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FCTUC FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE DE COIMBRA

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# Bio-inspired robotic gripper with hydrogel-silicone soft skin and 3D printed endoskeleton

Dissertation presented to the University of Coimbra in order to complete the necessary requirements to obtain the Master's degree in Engineering Physics.

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# Abstract

On this project, an innovative and bio-inspired finger is developed, resembling the physiology of a biological human finger. The soft finger is made of a 3D-printed core to substitute the fingers' endoskeleton, a silicon elastomer skin to substitute the elastic and resilient epidermal layer and a hydrogel filling to substitute the dermal layer. The dermal layer in human finger is softer than the epidermal layer and contains a considerable amount of water, and therefore should be protected by the more resilient epidermal layer, that not only protects the underlying layer from mechanical wear, but it also provides a barrier against losing the water. On the other hand, the softer dermal layer helps in better local adaptation of the skin to objects for efficient grasping. The silicone epidermal layer is intended to be elastic, malleable and protects the hydrogel from losing water over the time. The hydrogel filling of the finger is made from sodium polyacrylate (SPA) and distilled water; the material used as the silicone is Ecoflex 00-30 and the finger core is made of acrylonitrile butadine styrene (ABS).

A low-cost prototype of an under-actuated gripper was also developed integrating three of these fingers. It has a mechanism based on the push base toys and it was fully printed on a fusion deposition modelling (FDM) printed with polylactic acid material (PLA). A single motor actuates the system by pulling up and down the tendons that are integrated in the fingers, making them open or close, in order to grip or drop objects.

Fingers were tested first individually.The required force for full flexion of the fingers were measured and compared to a previous version of the finger that contains only the epidermal layer without containing the hydrogel dermal layer. Results show an improvement in reduction of the required force for flexion. Also the integrated gripper with the new version of the fingers were developed and tested for grasping several objects including soft fruits.

At the end of the dissertation, some gripping tests are analysed and concluding that was achieved an optimal soft finger that can be used in grippers and prosthesis. Despite its excellent performance, the overall bill of materials of the full gripper developed in this dissertation is 15 Euros, including the actuator. Also future work is presented both for the gripper and the soft finger.

**Keywords**: Soft finger, Hydrogel, 3D Print endoskeleton, Under-actuated gripper, Soft gripper, Silicone elastomer, Pick and place.

# Resumo

Neste projeto, desenvolve-se um dedo inovador e inspirado biologicamente, com fisiologia semelhante à de um dedo humano. O dedo mole é feito com um núcleo impresso em 3D para substituir o endoesqueleto dos dedos humanos, com uma pele elástica de silicone para substituir a camada epidérmica elástica e resiliente e um enchimento de hidrogel para substituir a camada dérmica. No dedo humano, a camada dérmica é mais macia do que a camada epidérmica e contém uma quantidade considerável de água, portanto, deve ser protegida pela camada epidérmica, que é mais resistente. Esta não só protege a camada subjacente do desgaste mecânico, mas também fornece uma barreira contra a perda de água. Por outro lado, a camada dérmica, ao ser mais suave, ajuda numa melhor adaptação local da pele para agarrar os objectos eficientemente. A camada epidérmica de silicone destina-se a ser elástica, maleável e protege o hidrogel de maneira que este não perca água ao longo do tempo. O enchimento de hidrogel do dedo é feito de poliacrilato de sódio e água destilada; o material utilizado como silicone é Ecoflex 00-30 e o endoesqueleto do dedo é feito de acrilonitrilo butadina estireno (ABS).

Também foi desenvolvido um protótipo de baixo custo de uma pinça sub-atuada integrando três destes dedos. Tem um mecanismo baseado nos *push base toys* e foi inteiramente impresso numa impressora *fusion deposition modelling* (FDM) com material ácido poliláctico (PLA). Um único motor acciona o sistema puxando para cima e para baixo os tendões que estão integrados nos dedos, forçando-os abrir ou fechar, com o propósito de agarrar ou soltar objetos.

Os dedos foram primeiramente testados individualmente. A força necessária para a flexão total dos dedos foi medida e comparada com uma versão anterior do dedo que contém apenas a camada epidérmica sem a camada dérmica de hidrogel. Os resultados mostram uma melhora na redução da força necessária para a flexão. Também a pinça integrada com a nova versão dos dedos foi desenvolvida e testada para agarrar vários objectos incluindo frutas macias.

No final da dissertação, alguns ensaios de *pick and place* são analisados e é concluído que foi conseguido um dedo mole óptimo que pode ser usado em pinças e próteses. Apesar do seu excelente desempenho, o preço geral dos materias usados para a pinça robótica desenvolvida nesta dissertação é de 15 Euros, incluindo o actuador. Também é apresentado trabalho futuro tanto para a pinça como para o dedo mole.

**Palavras-Chave**: Dedo mole, Hidrógel, Endoesqueleto impresso em 3D, Pinça sub-atuada, Elastómero de silicone, Distríbuidor automático.

# Contents

# Acronyms

**2D** Two-Dimensions

**3D** Three-Dimensional

**ABS** Acrylonitrile Butadiene Styrene

**DOA** Degree oOf Actuation

**DOF** Degree Of Freedom

**FDM** Fusing Deposition Modeling

**PLA** Polylactic acid

**PDMS** Polydimethylsiloxane

**SDM** Shape Deposition Modeling

**SFF** Solid Freeform Fabrication

**SPA** Sodium Polyacrylate

**STL** Stereolithographic format

**SLA** Stereolithography

**SLS** Selective Laser Sintering

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# Chapter 1

# Introduction

Machines in engineering are rigid, while the biological organs are soft. This contradiction is the motivation for the novel field of soft robotics. In the present century, the industrial automation and robotics are growing. The field of soft robotics is a recent sub-field of robotics that intends to take inspiration from the biological systems and integrate compliance into human-made architectures, such as robots. This is achieved by integration of elastic element such as elastic polymers that are soft and stretchable to replace the rigid elements in the traditional machineries. Some examples of materials can be seen in figure 1.1: Majidi et al. presented a silicone based robot that moves forward and backward which is light-weight and works with pneumatic channels [1]; Lyne et al. presented a soft pneumatic rubber glove to produce bending motions in order to help hand rehabilitation [2]; Walters et al. presented a tentacle-like active structure made of plastic [3]; Chenal et al. presented a soft robot made of fibers with variable stiffness capable of adjusting [4]; Yuen et al. presented a soft robot with embedded actuation and sensing made of cloth [5]. These materials are very convenient for the researchers of soft robotics because they are affordable, lightweight and easily customized. But still, some rigid structures are used in soft robotics, like endoskeletons or exoskeletons, to help in movement, strength, stiffness, elasticity and some surface properties of the soft tissues [17], [18].

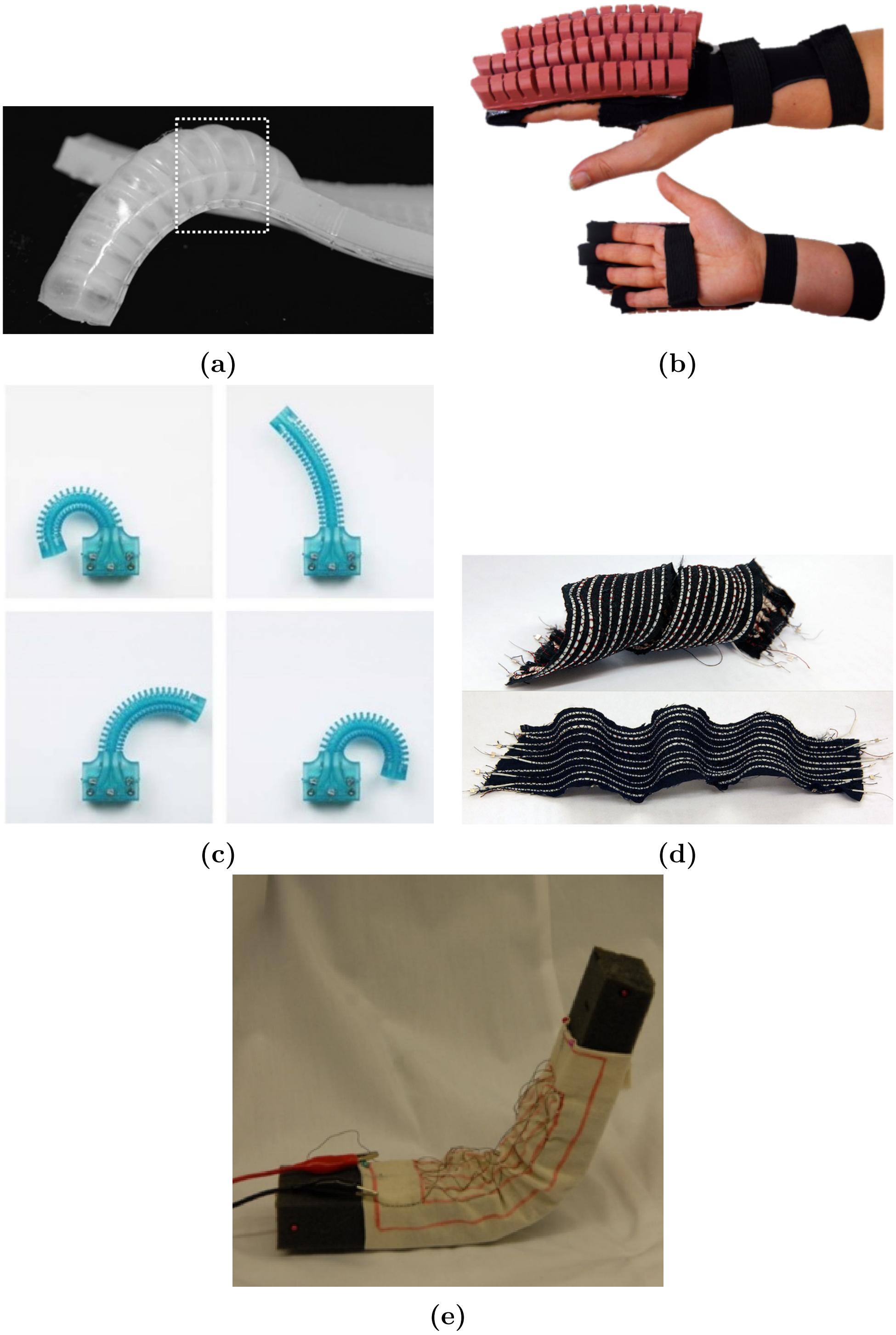



**Figure 1.1:** Examples of soft robots with different materials:(a)example of silicone material used by Majidi et al. [1]. (b)example of rubber material used by Lyne et al. [2]. (c)example of plastic material used by Walters et al. [3]. (d)example of fiber material used by Chenal et al. [4]. (e)example of cloth material used by Yuen et al. [5]

Since the soft robots are deformable and malleable, they can adapt to different tasks, objects or environments. The adaptability involves the strength, the form and even the size to do the tasks [19], but of course it depends on the main purpose of the specific soft robot, for example, a soft gripper designed to grip little fruits, probably is not intended for large objects. One specific advantage of soft grasping mechanisms is their inherent safety. Due to integration of soft elements that match with the biological organs better than the traditional rigid-matter systems, soft robots and soft grasping mechanisms are naturally more safe to interact with. This is an important advantage for these system, since they allow humans to interact with robots in a safe manner. One downside of soft robotics is that it's harder to control and to model perfectly, but since this "science" is recent, most of the work done is in prototype stage. One particular disadvantage of soft robotics system is that they are harder to model. Mathematical modelling of rigid bodies has been studied during the last couple of centuries, while the foundations for modelling of soft robots are still in its infancy. The immediate problem that arises is that these systems are as controllable as rigid-bodied robots. Soft robots are often inspired on the biology of animals, like the elephant's trunk or the octopus' tentacles [20], [14], [21], the fishes' physiognomy [15], but most of all, they are inspired on humans, for example most grippers are created based on the human hand and/or the human fingers. In table 1.1 we can see the similarities between the biology of these previous stated animals and some of their based soft robots.

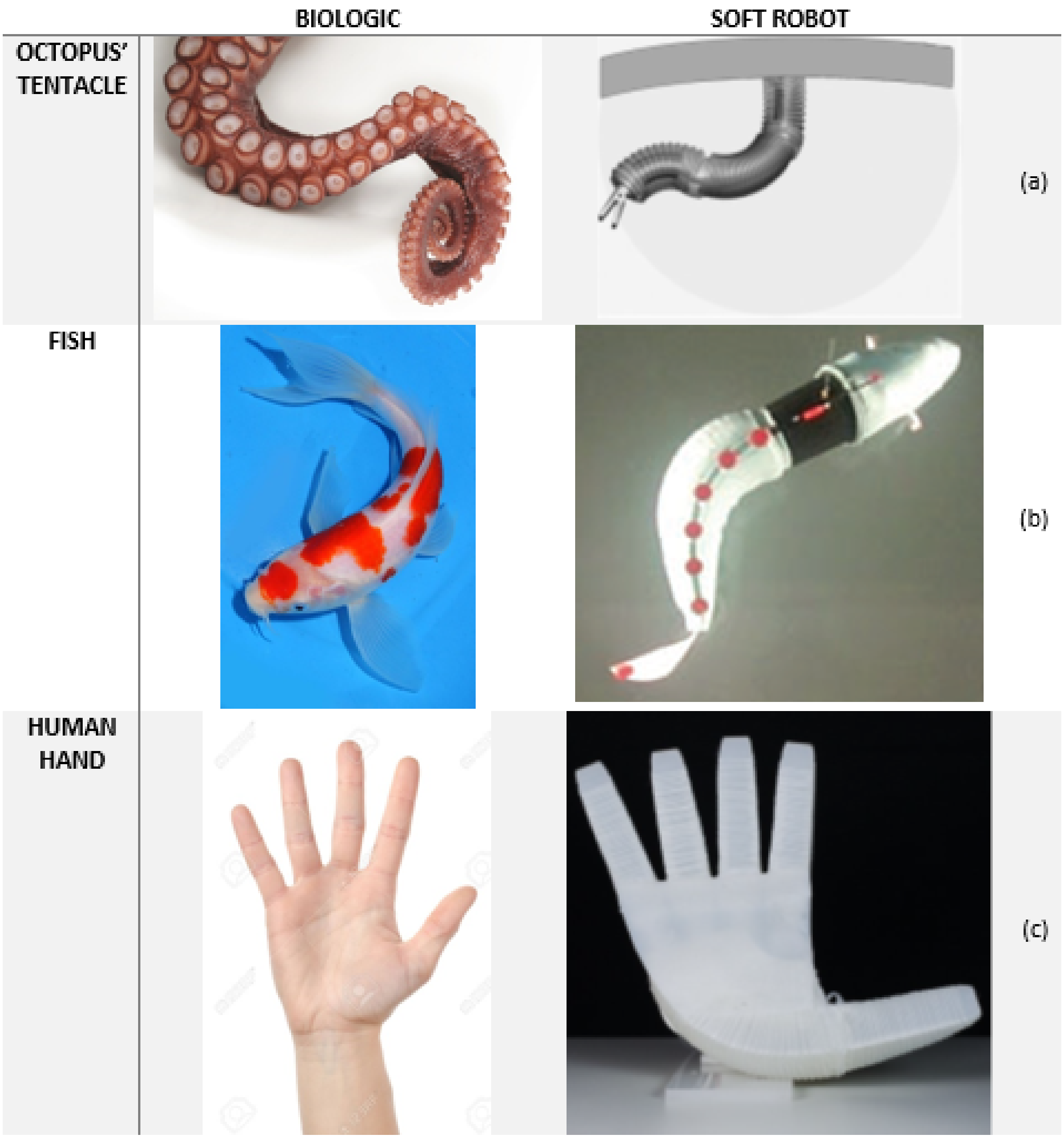
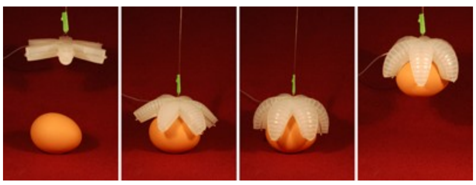



**Table 1.1:** Table that shows similiraties between a biologic organ and a soft robot: (a) Soft robot that resembles an octopus' tentacle used by Cianchetti et al. [14] (b) Soft robot that resembles a fish used by Marchese et al. [15] (c) Soft robot that resembles the human hand used by Deimal et al. [16]

The softness on the robotics is also needed for the implementation of embodied technologies, such as embodied intelligence, which gives a stronger role to the physical body and the interactions with the environment [22], [23]. If the material properties are well exploited, a robust behaviour, fast and efficient movements of a robot are achievable. The fact that the skin of a soft robot is soft, deformable, and at the same time, robust and waterproof, is perfect for adaptation, manipulation and grasping. In figure 1.2 we can see some soft robots that have the previous stated characteristics.


