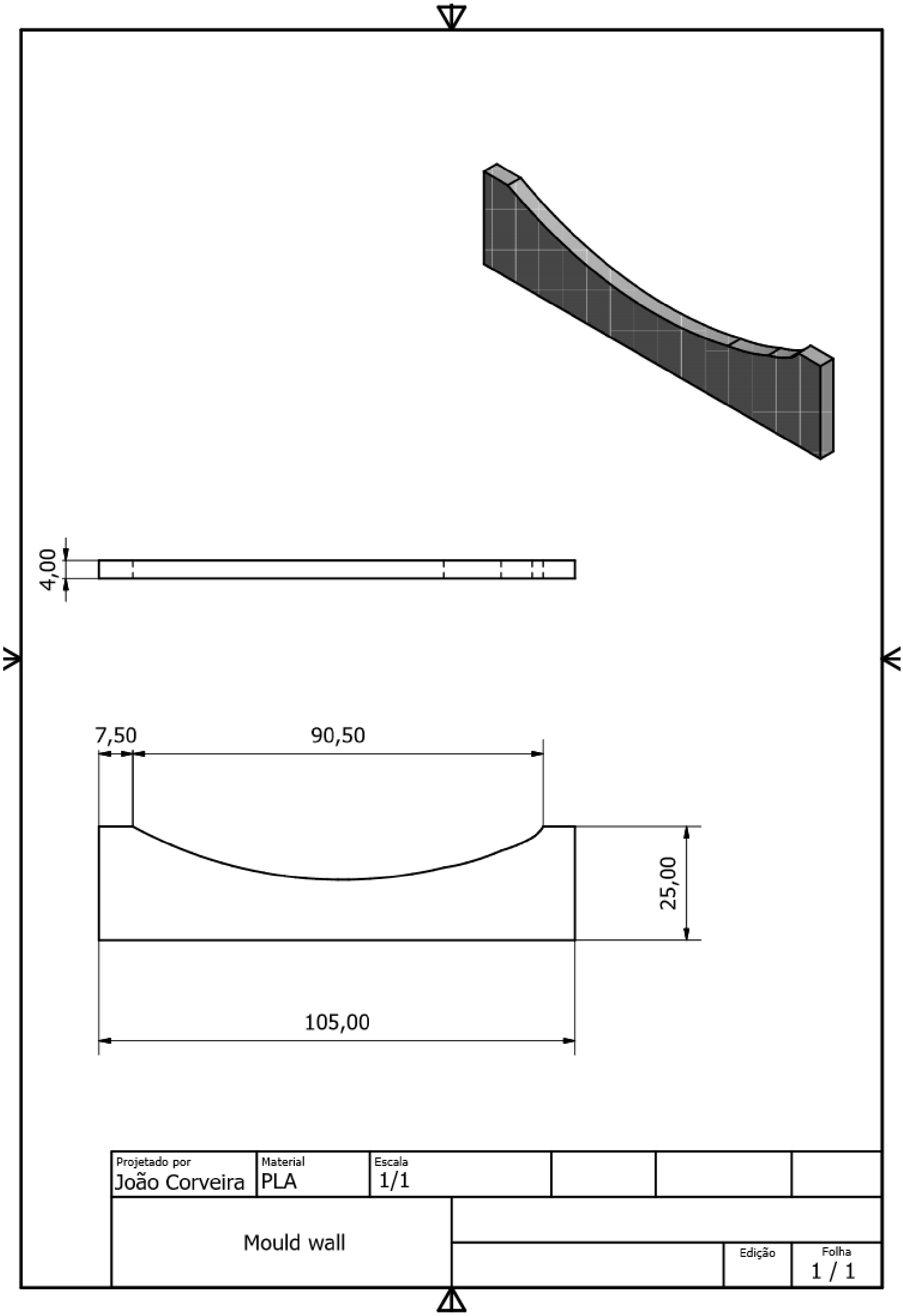
A2 . Arm part drawing



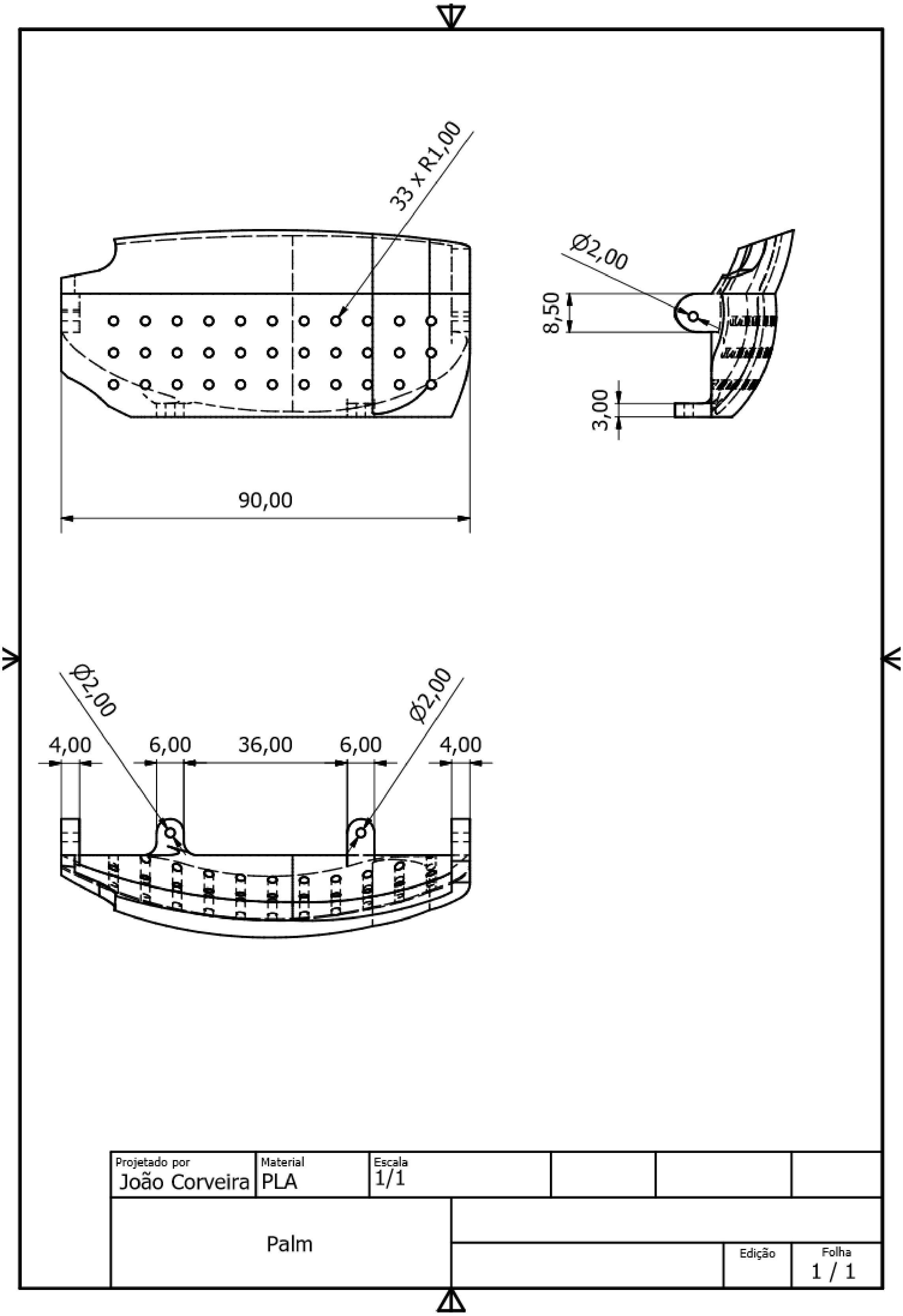
A3 . Mould Drawing



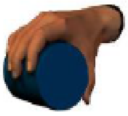
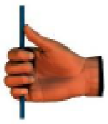
A4 . Mould Wall Drawing

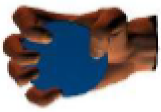


A5 . Palm Drawing



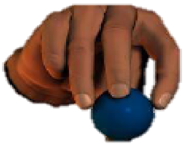
A6 . Detailed representations of grasps performed

Synergy	Object	Hold	Prosthesis in study	Comment
1. Large diameter 	Tube2, d= 80 mm	+		
2. Small diameter 	Tube, d=40mm	+		
3. Medium Wrap 		+		
4. Adducted thumb 	-	-	-	Impossible to perform with thumb in the abducted position
5. Light Tool 	Pen, d= 15mm	-	-	Impossible to perform with thumb in the abducted position
6. Prismatic 4 finger 	Pen, d= 15mm	+		

7. Prismatic 3 finger 	Pen, d= 15mm	+/-		Possible, if the tension of the fingers tendon cord is adjusted for the purpose
8. Prismatic 2 finger 	Pen, d= 15mm	+/-		Possible, if the tension of the fingers tendon cord is adjusted for the purpose
9. Palmar Pinch 	Battery, d=14mm			
10. Power disk 	CD, d=120mm	+	 	
11. Power sphere 	Tennis Ball, d=65mm	+		