**(a)**

**(b)**



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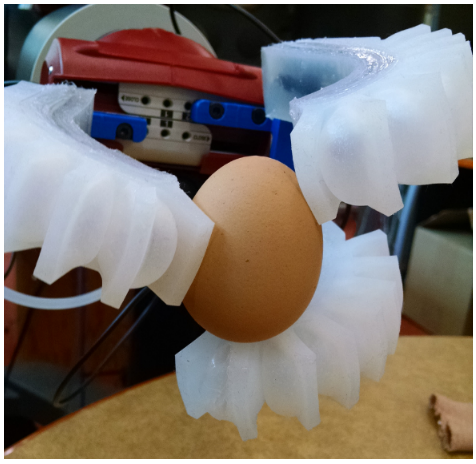


**(d)**

**Figure 1.2:** Examples of soft grippers: (a)Versaball made by Empire Robotics based on the jamming of granular material [6]. (b) Soft Robot made by SoftRobotInc. (c) Ilievski et al. [7]. (d)Homberg et al. [8].

## 1.1 Motivation and Goals

Most of the grippers used in the industrial market are rigid, expensive and have difficulties operating in food processing environments because of the different weight, size and shape of the products that are being handled, for example, tomatoes and carrots. In addition, soft fruits such as the berry familly should be handled by care and without exerting excessive forces, which is difficult, if not impossible by the traditional rigid robotics hands.

A study made in United States of America says that fresh-cut fruits and vegetable market is one of the fastest growing segments in the category of industry. They estimated a twenty-seven billion dollars market, while the retail dollar and volume sales are increasing. For this segment it is expected a continued growth, since the need for convenience continues to be relevant to consumers. The Euromonitor International reports that fresh-cut produce offers healthier grab-and-go options for new consumption patterns. [24]

According to the American Farm Bureau Federation, the labour shortages in the U.S. industry will result in losses of up to nine billion dollars. These labour shortages are happening because of the anti-immigration measures; this is a problem for the U.S.A. because the majority of the workers of the agriculture industry are undocumented. [25]

*"65% of distribution center labour is focused on pick and place"* [26] and since the pick and place market in fruits and vegetables industry is growing so much, all these factors motivated the start of this thesis to create a low cost, soft and under-actuated gripper that can grasp different objects with different shapes and textures.

The gripper fingers are the most important component. They have to be able to adapt to different forms and weights. The human finger is one of the best examples of a tool to pick, grab and grip objects and that's the main reason that motivated the creation of a finger based on the human biology.

The main goal of this work is to create an optimal soft finger, inspired on the human finger, with continuous skin, and by using three of these fingers on an under-actuated gripper, use it as a pick and place robot, which is able to grasp soft objects such as fruits without breaking them. The main contributions of this dissertation can be stated as:

- Design and implementation of a soft finger that requires small forces to bend thus making the overall gripper light-weight
- A bio-inspired approach for implementation of a continious soft skin that can adapt well with various geometries without exerting excessive normal force and breaking them
- Design and implementation of an adaptive grasping mechanism that can adapt to various objects with only a single actuator

## 1.2 Thesis Overview

This thesis is divided into six chapters. In the first chapter is presented an introduction about the theme of this thesis, also the motivation and the goals.

The second chapter is about the state of the art, which is divided into four subchapters. One gives an overview about industrial grasping mechanisms, soft hands and grasping mechanisms for agriculture. The second subchapter is about the subject of 3D printing, 3D printers, printing material and their differences. The third subchapter is about the human finger and how it is structured. On the last, it is presented what is the hydrogel and the one used on this project.

The third chapter explains the soft fingers used on this project, their design, how and why they are made the way they are, also some failures that happened along the project.

The fourth chapter is about the under-actuated gripper, its design and measures, explanation of every piece, the multiple iterations that were made along the process.

The fifth chapter shows the results. It's divided in two subchapters, one is for the fingers flexions forces and comparisons, and also for the fingers weight over the time and their waterproof feature. The other subchapter is about the grasping action, forms and weights of objects it can grasp.

The sixth and final chapter concludes this dissertation and discusses the future work that can be made.

# Chapter 2

# State of the Art and Materials

In this chapter is presented the state of the art about the human finger, hydrogel, 3D printing and some robotic technology important to this project. The basic theoretical concepts are explained and some of the most relevant examples for this project are mentioned. Namely this chapter will give an overview in:

- Soft and adaptive robotic grasping mechanisms.
- 3D printing, 3D printers, printing material and their differences.
- Human finger and its structure.
- Hydrogels.

## 2.1 Soft and Adaptive Robotic Grasping Mechanisms

### 2.1.1 Soft and Adaptive Robotic Hands

A review of research about robotic grasping was made by Boubekri et. Al. [27], where they claim that in order to develop a versatile robotic hand, the inclusion of tactile sensing, sensor fusion technologies and the development of methodologies using incomplete or imprecise information about the objects to grasp are necessary. Researchers have been developing grippers in a way to be adaptable to different type of objects, shapes and textures.

This subchapter is about some soft and adaptive robotic hands that in a certain way were important for this thesis, both the fingers fabrication and the pulling mechanisms. Being them:

- Universal soft pneumatic robotic gripper
- The SDM Hand
- PISA/IIT SoftHand
- ISR-SoftHand
- UC Soft Hand

#### 2.1.1.1 Universal soft pneumatic robotic gripper

A soft pneumatic robotic gripper with variable effective length, made of soft materials, was developed by Hao et. Al. [19]. It has four fingers and their length can be modified. The gripper is controlled by pneumatically actuation, the fingers are inflated to close and deflated to open.

The fingers are made of silicone rubber, fixed on a support and linked to an air tube used to inflate and deflate, as shown in Figure 2.1.

Hao et. Al. propose a novel approach for gripping objects, to open the gripper claw, the fingers are deflated to curl outwards, then, when inflated with compressed air, they curl inwards in order to gripp the objects. To regulate the fingers length, an inelastic nylon tendon is used to regulate the finger area of inflation and deflation, as shown in Figure 2.2.

Their results demonstrate that this gripper is able to grip a wide range of different objects. Although it has a maximum pull-force of 13.5 N, it can grip objects larger then itself, with a maximum of 160 mm of size range, also objects like a plastic bag filled with liquid and a compact disk which are difficult to manipulate with other universal grippers.

Gripping tests made with different finger length, from 30 mm to 100 mm, showed that each object with different size prefered a selective effective finger length.

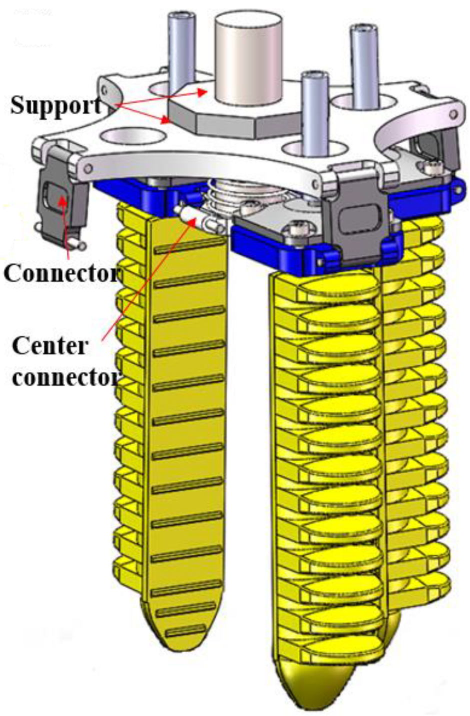



**Figure 2.1:** Design of the 3D structure of the soft robotic gripper made by Hao et. Al.

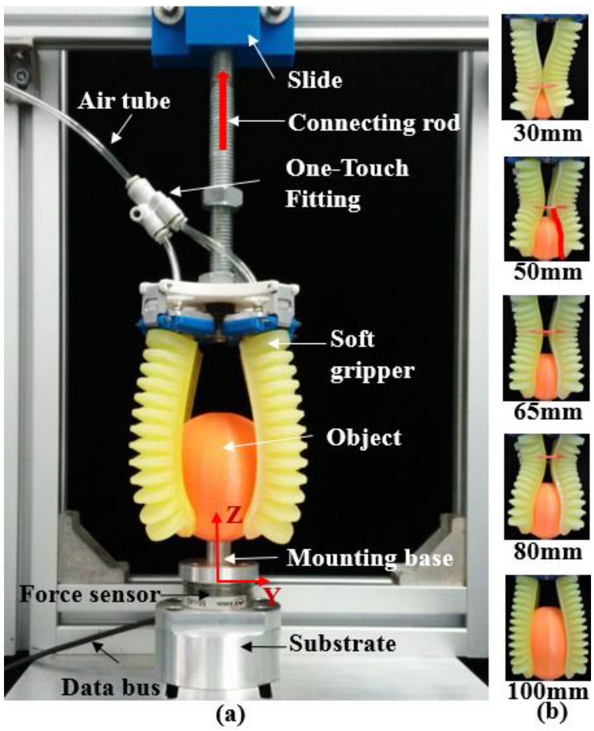



**Figure 2.2:** Apparatus for measuring force of the soft gripper under different effective lengths made by Hao et. Al.. (a) Schematic illustration of the force measurement platform. (b) Images of the soft robotic gripper under five selected effective finger lengths while gripping, regulated with an inelastic nylon tendon.

#### 2.1.1.2 The SDM Hand

Dollar et. Al. [28] developed a soft hand with a good level of robustness, adaptability and other performance properties. Has a simple design with four fingers and requires only one actuator to perform the grasps, as shown in Figure 2.3. The fingers and the base of this hand were fabricated using polymer-based Shape Deposition Manufactoring (SDM). [29]

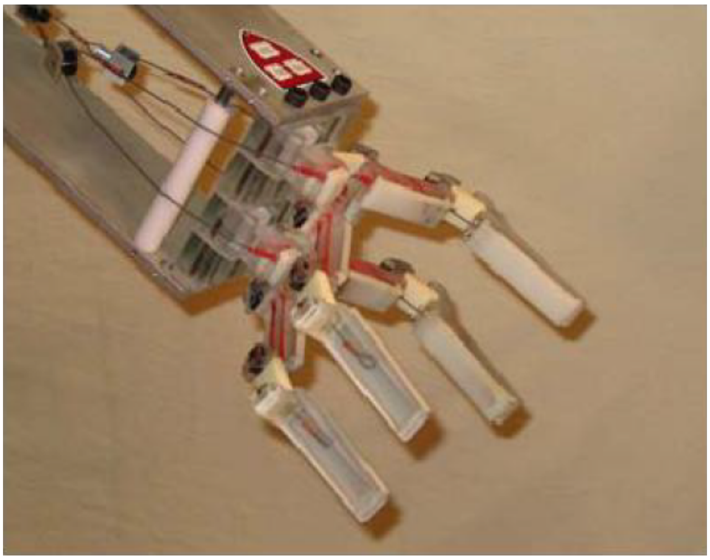


**Figure 2.3:** SDM hand

SDM is a solid freeform fabrication (SFF) process, which systematically combines material deposition with material removal processes. It is a layering process where prototypes are relatively identical with the final product.

To increase the grasp stability, there is a soft finger pad in the concave side of each link to maximize friction and contact area. The links are connected via elastomer joint flexures. The joints are made of polyurethane which have a viscoelastic behaviour, important to reduce severity of joints oscillations. In Figure 2.4 we have a better perspective and details of the SDM finger. This hand has an approximately weight of 200g, not including the actuator and the base. The two links between each finger are 70mm long, and the hand have a total aperture of 113mm.

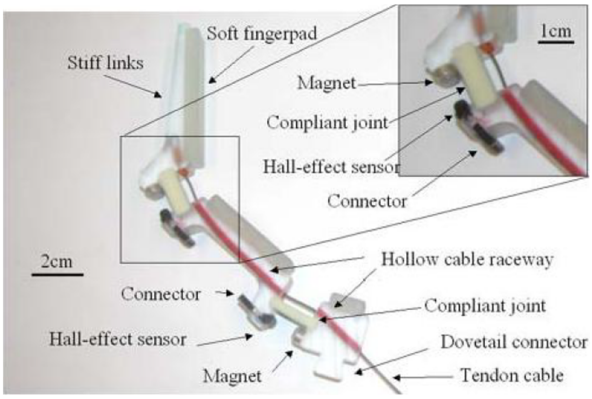



**Figure 2.4:** Details of the finger parts of the SDM Hand

This hand only uses one actuator to pull the four fingers, which makes the gripper simpler and lighter. Using the design shown in the Figure 2.5, even if the inner link has contact with an object, the outer link will continue the grasp and will adapt to the shape of the object. If one or more fingers are immobilized by contact, the remaining fingers continue to grasps the object, this happens thanks to the pulley transmission because an equal amount of tension is given to all four fingers. The four fingers are positioned on the palm of the hand in a way that when they close, they don't touch each other.

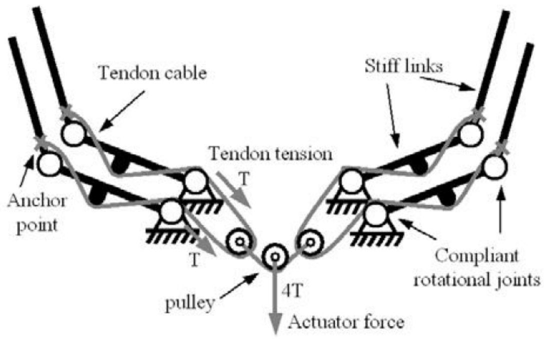



**Figure 2.5:** Schematic of the SDM Hand

Although this hand is robust, light weighted, adaptable, reliable and easy to use, it has a downside. It can't do precision grasps without manually positioning the fingers. To solve this, a thumb digit could be added or an additional degree of actuation implemented.

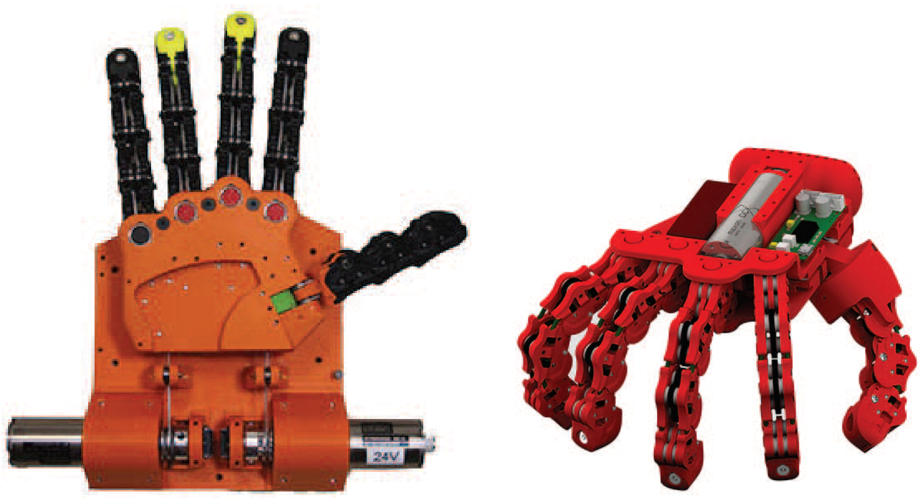
#### 2.1.1.3 PISA/IIT SoftHand+

Della Santina et. Al. [30] analysed and presented the PISA/IIT SoftHand+, shown in Figure 2.6a. Which is an under actuated softhand with five fingers and just 2 degrees of actuation (DOA). Is important for a robotic hand to be under actuated because this way the number of degrees of actuation is reduced and thus their design is simplified.

This soft hand is an upgrade of the original Pisa/IIT SoftHand [31], which has one soft synergy, actuated by a system that only uses one tendon, pulley and one motor, as shown in Figure 2.6b. This hand has very good grasping skills for different tasks, has a good robustness and it is easy to control.

Della Santina et. Al. upgraded this soft hand with the goal to add dexterity without increasing complexity by using two smaller motors instead of one. With this change, the hand has the one additional DOA and thanks to this, it has a better performance regarding the grasping and the manipulation.

Overall, this under-actuated soft hand is excellent in grasping and manipulating, exploits the friction component, but has the downside of the high price of the components like the motors.



**(a)** **(b)**

**Figure 2.6:** (a) PISA/IIT SoftHand+; (b) PISA/IIT SoftHand

#### 2.1.1.4 ISR-SoftHand

Tavakoli et. Al. created an adaptive under-actuated anthropomorphic robotic hand with elastics joints and soft pads called the ISR-SoftHand [32]. By using only three actuators, it can perform the top ten grasps used by humans. An anthropomorphic hand is a hand that can be integrated in a robotic arm or can be implemented as a prosthesis.

This hand has 5 fingers, being one the thumb digit. Each one have two elastic joints for finger flexion, with the exception of the thumb, which just have one elastic joint and a abduction-adduction joint that has to be rotated manually, has shown in Figure 2.7.

The finger joints are made of an elastic resin wih good physical properties and the finger pads are made of a high friction polymer, specifically, the Vytaflex.

The ISR-SoftHand is driven by three actuators, one for the thumb digit, one for the index finger and the last one for the resting three fingers, as shown in Figure 2.8.

Some disadvantages of this hand are the motors, which are over-sized for just one finger and under-sized for simultaneosly driving three fingers. This hand could do the top ten grasps used by humans, although in some cases the exact pose of the human hand could not be imitated. One reason for this is the fact that the abduction adduction movement of the thumb is not actuated. The total cost of this hand is between 400 and 800 Euros, depending on the actuation system.

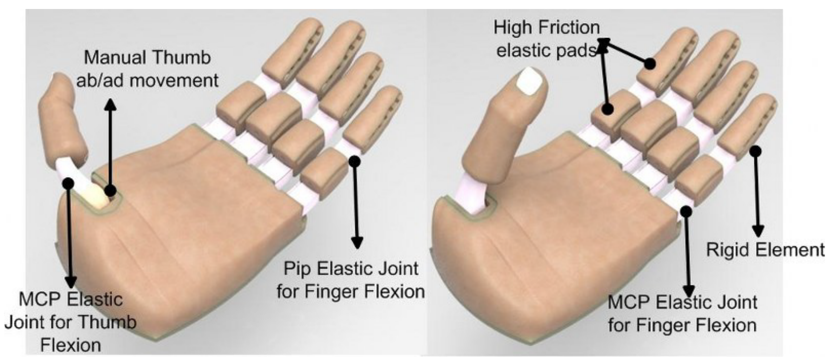



**Figure 2.7:** Conceptual design of the ISR-Softhand

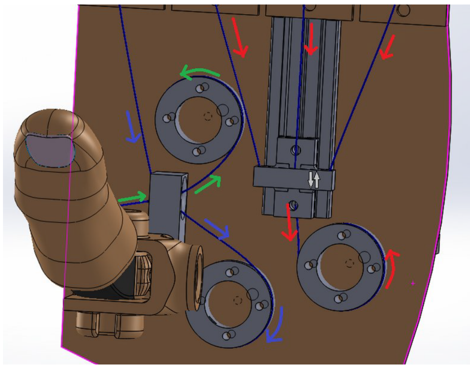


**Figure 2.8:** Schematic of how the actuators work in ISR-SoftHand

#### 2.1.1.5 UC Soft Hand

Tavakoli et. Al. designed and developed a low cost, bionic and adaptive hand called the UC Soft Hand [33], as shown in Figure 2.9. This hand is similar to the ISR-SoftHand, but has a compact twisted string actuation mechanism which allows a considerable weight and cost reduction.

The fingers integrated on this hand were made of a 3D printed endoskeleton, then filled with a low stifness material such as sponge and then it's placed inside a mold, to cure it with resin. The fingers have the measures of an adult human finger and the surface has a texture similar to the human skin. This procedure can be seen in Figure 2.10.

This hand has a two-phase twisted string system to pull the strings in order to bend the fingers, as shown in Figure 2.11. The first phase is where the strings twist around each other, the second phase is the overtwist, where the strings form a bundle and twist together. After ten twists of the strings, the overtwisting starts, and after fifty the system starts to have unwinding problems.

The weight of this hand is 280 grams, which make it one of the lightest actuated hands developed so far. Has a low cost of almost 280 Euros, which is very good for an under-actuated soft hand. It can also perform several precision and power grasps.

Still, have the disadvantage of the abduction adduction movement of the thumb being manual, and although the twisting system is a good idea, the overtwist brings many problems for the hand performance.

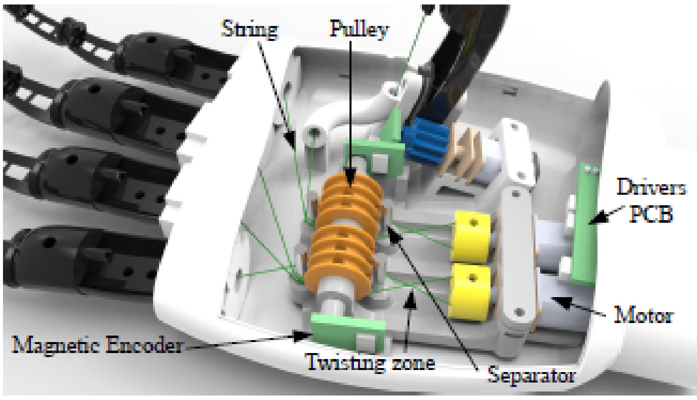



**Figure 2.9:** 3D model of the UC-softhand

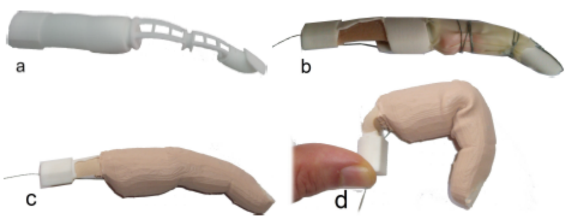



**Figure 2.10:** Fabrication process of the soft finger of the UC Soft Hand. (a) 3D printed endoskeleton; (b) Joints filled with sponge and covered by a sealing sleeve; (c) Soft finger after the curing of the resin; (d) The soft finger bending.

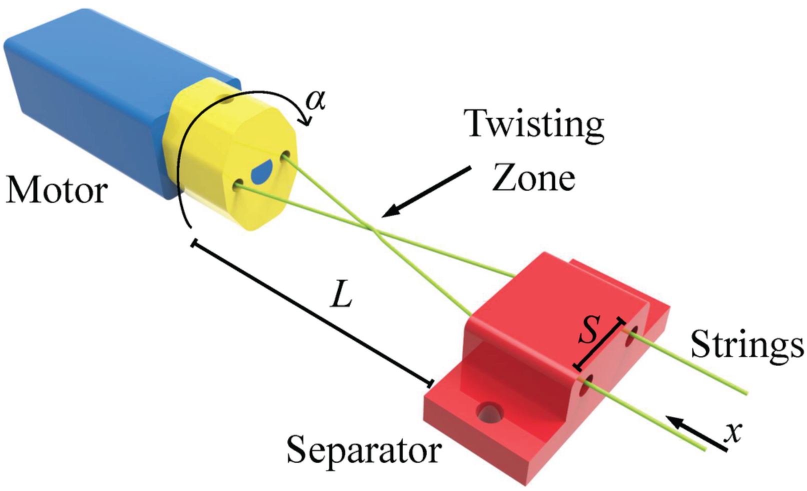



**Figure 2.11:** Twisted string system. With an electric motor (blue), strings (green), connection between motor shaft and strings (yellow) and separator (red). Where L is twisting zone length, a is the rotational angle of the motor shaft, x is the linear displacement of the strings and S is the distance between the holes of the separator.

### 2.1.2 Grasping Mechanisms for Agriculture

A lot of research is being developed in the agriculture area, especially in order to improve fruit harvesting, both to detect and to pick.

Blanes et. Al. made a detailed research about the technologies for pick and place robotics of fruits and vegetables [34]. The pick and place actions must be quick and short, without damaging the products, the grippers must adapt, have a good adherence without pressuring too much the product, be lightweight and easy to do their maintenance. Figure 2.12 shows a flow chart of the pick and place process.

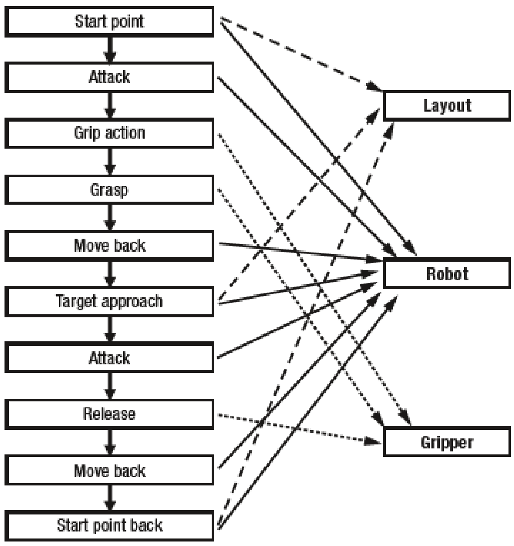



**Figure 2.12:** Flow chart process of a pick and place operation made by Blanes et. Al.

The most common type of grippers in agriculture robotics are the contact grippers and the ones based on suction cups. A table for each was made with their advantages and drawbacks, shown in Table 2.1 and Table 2.2.

Using pneumatic air for grasping in agricultural robots may not be optimal since additional equipment is necessary for providing high pressure air, and an electric motor is preffered. While most of the soft grasping mechanisms use pressure air for operation, one of the objectives of this thesis is to have the same functionality, but with an electric actuator.

| Advantages | Drawbacks |
|---|---|
| • Widespread standardization with materials approved for contact with foodstuffs.<br>• Good resistance to different temperatures.<br>• Increasing the number of lips improves:<br>– Vertical dimensional tolerance.<br>– Performance with dynamic forces.<br>– Adaptation to different shapes.<br>• Reducing the number of lips improves:<br>– Positioning.<br>– Load capacity.<br>• It is possible to manipulate several products at the same time. | • Works poorly on irregular, rough surfaces, dirty products.<br>• Surface can be damaged and must have little or no porosity.<br>• Handling times are higher when vacuum volume to be created increases.<br>• Uncertain final position grows by increasing the number of lips.<br>• Poor performance:<br>– In dirty environments.<br>– Under shear stress.<br>– On irregular, rough and dirty products.<br>• High energy consumption when the vacuum system is working continuously.<br>• The fruit or vegetable may possibly get marked. |

**Table 2.1:** Advantages and drawbacks of using air in a gripper for a Pick and Place process in fruit and vegetables made by Blanes et. Al.

| Advantages | Drawbacks |
|---|---|
| • Gripper can adapt to the shape of the product and to the range of all available products.<br>• Adaptation to the range of all available products.<br>• High repeatability.<br>• Can achieve required end precision.<br>• Possibility of varying the forces according to the mass, shape, and surface of product.<br>• Simple models have easy maintenance and control, high reliability and low cycle times.<br>• Opportunity to get information about fruit ripeness during gripping process. | • High speed grasp contact can damage sensitive fruit and vegetables.<br>• Gripper complexity increases in the same way as complex shapes.<br>• Complex grippers are less robust, heavy and bigger.<br>• Gripper components should be approved for food contact and have good fatigue resistance.<br>• Design should be easy to clean, without hollows and cavities, with good ingress protection.<br>• Picking products very close to other products is difficult.<br>• Avoidance of hollows and cavities or hidden areas where leftovers can accumulate in order to make the gripper cleaning easier. |

**Table 2.2:** Advantages and drawbacks of using contact in a gripper for a Pick and Place process in fruit and vegetables made by Blanes et. Al.

An example of a contact gripper was developed by Song et. Al. for fruit picking [35]. It's an underactuated gripper with tendon-driving, low cost, has a simple structure, is easy to operate and to do maintenance, an image of this gripper can be seen in Figure 2.13.

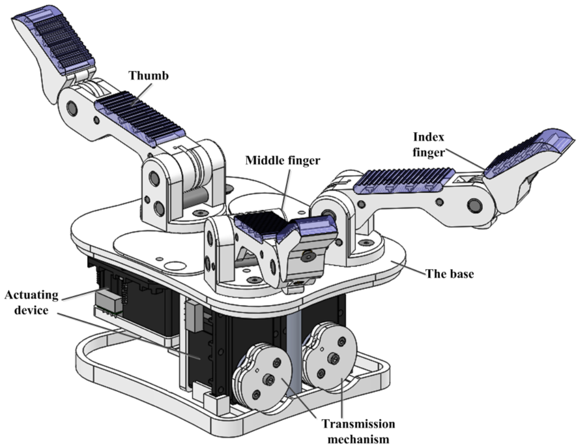



**Figure 2.13:** Design of the gripper made by Song et. Al.

It has a base, a actuating system, a transmission mechanism and three fingers: thumb, index and middle digits. Each of the three fingers have two joints, proximal and distal joint. The thumb digit is fixed but the index and middle digit can be changed regarding the angle they make with each other. Each finger is bended by pulling a tendon with a pulley system, as shown in Figure 2.14. The fact that these fingers have an elastic underactuated mechanism driven by tendons is what makes it safe to handle fruits without damaging them. One particular problem of this hand, which will be address in this dissertation, is that the soft skin is not continuous. Instead it is composed of islands of the finger. In this way,this hand looses the possibility of grasping objects in the entire surface of the finger.

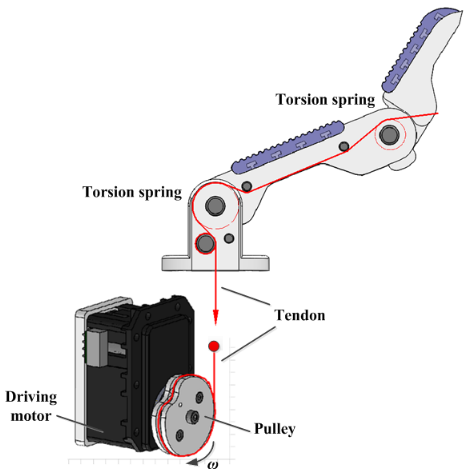



**Figure 2.14:** Design of the finger and its pulley mechanism made by Song et. Al.

An example of a gripper based on air is the one that jam granular material [6]. This gripper can be made of different ways, the universal way is by filling an elastic bag with granular material, like coffee beans, and by evacuating the air inside it with a vacuum pump, the granular material jam and the gripper becomes rigid. A schematic ilustration of how this gripper works can be seen in Figure 2.15. Through the combination of friction, suction and geometrical interlocking mechanisms, this gripper can graps different type and shape of objects. Because this gripper adapt and conform autonomously to the surfaces of the objects, it doesn't need a previous initial information of the objects.

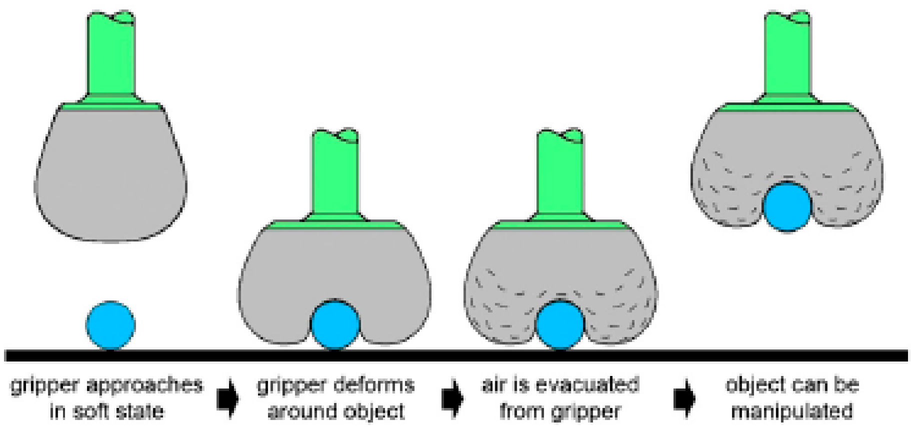



**Figure 2.15:** Schematic of operation of an universal gripper based on air

An important feature for fruit harvesting is the ability for the robot to detect the fruits. Varied reasearches in this branch are being performed, by creating a system to detect the fruits by their colours and shapes [36], [37], [38], [39], [40], [41]. The common objectives on these reasearches are how fast can the software detect the fruits and the percentage of how many of them, because some are hidden between leaves, or in shadows and is hard for the algorithms to detect them.

## 2.2 3D printing

3D printing is a technology that's having a huge growth in the last years. Basically it is a prototyping process, where, from a 3D design of an object, we can make it physically real. The 3D design is saved in stereolithographic format (STL format) on which the printer can read, and then, the object is printed layer by layer. The most used software to create parts for printing is SolidWorks, but the one used for this project was Autodesk Fusion 360.