12. Precision disk 	CD, d=120mm	+		

13. Precision Sphere 	Tennis Ball, d=65mm	+		
14. Tripod 	Ping Pong Ball, d=40mm	+		
15. Fixed Hook 	Tube, d=40mm	+		
16. Lateral 	-	-	-	Impossible to perform with thumb in the abducted position
17. Index Finger Extension 	Tube, d=40mm	+/-		Possible, but the grasp is unstable
18. Extension type 	Plate	+		

19. Dystal type 	Scissors	+		
20. Wrinting tripod 	-	-		Not possible to perform
21. Tripod Variation 	-	-	-	Not possible to perform
22. Parallel Extension 	-	-	-	Not possible to perform
23. Abduction Grip 	-	-	-	Not possible to perform without an abd./add. movement between the index and middle fingers
24. Tip Pinch 	Hex Key	+		
25. Lateral Tripod 	Battery, d=14mm	+		

26. Sphere 4 	Tennis Ball, d=65mm	+		
27. Quadpod 	Ping Pong Ball, d=40mm	+		
28. Sphere 3 Finger 	Tennis Ball, d=65mm	+		
29. Stick 	-	-	-	Not possible to perform
30. Palmar 	-	-	-	Impossible to perform with thumb in the abducted position
31. Ring 	Tube2, d= 80 mm	+		
32. Ventral 	-	-	-	Not possible to perform
33. Inferior Pincer 	Ping Pong Ball, d=40mm	+