3D printing is helping a lot the medical field or industry, like in hand rehabilitation [42], in vitro biomedical research [43], or oral health [44]. The doctors can print the patients' organs or body parts, and even use these models for transplants, practice and/or study for surgeries [45]. 3D printing is also used a lot in aerospace, architecture, fashion, art, interior design and industry. This technology allows a designer, developer and/or a scientist to go from a digital design sketched from scratch to a real and physical object/part.

A 3D printer prints in three dimensions. Most of them print layer by layer, each one is printed directly on top of the previous one [46]. Some call this process as rapid prototyping. Some disadvantages are the fact the professional 3D software and model design are in a high cost range, the same happens with a good 3D printer, also, some complex objects take a lot of time to print. In other hand, there are some low cost printers that use less expensive materials, but they are not as accurate as the professional ones, because the printed objects/parts come with some flaws in measures and material, and need some "hand refining".

Usually, 3D printers are compact and small, ideal to use in office, also they are relatively easy to handle and cheap to do their maintenance. Anyone can buy one printer kit and build it up alone, for example, the one used in this project just costed around five hundred euros plus the time to build it.

About the 3D printing technologies, the main difference between each type of printer is how layers are built to create the objects. The most used technologies are Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM) and Stereolithography (SLA). To produce layers, SLS and FDM technologies use melted or softened materials. On table 2.3 we can see some similarities and differences between these printing methods.

| | **SLS** | **FDM** | **SLA** |
|---|---|---|---|
| **Description** | Laser Sintered Powder | Plastic Filaments | Laser Cured Photopolymer |
| **Example of used materials** | Nylon, Metals | ABS, PLA | Resins, Photopolymers |
| **Complexity of printed objects** | Good | Good | Good |
| **Surface Finish** | Medium | Poor | Excellent |
| **Price** | Medium | Good | Expensive |

**Table 2.3:** Overview of different 3D Printing Methods

### 2.2.1 3D Printers

#### 2.2.1.1 SLA

SLA is an additive manufacturing process that creates models, prototypes and patterns with photopolymerization, a example of one SLA printer can be seen in Figure 2.16. Based on a design of an object, an UV (ultraviolet) laser solidifies, layer by layer, the photopolymer resins. The resin cures when exposed to the UV laser light and the patterns solidifies. The resins that remains as excess, is removed by heating in an UV oven.

Compared to other printing processes, SLA can produce excellent parts with perfect surface finishes and complex geometries. [47]

In medical field, SLA has been used to print molds, so the doctors can prepare for implants in cranial surgery and to develop implantable devices.

Some disadvantages are the price of a SLA printer, also the durability and strength of the printed parts are not that good.


**Figure 2.16:** Example of a SLA Printer

#### 2.2.1.2 SLS

SLS is an additive manufacturing process which uses a laser to create objects/parts by fusing small particles of plastic, metal, ceramic or glass, layer by layer, starting on bottom untill the top of the designed object. With this process, durable and accurate parts can be created, but the finish will be not good. The process begins by depositing a thin powder layer in a cylinder, which gives the form to the desirable object. After the object is complete, the powder that isn't laser sintered, is extracted. In Figure 2.17 we can see a schematic of how it works. With this process, complex geometries can be achieved, but because there is low strength between the fused particles, the objects tend to be weak. [48]

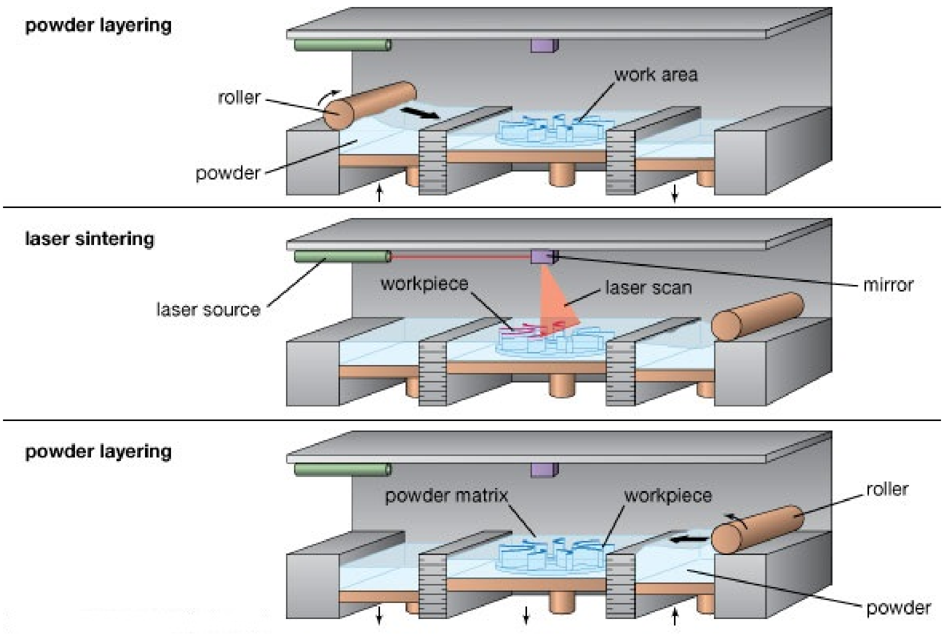



**Figure 2.17:** Schematic of how SLS printer works [9]

#### 2.2.1.3 FDM

FDM is an additive manufacturing process that melts plastics through an extruder, and then the material cools and form an intended object, layer by layer, from bottom until top, based on its design. A FDM printer is affordable by almost everyone and the materials used for this process are also cheap. An exemple of one FDM printer can be seen in Figure 2.18. Objects printed with this process are usually stronger and/or flexible. In other hand, they can't be very complex and many problems are obtained in this process, like warping, missing layers, under-extrusion, over extrusion, gaps and others [49]. These problems depend a lot from the object design, printer and printing settings, they can be allways be avoided or solved but sometimes it is hard to do so. [48]

**Figure 2.18:** Example of a FDM Printer [10]

The FDM printer was the chosen one for this project because it's accessible and has a low cost both in the materials and also in the printer itself. It's important to note that one of the primary goal of this project is the low cost strand. Although, the printed parts with this method don't have a perfect finish, that doesn't affect much this project because the printed parts are designed around that and don't have a complex design.

### 2.2.2 Printing Material

There are a lots of materials for 3D printing, but the most used are the Acrylonitrile Butadiene Styrene (ABS) and Poly Lactic Acid (PLA), at least for plastic printing. Both are mouldable and soft when heated and return to a solid state when cooled; in a word, they are thermoplastics. They have the ability to melt and be processed again, and this is why they are the most materials used.

There are many thermoplastics, but only some of them are used in 3D Printing. The materials have to pass three different tests, so they can be used for 3D Printing: [50]

- Initial extrusion into Plastic Filament
- Second extrusion and trace-binding during 3D Printing process
- Appropriateness for the end use application as a 3D Printed part/object

ABS is a plastic based in oil. It's strong and sturdy, has a high melting point, but sometimes warps on the edges when cooled, that's why this material must be printed on a heated surface. Ventilation is required when printing because the fumes are unpleasant. [51]

PLA is made of organic material, like corn starch and sugarcane. This material is easier and safer to use, also gives a smooth and shiny appearance. PLA has a more pleasant smell, because it's mostly made of sugarcane, when heated gives a slightly sweet smell. This material is weaker but gives more printing detail and has less errors when printing. [52]

These materials absorb moisture from the air, so it's best if they are stored and sealed off from the atmosphere. Even if they are well stored in a dry place, it's recommended to use them sooner than later. When ABS has moisture, it tends to create bubbles and spurts at the printer nozzle during printing, this reduces the visual quality, accuracy and strength of the printed object/part. PLA creates the same bubbles and spurts and also loses some color in the process. [53]

The two materials are well capable of creating good accurate objects/parts, but both of them, sometimes have some problems. In the case of ABS, sometimes it curls upwards of the surface, and to avoid this, it needs a heating bed, smooth, flat and clean. Sometimes, some sharp corners are printed slightly round and because of that, the printing procedure needs to have a small active cooling around the nozzle with a fan, but if too much cooled, leads to cracks in the printed object/part. The PLA material has less warping, and that's why a heated table is not required for printing small parts with this material. It also suffers more when heated, it becomes more liquid and if it's actively cooled, much sharper details can be seen on the corners with no risk of cracks or warps, and if the flow is increased, it leads to a stronger binding between the layers, adding more strength to the piece.

In conclusion, ABS is more strong, flexible and has a higher temperature resistance but has a toxic smell and it requires a heated bed. PLA has a wider range of available colours, has a nice smell when printing, and if properly cooled, usually can be printed faster and with sharper corners. The fact that has low probabilities to warp, makes it a great and easy material to print.

## 2.3 Human Finger

Is important to talk about the human finger in this dissertation because the fingers that were created in this project are based on its structure.

The human fingers are a part of the human body, a manipulation organ that has bones, tendons, skin and nerves, but no muscles. They are a flexible, long and thin extension of the hand, usually called the digits. Although it's a flexible organ, there is a high concentration of receptors that make it an important sense organ.

### 2.3.1 Anatomy of the fingers

The human finger is composed by a bone structure with multiple joints that give it strength and flexibility. A finger(digit) has two surfaces, palmar surface, which is the continuation of the palms of the hand, and the dorsal surface, that contains the fingernails at the fingertips.

### 2.3.2 Finger Bones

Phalanges is how the finger bones are known. Each finger has three phalanges with the exception of the thumb that just has two, which can be seen in Figure 2.19. Each phalanx has a name according to its location:

- Proximal Phalanx (first finger bone next to the palm)
- Intermediate Phalanx (middle finger bone which thumb doesn't have)
- Distal Phalanx (last finger bone that is the furthest away from the hand)

The phalanx is composed by three parts: base, shaft and head. The base articulates with the head of the preceding phalanx, although the proximal one articulate with the head of the metacarpals (hand bones). The enlarged end of each phalanx is also known as the knuckle bone.

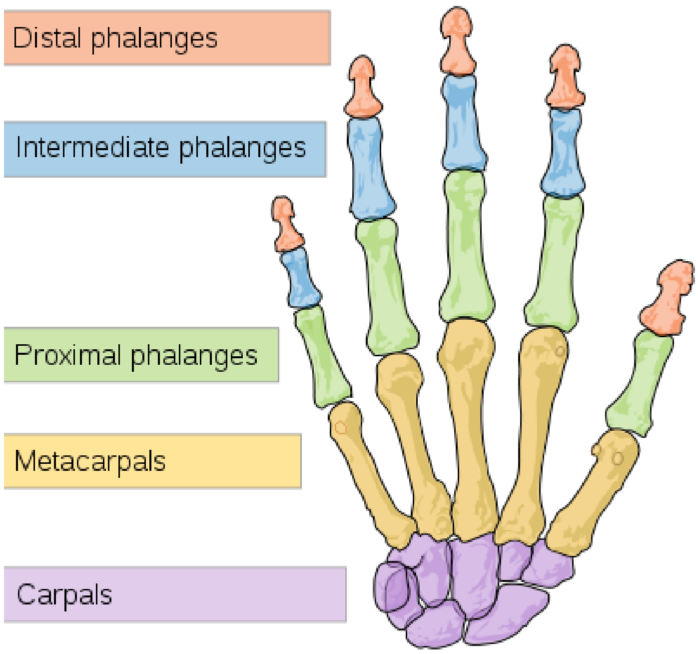



**Figure 2.19:** Bones of the human hand [11]

### 2.3.3 Finger Joints

The finger joints are known as knuckle joints and there are two types:

- Interphalangeal Joints (the ones between each finger joints)
- Metacarpophalangeal Joints (the ones between hand bones and the proximal phalanx)

Each finger has two interphalangeal joints, the tumb just has one. Proximal interphalangeal joint is the one between the proximal and the intermediate phalanx. Distal interphalangeal joint is between the intermediate and distal phalanx. [54]

### 2.3.4 Muscles and Movements

The movements of the fingers are controlled by the muscles that are in the hand and forearm. The tendons that come from these muscles are attached to various points on the finger bones. The tendon is pulled and the finger moves when there is a contraction on the muscle. The muscles controlling the fingers are classified in two ways. One by location and the other by movement. [54]

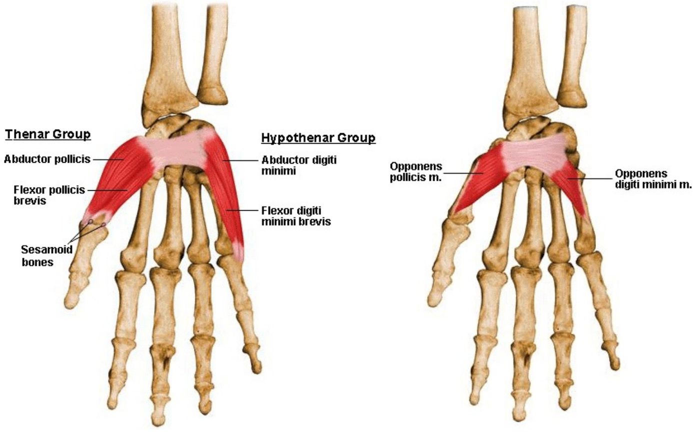
By location:

- Intrinsic Muscles (located in hand) as shown in Figure 2.20
  - Thenar and hypothenar muscles
  - Interossei and lumbrical muscles
- Extrinsic Muscles (located in forearm) as shown in Figure 2.21
  - Extensors muscles

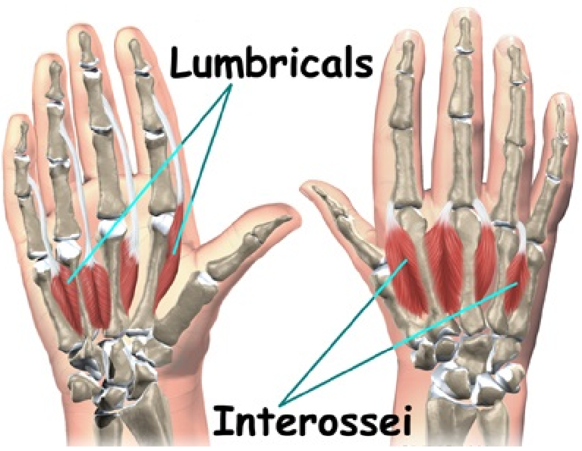
- Flexors muscles

By movement:

- Flexion (fingers moving towards the palm)
  - Thenar and hypothenar muscles
  - Flexors muscles
- Extension (fingers straighten out, moving away from the palm of the hand)
  - Interossei and lubrical muscles
  - Extensors muscles

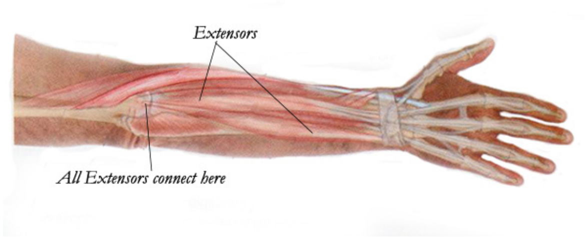



**(a)** Thenar and hypothenar muscles [55]

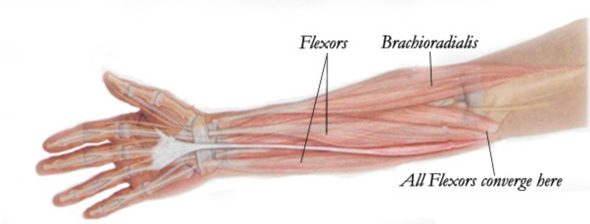



**(b)** Interossei and lumbrical muscles [56]

**Figure 2.20:** Hand Anatomy and Intrinsic Muscles that Actuate the Fingers




**(a)** Extensors muscles



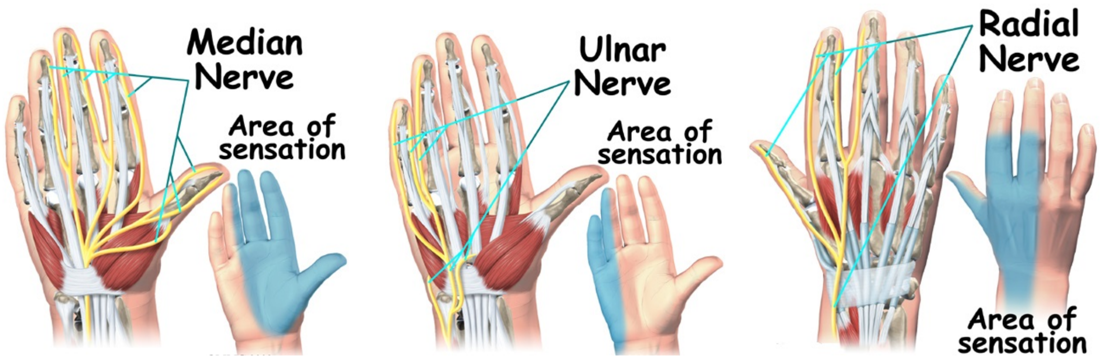

**(b)** Flexors muscles

**Figure 2.21:** Forearm Anatomy and Extrinsic Muscles that Actuate the Fingers

### 2.3.5 Nerves

The brain motor nerves send signals to the muscles causing them to move, or the fingers nerves, which are sensory nerves, sends signals to the brain with the information of the felt sensation. The nerves on the finger skin, shown in Figure 2.22, are:

- Median nerve (present in the palmar surface, tips and nail beds of the thumb, index, middle and half of the ring fingers)
- Ulnar nerve (present in the palmar and dorsal surface of the other half of the ring finger and little finger)
- Radial nerve (present in the dorsal surface, excluding the tips, of the thumb, index, middle and half of the ring fingers and web between thumb and index fingers)




**(a)** Median Nerve **(b)** Ulnar Nerve **(c)** Radial Nerve

**Figure 2.22:** Fingers' Nerves [12]

### 2.3.6 Skin

The skin is the most extensive organ system, it shields the human body from ultraviolet radiation, bacteria, toxins and temperature extremes. It has others functions like the production of vitamin D, sensory perception, immunologic surveillance, thermoregulation and control of insensible fluid loss.

The skin has two main layers, which are the epidermis (outer layer) and the dermis (inner layer), as shown in Figure 2.23.

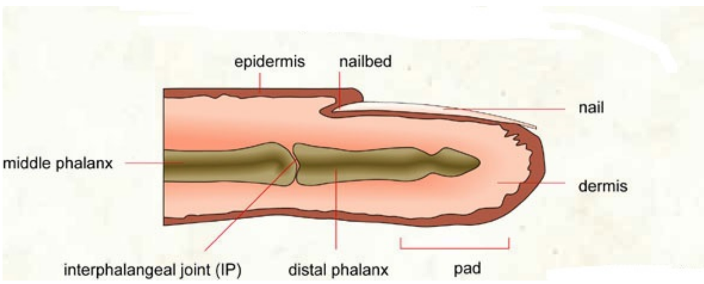



**Figure 2.23:** Longitudinal Schematic of the Human Finger [13]

#### 2.3.6.1 Epidermal Layer

The epidermal layer doesn't contain any blood vessels, is dependent on the underlying dermis for nutrient delivery and waste disposal, only the deepest cells of the epidermis get nourishment, the cells that are pushed away from this layer die. This layer is structured with other layers that have four cell types (Keratinocytes, Melanocytes, Merkels and Langerhans). The outer layer of the epidermal layer is thick with rows of dead cells keeping the skin elastic, malleable, resilient and having a waterproof behaviour. The epidermis also serves as a barrier to protect the body from UV lights, chemical compounds and microbial pathogens and even provides mechanical resistance. [57]

#### 2.3.6.2 Dermal Layer

The dermal layer is often called the “true skin” and it’s beneath the epidermis. It’s divided into two layers: superficial papillary dermis and deeper reticular dermis. Fibroblasts are the major cell type of the dermis, their job is to give strength, support and flexibility to the body [58]. It is softer than the epidermal layer and it’s mainly constituted of water. Helps in better local adaptation of the skin to objects in order to do efficient grasps.

## 2.4 Hydrogel

Hydrogel is a physical state of matter between solid and liquid, because, like solids, the hydrogel doesn’t flow and like the liquids, small molecules diffuse through it. Hydrogels are currently viewed as insoluble water, crosslinked, three-dimensional networks of polymer chains plus water that fills the voids between them. Hydrogel is mostly water, because the mass fraction of the polymer is much smaller regarding the water.

The hydrogels are divided into two types: physical and chemical linking. Physical hydrogels are sub categorised as strong and weak. Chemical hydrogels can be made by three processes: condensation, addition or cross-linking [59]. In Figure 2.24 we can see the different types and some examples.

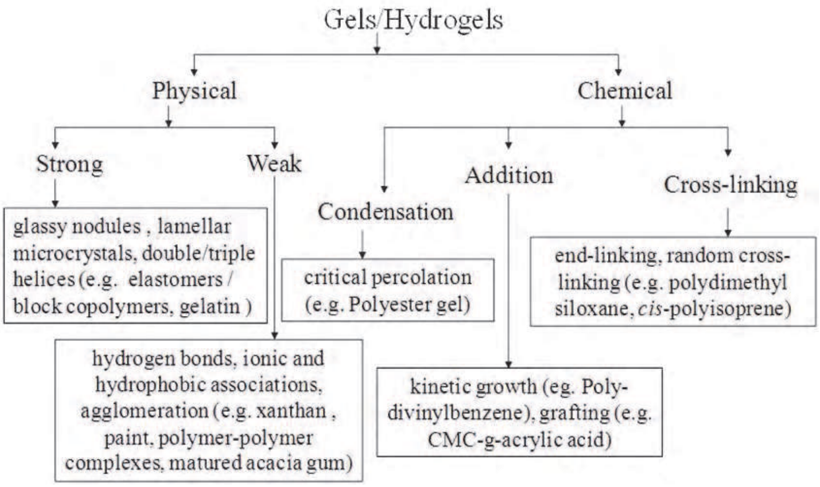



**Figure 2.24:** Hydrogel types and some examples

The hydrogels have a lot of applications in the biomedical field, the following are some examples:

- Soft contact lenses [60]
- Drug delivery [61]
- Scaffolds in tissure engineering [62]
- Disposable diapers
- Wound healing [63], [64]
- Glue

The ability to absorb large amounts of water makes the hydrogel useful for disposable diapers, because the hydrogel retains the liquids in, almost, a solid form.

### 2.4.1 Sodium Polyacrylate

Sodium polyacrylate is a sodium salt of polyacrylic acid, also known as waterlock, shown in Figure 2.25a. It can absorb up to 300 times its mass in water. It is used for hair styling gel, artificial snow, refreezable gel packs, lubricants, potting soil and disposable diapers.

When water is added to sodium polyacrylate, it swells, transforming it from a solid state to a hydrogel, shown in Figure 2.25b, by a purely physical reaction where there is no cross-link.

**(a)** **(b)**

**Figure 2.25:** (a) Sodium polyacryate in its pure state; (b) Hydrogel made by adding water to sodium polyacrylate.

# Chapter 3

# Soft Finger

One important factor on the quality of the human hand, is the skin, because it's compliant and provides excellent adaptability and contact properties. Human finger, as the most important part of the human hand, has always been a source of inspiration. A rigid skeleton, covered by a soft skin provides an excellent combination for grasping actions. The skin itself is composed of a softer, water containing dermal layer, protected by a more resilient epidermal layer, which protects the dermal layer against mechanical wear, and is also a barrier against loosing water.

Integration of compliance into robotic hands received an increasing attention due to their advantages in providing a better contact condition and a better adaptability to objects, resulting in overall better grasping performance and simplification of the hands as demonstrated in Pisa-IIT hand [30], ISR-Softhand [32], UC-Softhand [33] and SDM hand [28] for prosthetic applications or industrial grasping.

In both cases, the key component of all these hands is their finger design that integrates elastic elements directly into the skin and joints of the fingers. A particular problem in all the previous examples is that islands of soft materials are integrated into a rigid object in contrary to the continous and uniform soft skin, as it is the case in the human finger. In a previous research [65] it was designed and optimized a version of a soft finger composed of a 3D printed endoskeleton and a silicone skin which showed very promising for grasping applications, as shown in Figure 3.1. Nevertheless, the silicone skin around the endoskeleton, had to include a curved profile due to the buckling of the silicone skin. When the finger is bent, the upper half of the finger skin is stretched, but the lower half is under compression. While silicones have low Young Modulus when stretched, they are not compressible, resulting in buckling of the skin which leads to increasing the required tendon pulling force for flexion of the finger, and therefore larger actuators should be used.

To solve this problem, and inspired by the human finger, the new finger created for this thesis embeds a water containing hydrogel that can easily flow inside the more resilient silicone skin, thus providing an excellent analogy with the physiological architecture of the human finger, and also solves the problem of silicone buckling. In this way the exterior mould of the silicone skin can be formed at arbitrary shapes, making it possible to develop a more anthropomorphic geometry around the endoskeleton. Figure 3.2 shows the overall finger architecture. The 3D printed endoskeleton was also updated to make it possible to print with the more accessible FDM printers.

**Figure 3.1:** Previous version of a finger with a 3D printed endoskeleton and a soft skin.

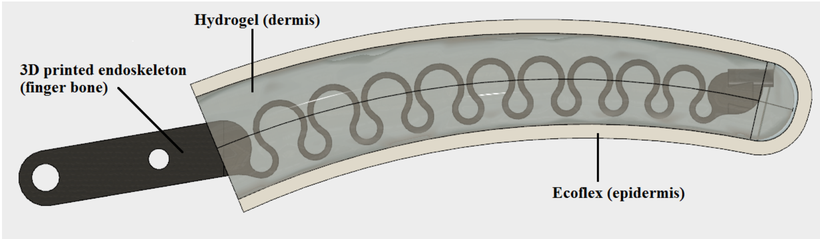



**Figure 3.2:** Longitudinal schematic image of the implemented prototype of the soft finger with a rigid 3D printed endoskeleton, a resilient silicone epidermal layer and a soft hydrogel middle dermal layer.

## 3.1 Finger Endoskeleton

Previous version of the endoskeleton [65] used a SLS printer with polyamide material which has excellent flexibility properties. Nevertheless, SLS is not yet as accessible as the FDM printers. Therefore, an updated version of endoskeleton was designed which has repetitive circular geometries all over the finger, in contrary to the previous version of the finger which has such structure only on the joint. This geometry then compensates the limited flexibility of the FDM process.

The finger endoskeleton weights in average 5.80 g, is made of acrylonitrile butadiene styrene (ABS) and can be seen in Figure 3.3.

**Figure 3.3:** 3D Design of finger endoskeleton

This was a great breakthrough because it was possible to create a good endoskeleton which can be printed in a FDM printer and when it was tested in the first prototype of the gripper, it grabbed some objects successfully.

Holes were opened from the fingernail to the base of the finger to put a string across them. The string is made of nylon, coiled in the fingernail, exits at the base and then it's coiled again in the gripper, explained in the next section, to work as a tendon to be pulled. After that, the finger was soaked in acetone in order to have a smooth surface finish, shown in Figure 3.4.

**Figure 3.4:** 3D printed endoskeleton embebed in acetone

The holes in the middle of the base are to help with the curing of the Ecoflex, it's explained better in the next subchapter. The two holes on the end of the base are to attach a shaft and to pin on the gripper.

The finger has 9 joints, decreasing their measure along the finger, and a fingertip.

The final version of the finger has the following measures:

- 80.5 mm from the fingertip to the last joint
- 0.4 mm of minimal distance between each joint
- 0.8 mm of thickness of the joints
- 16 mm of width on the base and 10 mm on the fingertip
- The outer circle of the first upper joint has 8 mm diameter and drops by 0.2 in 0.2 mm for the following joints.
- The outer circle of the first bottom joint has 5 mm diameter and drops by 0.1 in

0.1 mm for the following joints

- The joints make a curvature of a 130 mm radius circle, which change a bit after the acetone soak.

A experimental study was made to choose which thickness of the joints would work better, shown in table 3.1. The first fingers were printed with 1 mm of thickness, which was good but required too much force for the purpose of the gripper. Then, three fingers were printed, one with 0.9 *mm* and the others with 0.8 and 0.7 *mm* of thickness. Three different flexion pulls were tested with each one, using an electronic portable dynamometer:

- Full flexion, or 180° flexion, making the fingertip touch the base of the finger
- Half flexion, or 90° flexion, making the finger do a 90° angle with himself
- Lateral flexion, making the finger do a 45° lateral angle

| | 0.7 *mm* | 0.8 *mm* | 0.9 *mm* |
|---|---|---|---|
| Full Flexion | 8.5 +/- 0.4 | 8.0 +/- 0.4 | 15.7 +/- 0.8 |
| Half Flexion | 2.5 +/- 0.4 | 2.9 +/- 0.2 | 4.7 +/- 0.3 |
| Lateral Flexion | 0.7 +/- 0.1 | 1.0 +/- 0.3 | 3.0 +/- 0.4 |

**Table 3.1:** Finger endoskeleton flexion test in *Newton* with different thickness

Some difficulties happened when doing the lateral bending because really small forces were being dealt with. There's a big difference of bending forces between the finger with 0,9 *mm* of thickness and the other two because this one is printed with two perimeters of material, while the other two just have one. There aren't much differences between the fingers with 0,7 *mm* and 0,8 *mm* of thickness, but for some reason, probably because of some details in the printing process, the finger with 0,8 *mm* need less force to do the full flexion. For that reason, and also the fact that is thicker and stronger, it was the chosen one.

## 3.2 Development of the soft layers of the finger

In order to reach an optimal soft finger based on the human biological finger, different methods were used untill a functional one was obtained. The goal is for the finger to have an elastic and resilient epidermal layer, also a soft and adaptable dermal layer.

The chosen material for the epidermal layer was silicone, specifically the Ecoflex 00-30 from Smooth-on. The reason for this choice is because the silicone has the elastic and resilient behaviour needed for the soft finger, also has a waterproof feature which is really important for the hydrogel implementation.

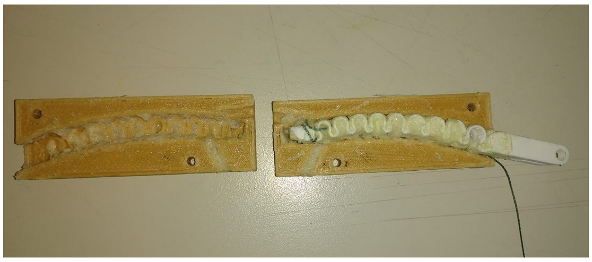
The first attempt to create the dermal layer was by using flexible polyurethane foam from Smooth-On, specifically FlexFoam-iT! III, and then curing Ecoflex around it. It was poured inside a 3D printed mold with an endoskeleton finger inside, after the curing, the result can be seen in Figure 3.5. To do a full flexion of the finger, it was necessary to withdraw the foam that was between the upper joints and to apply $21.57N$ of force, which is too much, regarding just the endoskeleton bending force. The foam is too much rigid for this application, thus this method is not acceptable.

The second attempt was by curing Ecoflex around the endoskeleton which was inside a latex finger, as shown in Figure 3.6. After the curing time, the mold was opened, and because of the latex and Ecoflex properties, the latest didn't cure around, making this a not viable method.

The third attempt was by using hydrogel to create the dermal layer, which has the soft and adaptable properties looked for and ended up to be the chosen material.

Since the chemical hydrogels are too complex to make and it wasn't a priority on this project, a simple physical hydrogel was made. The most easily acessible is the sodium polyacrylate which was extracted from baby diapers for this project.

**(a)**



**(b)**

**Figure 3.5:** First attempt to create the soft finger using flexible polyurethane foam: (a) Endoskeleton finger casted with foam; (b) Endoskeleton finger with foam inside the mold after the curing.

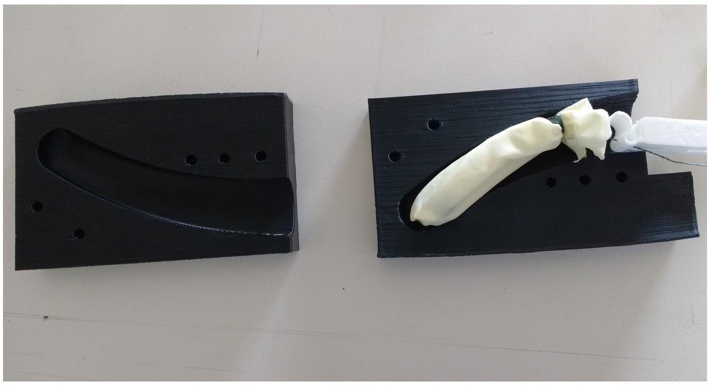
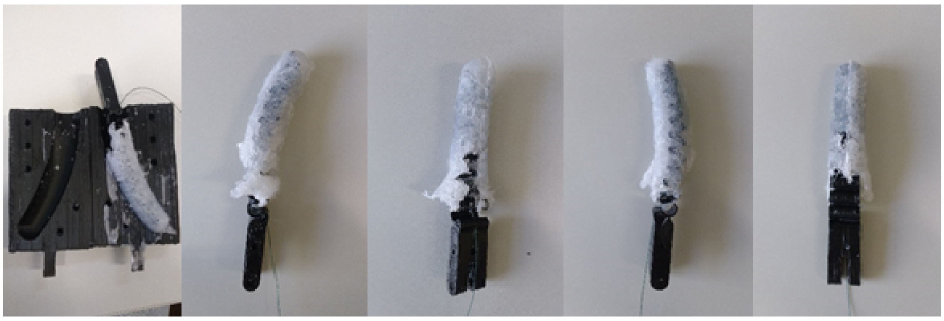


**Figure 3.6:** Second attempt to create the soft finger by using a latex finger.

The 3D printed mold mold used for curing Ecoflex and hydrogel or just Ecoflex is shown in Figure 3.8a. The hole inside it, has the length and curvy shape of the endoskeleton finger. Aluminium tape was required to put around the mold in order to the Ecoflex don't come out through the opening between the two mold faces, the molds have this opening because the printing in a FDM printer is not perfect.

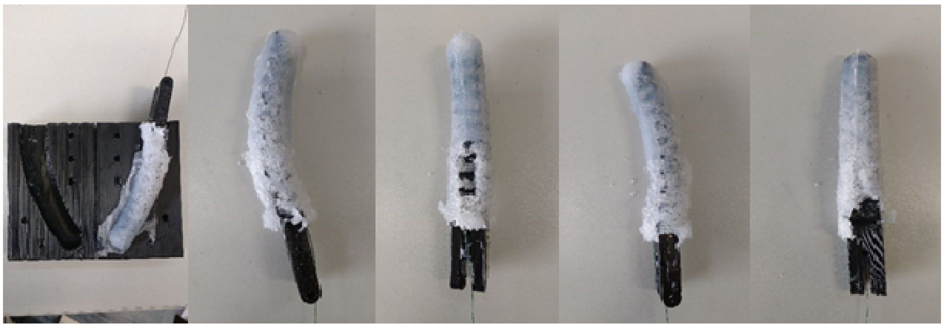
The firsts attempts to make the finger with Ecoflex and hydrogel were made by curing them together. It was hard to discover a good ratio of hydrogel and Ecoflex, which ended up to be three fifths of Ecoflex and two fifths of hydrogel. When it gotten a good ratio, the hydrogel and Ecoflex weren't well distributed after the cure. Two ways to cure were attempted, one by mixing them together before pouring in the mold and the other was by pouring one at a time in the mold. Either way, this method doesn't work because there are many holes in the finger resulting in a great loss of water over the time and, in some cases, the hydrogel and the Ecoflex are not well distributed across the finger. The resulting fingers are shown in Figure 3.7.

At this point, it was concluded that the Ecoflex and the hydrogel layers had to be made separately. To create the Ecoflex layer, a shaping mold was designed and printed, shown in Figure 3.8b. The main mold, shown in Figure 3.8a, and the shaping mold are designed in a way to have a 2mm space between them to thereby create an Ecoflex layer with 2mm of thickness. It was chosen 2mm of thickness for the silicone layer because 3mm was too thick, making harder to bend the finger, and 1mm was too thin creating a lot of holes and was ripped easily when stretched out, thus the 2mm is the best option. The Ecoflex 00-30 is poured inside the main mold and then the shaping mold is placed inside, as shown in Figure 3.9a, after the curing time, which is approximately four hours, the result is an epidermal layer of silicone shown in Figure 3.9b. On a side note, a lot of Ecoflex layers didn't cure the right way because it was hard to center properly the shaping mold inside the main mold, making the layer thicker on a side and thinner on the other.

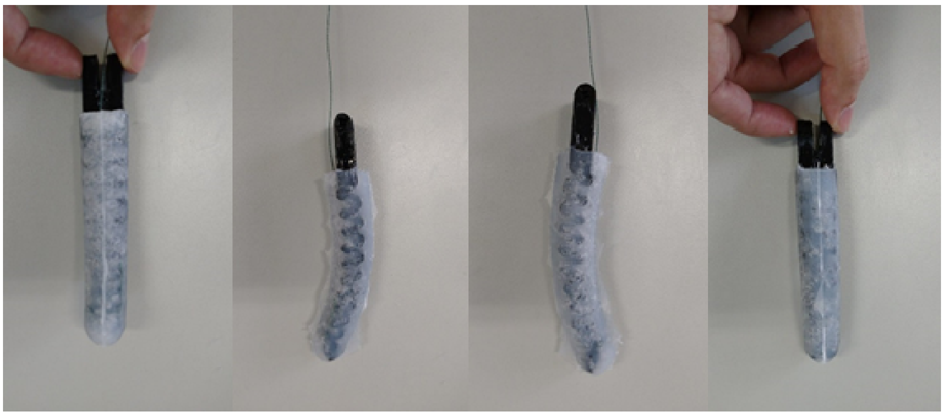


**(a)**

**(b)**

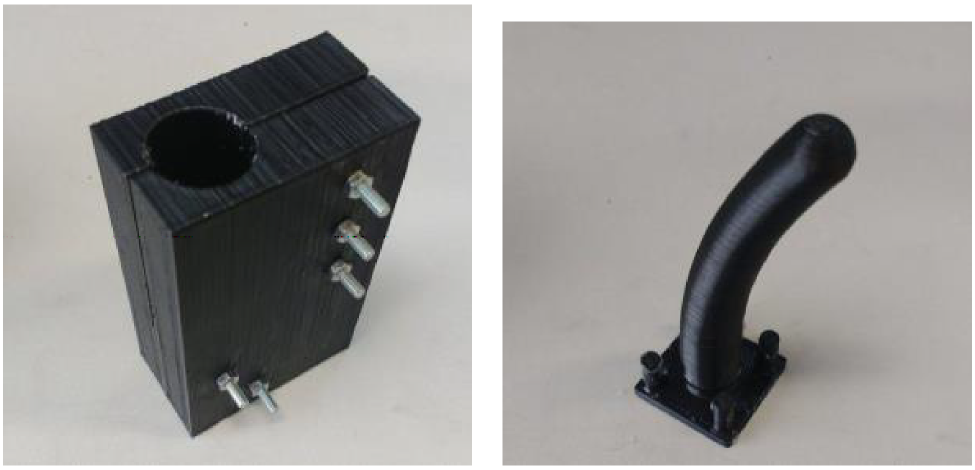


**(c)**



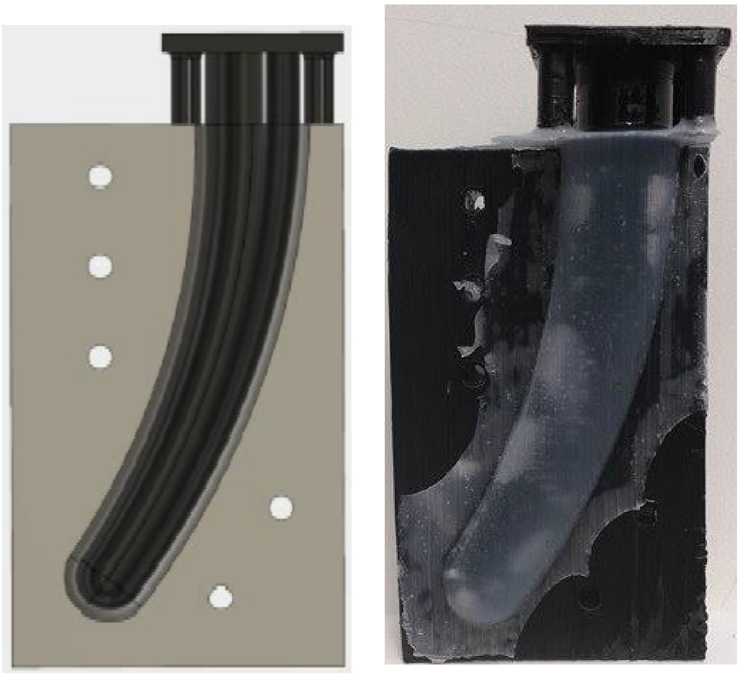
**(d)**

**Figure 3.7:** Failed soft fingers after the hydrogel mixed with Ecoflex cure: (a) Cure attempt with little Ecoflex, (b) Cure attempt with too much hydrogel, (c) Cure attempt with good ratio but not well distributed, (d) Cure attempt with the perfect ratio but with a lot of holes and ecoflex between the joints.



(a) (b)

**Figure 3.8:** 3D printed molds for the Ecoflex curing: (a) Main mold; (b) Shaping mold.



(a) (b)

**Figure 3.9:** Longitudinal schematic of both molds: (a) 3D design; (b) Real picture after curing.

After the creation of the Ecoflex epidermal layer, to create the dermal layer, the SPA powder is poured manually inside the Ecoflex layer. Then, the endoskeleton finger is inserted in the Ecoflex layer and distilled water is added inside until filled, in order to create the hydrogel as the dermal layer. The reaction of the SPA and distilled water is purely physical, the SPA swells when in contact with water, thus creating the hydrogel. A finger with both these layers can be seen in Figure 3.10.

**Figure 3.10:** Soft finger with a silicone layer filled with hydrogel.

To do the final enclosure, a small mold was printed, with a very thin perimeter, and attached to the finger, as shown in Figure 3.11. More Ecoflex is poured inside this little mold with a syringe, and after the curing, the cylindrical wall part is carefully removed with a scissors, so as not to rip the Ecoflex, shown in Figure 3.12 thus creating the optimal soft finger, with a silicone epidermal layer, a hydrogel dermal layer and a 3D printed endoskeleton, shown in Figure 3.13.

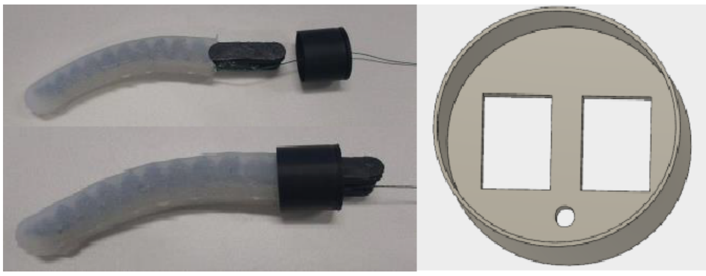


**Figure 3.11:** Little mold printed and attached for final enclosure.

**Figure 3.12:** Little mold cure and removal of the thin perimeter after curing.

**Figure 3.13:** Final form of the soft finger.

# Chapter 4

# Soft Gripper

On this subchapter is presented all the parts of the gripper, its iterations, measures and their functions.

This gripper has a mechanism, which is explained posteriorly, based on the "Push base" toys 4.1, which are toys that when their button is pushed, they disassemble, and when released they assemble back together.

**Figure 4.1:** Example of a "Push Base" toy.

One important thing to note, is that, since the idea for this gripper is to be low-cost, the less material used to make it, the better.

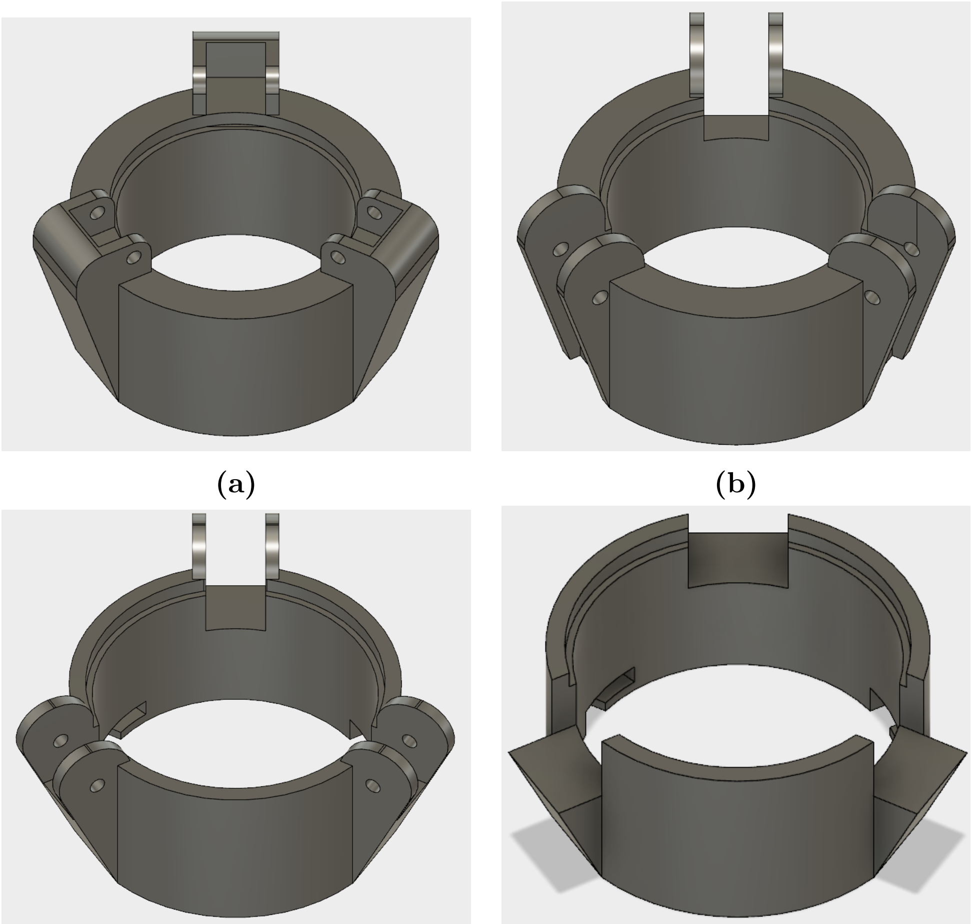
All the pieces for the gripper were printed in a printer called Prusa-i3, the material used was PLA, designed with the software Autodesk Fusion 360 and printed with the help of the Repetier software, with the exceptions of the strings, shafts and the gear motor.

Most of them had to be separately printed because the printer only prints from bottom to top, and otherwise, if some parts were printed together they had no support. Although we can add support for the pieces, by changing settings before printing, it would be too much, and in that case is preferable to print them separately and mount everything together after.

## 4.1 Gripper parts

The first piece designed was the body of the gripper, with the purpose to cover the mechanical parts and to attach the fingers, shown in Figure 4.2a. As this part was created, the first iteration that it suffered, Figure 4.2b, was to lower the position holes because otherwise they would be too much far away from the gripper body. Then, was concluded that the walls were too thick for its porpuse, so it was changed from $14mm$ to $7mm$ of thickness. There were added three holes in the bottom part to attach the cup that will cover the interior and it will function as a holder, as shown in Figure 4.2c.

For the final version, Figure 4.2d, the parts to attach the fingers were removed and printed apart, which are shown in Figure 4.3, because the fingers final geometry changed. The reason for printing apart these parts is because, since they are smaller, they need to be printed in a lying down position, so the printer prints circular patterns around the hole, otherwise the patterns would be horizontal and that way they would tend to break easily with a stronger grasp.



(a) (b) (c) (d)

**Figure 4.2:** Grippers body iterations: (a) Initial body; (b) First iteration; (c) Second iteration; (d) Final version.

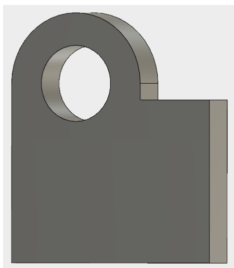
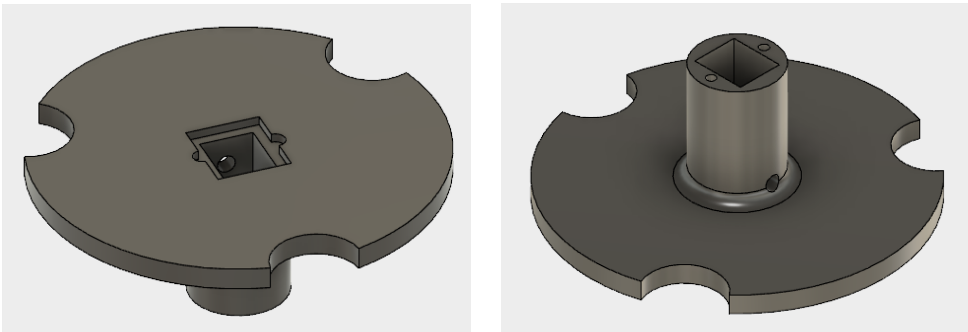


**Figure 4.3:** Support to attach soft fingers in the gripper body.

The inner wall of the body is where the base shield is attached, Figure 4.4. This shield has two functions, one to cover the gripper, and the other to shelter the gear motor. The hole on the side of the little tube, which can be seen in Figure 4.4b is for the wires that are connected to the actuator can come outside to connect them with a battery.

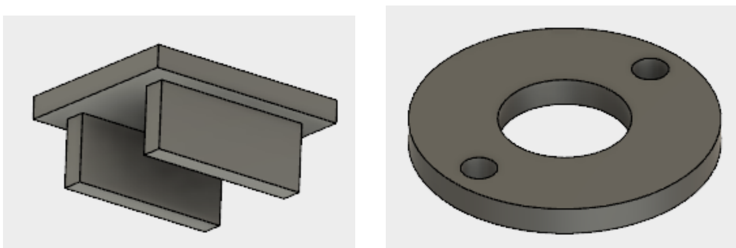
The first version of this piece had a problem because the actuator was a little loose inside, and in consequence of that, when the gripper was opening or closing, it tended to loosen up from the other pieces, and that way the gripper stops working. So, to avoid this from happening, the hole where is the gear motor needs to be really tight, and then it was designed with just 1mm between the walls and the gear motor.



**(a)** **(b)**

**Figure 4.4:** Base shield: (a) Top view; (b) Bottom view.

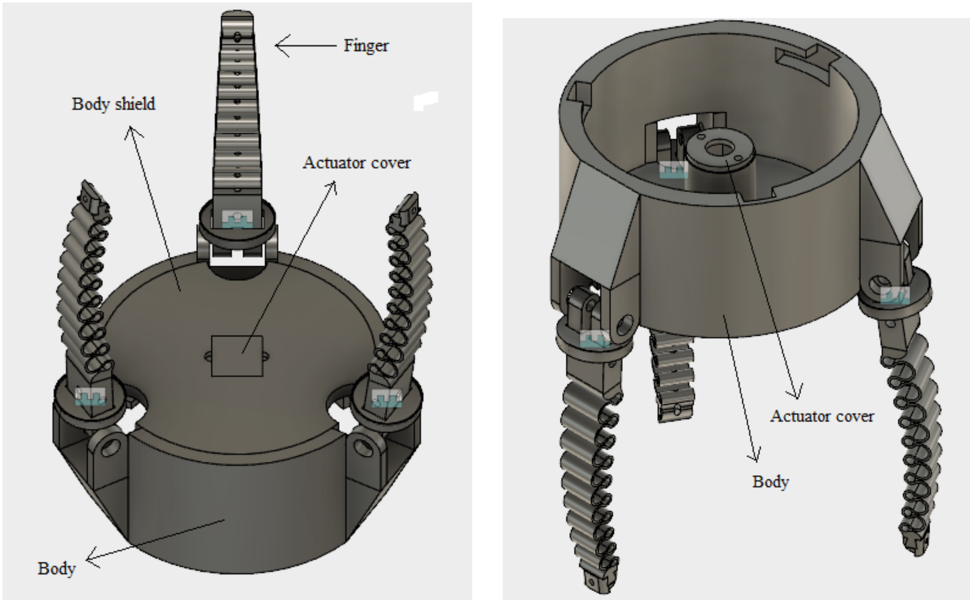
Other piece is the actuator cover, Figure 4.5a, which is a piece that is inserted on the top face of the base shield, with the purpose to open in case the actuator need to be changed or when some fix in the wires is needed. Another actuator cover is necessary, Figure 4.5b, created with the objective to hold the actuator inside the base shield.



**(a)** **(b)**

**Figure 4.5:** Actuator covers: (a)Actuator cover attached on top part of the base shield; (b) Actuator cover attached on the bottom part of the base shield.

To have a better visualization and understanding of this pieces, in Figure 4.6 we can see an assemble with all the previous parts.




(a) (b)

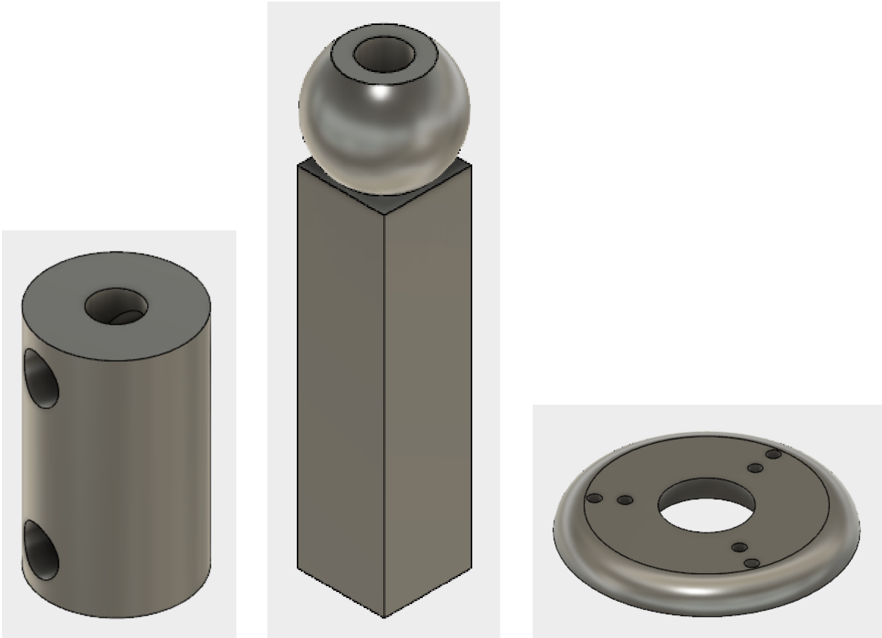
**Figure 4.6:** First assemble of the soft gripper: (a) Top view; (b) Bottom view.

To connect the actuator shaft and a threaded shaft of the gripper, it was designed a junction, shown in Figure 4.7a. One side is attached to the actuator shaft and the other to the threaded shaft. It has two holes on the sides to put screws to tighten both shafts so they don't come out.

The threaded shaft that is connected to the previous junction, is also inside a piece that it was called "Ballcube", shown in Figure 4.7b. This is the piece that goes up and down when the gear motor is rotating.

Around the ball that is on top of the "Ballcube" is a dish, shown in Figure 4.7c. This is where the strings that come from the fingers are tied. The purpose of this piece is for when a finger or two are closed enough regarding the others, the dish loosens up a bit the string so the finger doesn't do more force on the object that is being gripped.

For a better understanding, in Figure 4.8 is shown a second assemble with all the previous parts.



(a) (b) (c)

**Figure 4.7:** Gripper pieces: (a) Junction that connects the actuator and the threaded shaft; (b) "BallCube" which is around the threaded shaft; (c) Dish that is attached on the ball which is on top of the "BallCube".

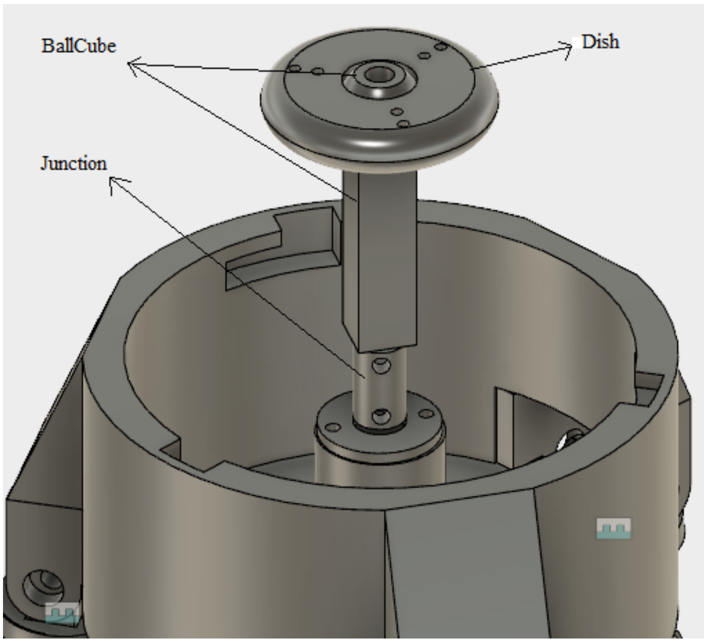


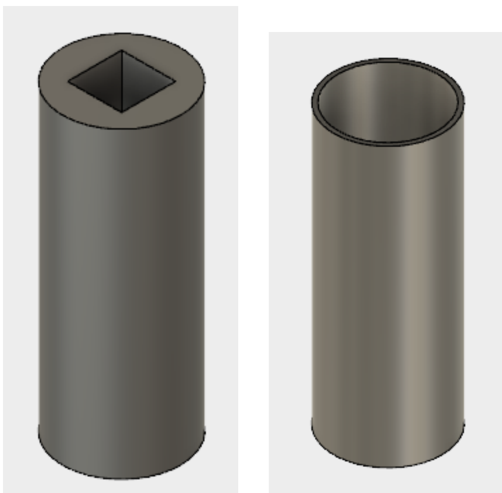

**Figure 4.8:** Second assemble of the soft gripper.

Around the junction and the "BallCube", and attached to the actuator cover, there is a tube, shown in Figure 4.9, part circular part squared. The circular part is covering the junction, while the squared part is around the "BallCube". Its purpose is to create friction between its walls and the "BallCube", for when the motor is actuated, the threaded shaft rotates, making the "BallCube" rotate too, but since the squared part of the tube doesn't let him rotate, it starts going up or down, pulling this way the strings, making the fingers close or open. Also, around the tube, is a disc, shown in Figure 4.10, with the purpose to align the strings that come from the fingers with the dish.

The final assemble with these final parts can be seen and perceived in Figure 4.11.

The total weight of the gripper, with the soft fingers integrated, the motor and the cup is 295$g$. The cup weights 70$g$, but still can be improved to weight less, shown in Figure 4.12. The real picture of the final assemble can be seen in Figure 4.13.

The motor has a cost of 10€, each finger has a cost of 0.52€and the gripper parts have a combining costs of 3.1€. Combining these prices, and adding the shafts and strings, the total cost of the gripper is around 15€, which is an optimal price for a functional under-actuated gripper.



(a) (b)

**Figure 4.9:** Gripper Tube: (a) Squared part of the tube; (b) Circular part of the tube.

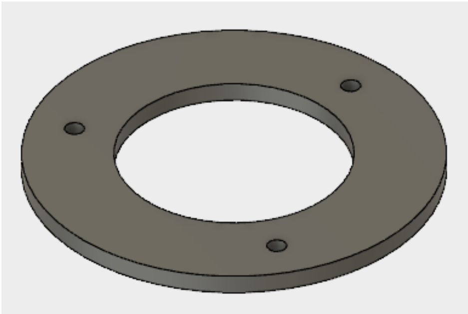


**Figure 4.10:** Disc to align the strings.

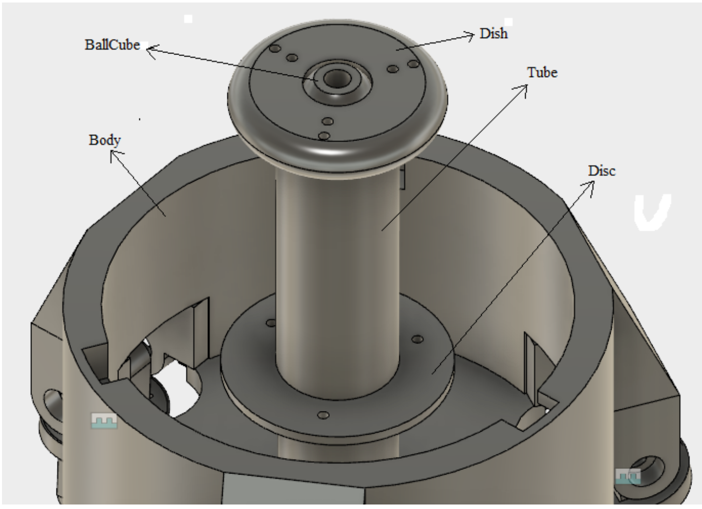



**Figure 4.11:** Final assemble of the soft gripper.

**(a)** **(b)**

**Figure 4.12:** Real picture of the cup: (a) Outside view; (b) Inside view.

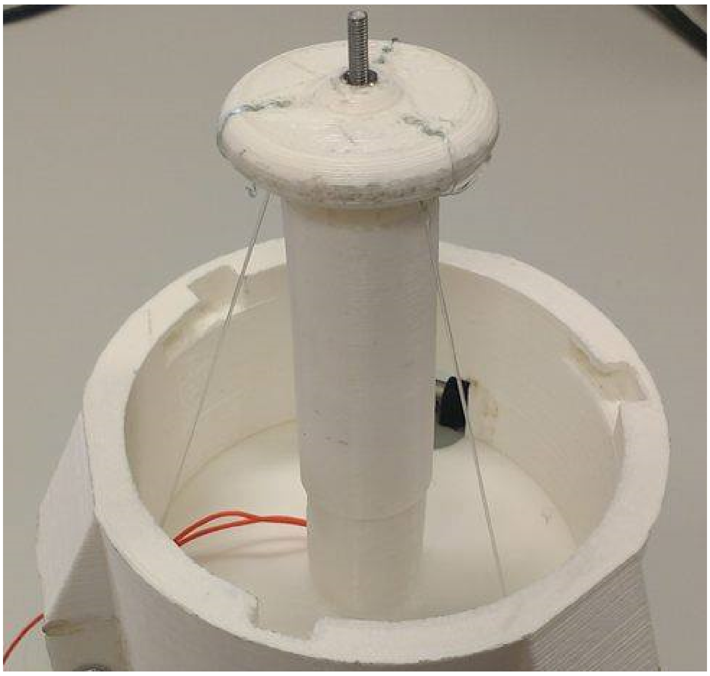


**Figure 4.13:** Real picture of the final assemble of the soft gripper.

### 4.1.1 Gripper actuator

The motor used to make this gripper work is a 30:1 dual-shaft micro metal gearmotor, shown in Figure 4.14. It has one small shaft and a bigger one, when the small rotates thirty times, the bigger rotates one. Has a $12\,V$ of rated voltage and $800mA$ stall current. It has a high-power, with carbon brushed motor type (HPCB). Has a no-load speed of 1000 *rpm* and a approximate stall torque of 9 *oz-in*.

**Figure 4.14:** Image of the dual-shaft micro metal gearmotor.

# Chapter 5

# Results

In this chapter, bending forces of the soft fingers, with and without hydrogel, are compared, waterproof component is studied and the overall features are stated. Also, grasping tests are made with the under-actuated gripper and the adaptability of the fingers, while gripping objects, is studied.

## 5.1 Fingers results

The hydrogel is an important component for the finger functionality. A finger with the same geometry fully filled with Ecoflex was tested. Such finger could not perform a full flexion and with a $22N$ pulling force could do only a half flexion as can be seen in Figure 5.1a. In comparison, the finger filled with Hydrogel could perform a full bend with less than $10N$ of force, shown in Figure 5.1c and bending forces shown in Table 5.1, which is around 25% more than the endoskeleton alone.

Other option tested was to use an empty space in the epidermal layer, but also that doesn't work because, when the finger is bended, the Ecoflex layer wrinkles which affects the contact between the object and the Ecoflex skin, shown in Figure 5.1b.

Therefore, hydrogel is probably the best option as the dermal layer of the soft finger, giving strength, support and flexibility in the movements and grasping actions.

| Tested flexions | Final Fingers | | |
|---|---|---|---|
| | Finger #1 | Finger #2 | Finger #3 |
| 180º flexion | 9.87 +/- 0.64 | 9.81 +/- 0.98 | 9.80 +/- 1.00 |
| 90º flexion | 5.53 +/- 0.57 | 6.16 +/- 0.30 | 5.26 +/- 0.29 |

**Table 5.1:** Final soft fingers flexion forces in *Newton*.

(a) (b) (c)

**Figure 5.1:** Full flexion of the soft finger: (a) Finger fully cured with Ecoflex ($22N$ was required to make the half flexion); (b) Finger with empty space between the endoskeleton and Ecoflex layer ($8N$ was required to do this flexion, however, the wrinkles on the skin is not optimal for grasping objects, since it reduces the contact area); (c) Finger filled with hydrogel.

One associated problem with hydrogels is that they lose water over time. However, the Ecoflex epidermal layer should act as a barrier against losing of water. To verify this, fingers were weighted during a month. As Table 5.2 shows, they lose around $1g$ in the first 16 days. Important to note that fingers #9 and #10 had some openings in the base. So, regarding just the finger #11, which was the first sucessfull finger created, just loses $1.52g$ in a month, which is just 5.4% of its total weight. Although they weren't stored in a fresh environment, based on these values, it can be affirmed that the silicone layer is protecting the water from evaporating, thus having the waterproof component, concluding that the method used to create the soft finger is a sucess.

| | Day 1 | Day 3 | Day 6 | Day 10 | Day 13 | Day 16 | Day 30 |
|---|---|---|---|---|---|---|---|
| Finger #9 | 23.60 | 23.34 | 23.18 | 22.76 | 22.48 | 22.24 | 21.36 |
| Finger #10 | 24.80 | 24.62 | 24.50 | 24.16 | 23.92 | 23.68 | 22.94 |
| Finger #11 | 28.20 | 28.05 | 27.90 | 27.58 | 27.41 | 27.18 | 26.68 |

**Table 5.2:** Experiment soft fingers weight in *grams* with an error of 0.01.

For the final fingers used on the gripper, as can be seen in Table 5.3, they lost less than 3% of weight after 10 days, mainly because of the Ecoflex and water excess that is removed.

| | Day 1 | Day 3 | Day 8 | Day 10 |
|---|---|---|---|---|
| Finger #1 | 29.18 | 28.78 | 28.56 | 28.32 |
| Finger #2 | 28.80 | 28.48 | 27.90 | 27.48 |
| Finger #3 | 28.50 | 28.20 | 27.90 | 27.40 |

**Table 5.3:** Final Soft Fingers weight in *grams* with an error of 0.01.

Overall, the soft finger created on this thesis has the following features:

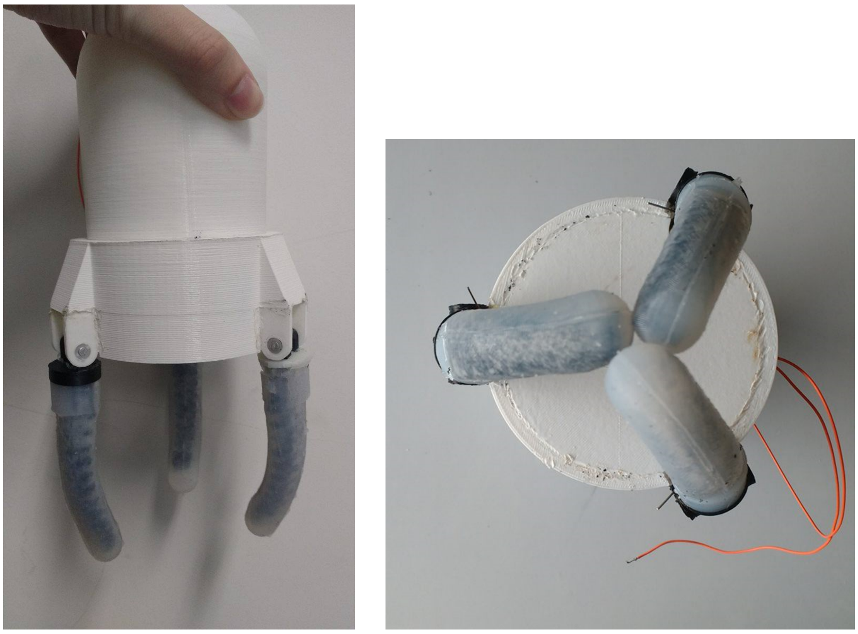
- Continuous skin
- Waterproof
- Excellent adaptability
- Easily acessible and low-cost (around 0.5€each finger)
- Low bending force and low contact force (doesn't devast the fruit)
- Can be implemented in different mechanism (e.g. prosthesis)

## 5.2 Grasping mechanism tests

Some grasping tests, with different objects, were made with the under-actuated gripper and the soft fingers, shown in Figure 5.2. As can be seen, the light-weight and simple under-actuated soft gripper adapts very well to different objects and is able to perform stable grasps on objects with various shapes, shown in Figure 5.3.

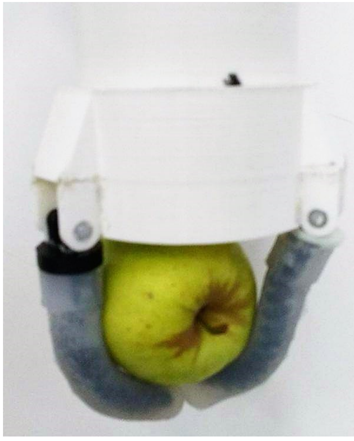
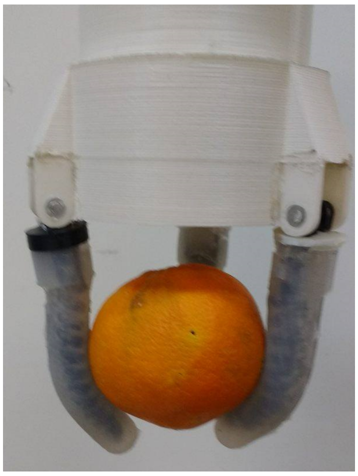
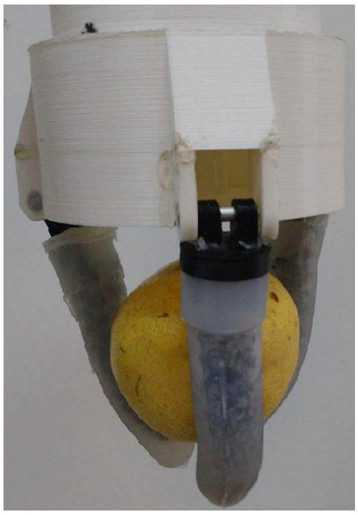
It is important to highlight how the fingers easily adapt to the form of the objects. When closing, they start with their original form, then when some point of the finger touches an object, the points that aren't touching start to involve around it, making this way a stable grasp without damaging the object.

Most of the objects in industry have spherical or cylindrical form, so it is important for the gripper be able to perform grasps on objects with these forms.

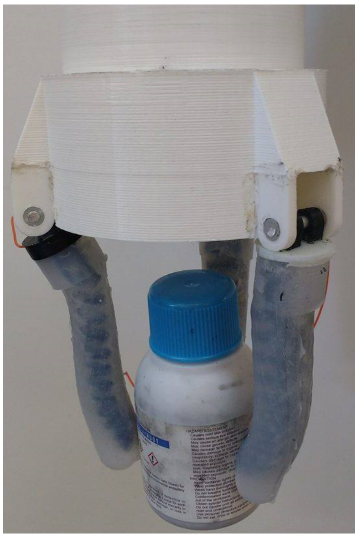


**(a)** **(b)**

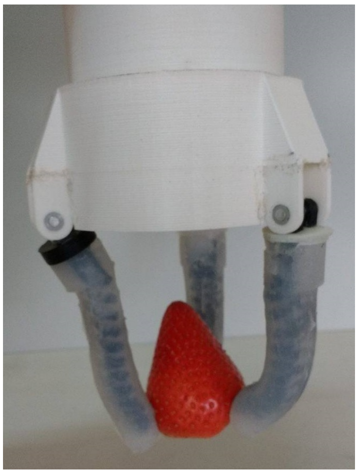
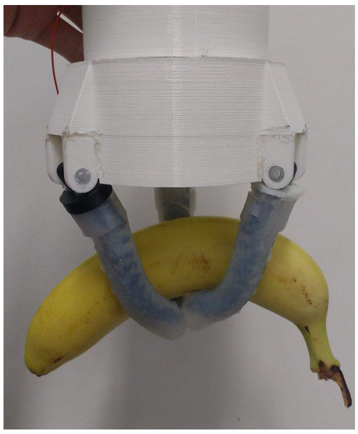
**Figure 5.2:** Pictures of the under-actuated gripper with the soft fingers integrated: (a) Side view; (b) Top view.

(a) (b) (c)


(d) (e) (f)

(g) (h)

**Figure 5.3:** Pictures of some grasping tests made witht the soft gripper: (a) Apple with 151.92 $g$; (b) Orange with 140.24 $g$; (c) Peach with 147.56 $g$; (d) Duct tape with 66.52 $g$; (e) Flask with 126.26 $g$; (f) Ball with 12.46 $g$; (g) Strawberry with 52.38 $g$; (h) Banana with 201 $g$.

# Chapter 6

# Conclusion

## 6.1 General Conclusions

In this dissertation it was presented design and implementation of a novel bio-inspired soft finger design, with a continuous skin, that resembles the human fingers physiology. Then, it was implemented a grasping mechanism with a single actuator and showed grasping of several objects with different geometries with this system.

The main goal of this project was to create an anthropomorphic soft finger and a low-cost protoype of an under-actuated gripper. Through different attempts and methods, with some failures in the process, an optimal soft finger with good grasping capabilities was obtained. Also the gripper suffered many iterations through the process, allways based on the needs of the fingers and with the goal to make it small as possible in order to use less material, and at the end, a good functional and lightweighted prototype was achieved.

The soft finger has a 3D printed rigid endoskeleton, made of polylactic acid and designed with circular geometries, has a water containing hydrogel, made of sodium polyacrylate and distilled water, to resemble the dermal layer and a resilient and stretchable silicone layer, made of Ecoflex 00-30, that resemble the epidermal layer, acting as a barrier to lose of water of the hydrogel and create good friction for grasping actions. Although the fingers were not stored in a chilly environment, it was shown that they preserve their water content during several days, making the innovative method, for creating a soft finger with a continous skin, sucessfull.

The under-actuated gripper has three soft fingers integrated making 120 degrees between them. It was designed from scratch and printed in a 3D printer with acrylonitrile butadiene styrene material. The mechanism is based on the "Push base" toys to pull the strings in order to close or open the fingers. Some grasping tests were made, with different objects, showing that the gripper adapts very well to them and is able to perform stable grasps on them with various shapes. Since the main objective for the gripper is to work as a pick and place robot for agriculture industry, the majority of the objects tested were fruits, which grasps were performed very well without damaging them, concluding thus, that this under-actuated gripper is suitable for this task.

The final prototype weights 295$g$, including an actuator of 10$g$, three soft fingers with a combining weight of 82$g$ and a cup with 70$g$, making it a very lightweight gripper regarding its purpose. The cost of making the gripper is around 15€, shown in Table 6.2 but without the motor and the fingers, which are 10€and 1.6€respectively, it only costs around 3.5€, making it one of the most cheapest gripper. Concluding thus, that all the objectives for the gripper were achieved, although it can still be improved in some aspects. Fingers calculation price is shown in Table 6.1.

| Materials | Average weight (g) | price (€) |
|---|---|---|
| **ABS** | 5,80 | 0,10 |
| **Hydrogel** | 12,40 | 0,25 |
| **Ecoflex** | 9,80 | 0,17 |
| **Total** | 28,00 | 0,52 |

**Table 6.1:** Table with the soft finger materials weights and prices.

| Pieces | Weight (g) | Price (€) |
|---|---|---|
| **Motor** | 10,00 | 10,00 |
| **Cup** | 70,00 | 1,05 |
| **Three soft fingers** | 83,20 | 1,56 |
| **Gripper parts** | 131,80 | 1,98 |
| **Total** | 295,00 | 14,59 |

**Table 6.2:** Table with the under-actuated gripper pieces weights and prices.

## 6.2 Future Work

The present work is a breakthrough on the soft robotics area. Improvements can still be made, regarding the soft fingers and the under-actuated gripper.

Future work for the soft fingers created on this thesis, is the implementation of pressure sensors on the fingertips and/or all over the finger. Also the length of the finger can be re-designed depending on the range of the objects that should be grasped. For example, if implemented in a prosthetic hand, they can be designed in order to have the measures of each one of human finger digits, even the thumb digit. Also, the texture and the external geometry of the silicone layer can be modified in order to be human like by changing the design of the mold.

Future work for the under-actuated gripper created on this thesis, is the implementation of a proximity sensor on its shield, in order to detect objects, also in its borders for a better positioning. The reduction of weight can still be made, especially the cup, which can be smaller, also the body can be improved too, having less infill and thickness. The actuator can be better positioned to do a smooth rotation. Another improvement is the implementation of a system with a button to actuate the motor, with a battery of 7 or 8 $V$. Another approach can be the implementation of a mechanism to turn off the motor when the "BallCube" reach its limits, in order to dont over-actuate the system, the idea is to put a button on top of the cup and in the tube, and when the dish reach it, it stops. One last improvement is the use of springs to put between the fingers and the gripper in order to have a wider starting open position for the fingers.

## 6.3 Publication

The article entitled "Hydrogel-Silicone conjunction as epidermal and dermal layers of bio-inspired soft finger skin" has been accepted in the 2017 IEEE 5th Portuguese Meeting on Bioengineering Proceedings (IEEE Xplore).

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# Appendices

# Flexible Polyurethane Foam

# Technical Bulletin

# FlexFoam-iT!® Series

## *Flexible Polyurethane Foams*

**3lb., 4 lb., 5lb., 6 lb., 7 lb., 8 lb., 10 lb., 14 lb., 17 lb., 23 lb. or 25 lb.**

SMOOTH-ON SINCE 1895

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## *PRODUCT OVERVIEW*

**FlexFoam-iT!**® Series foams are premium quality water blown flexible foams that can be used for a variety of industrial, special effects and art & crafts and projects. With several to choose from, uses include making theatrical props (swords, knives, hammers, etc.), industrial gaskets, custom padding and cushioning, and more. SO-Strong® colorants can be added for color effects.

Part A and B liquids are combined, mixed and poured into a mold or other form (apply release agent if necessary). Mixture will rise and cure quickly to a solid, flexible foam. Foams vary by density and offer good physical properties. The lower the number, the more the foam expands. **FlexFoam-iT® III** is the lowest density foam and expands the most. **FlexFoam-iT!®25** is the highest density foam and expands the least.

***FlexFoam-iT!® 7 FR is flame rated to FMVSS-302 specification***
***FlexFoam-iT!® 23 FR is flame rated to UL-94 HB specification***

***8oz./237ml. of FlexFoam-iT!® A+B poured into a 32oz./946ml. cup.***


**Highest Density** → **Lowest Density**
**Lowest Expansion** → **Highest Expansion**

## *TECHNICAL OVERVIEW*

| | A:B Mix Ratio by Volume | A:B Mix Ratio by Weight | Specific Gravity (g/cc) (ASTM D-1475) | Specific Volume (cu. in./lb.) | Pot Life (Cream Time) (ASTM D-2471) | Handling Time | Approximate Volumetric Expansion | Approximate Lbs. / Cu. Foot = Kgs. / Cu. Meter |
|---|---|---|---|---|---|---|---|---|
| FlexFoam-iT!® III | 1:2 pbv | 57.5:100 pbw | 0.05 | 504 | 35 sec. | 25 min. | 15 times | 3 $lb/ft^3$ = 48 $kg/m^3$ |
| FlexFoam-iT!® IV | N/A | 80:100 pbw | 0.06 | 420 | 30 sec. | 45 min. | 13 times | 4 $lb/ft^3$ = 64 $kg/m^3$ |
| FlexFoam-iT!® V | 1:1 pbv | 105:100 pbw | 0.08 | 315 | 50 sec. | 45 min. | 11 times | 5 $lb/ft^3$ = 80 $kg/m^3$ |
| FlexFoam-iT!® 6 | 1:1 pbv | 105:100 pbw | 0.09 | 280 | 35 sec. | 60 min. | 10 times | 6 $lb/ft^3$ = 96 $kg/m^3$ |
| FlexFoam-iT!® 7 FR | 1:1 pbv | 100:88 pbw | 0.11 | 229 | 35 sec. | 60 min. | 8 times | 7 $lb/ft^3$ = 110 $kg/m^3$ |
| FlexFoam-iT!® VIII | 1:2 pbv | 52.6:100 pbw | 0.13 | 194 | 35 sec. | 25 min. | 7 times | 8 $lb/ft^3$ = 128 $kg/m^3$ |
| FlexFoam-iT!® X | 1:1 pbv | 105:100 pbw | 0.16 | 157 | 50 sec. | 45 min. | 6 times | 10 $lb/ft^3$ = 160 $kg/m^3$ |
| FlexFoam-iT!® 14 | 1:2 pbv | 100:190 pbw | 0.22 | 114 | 60 sec. | 45 min. | 4 times | 14 $lb/ft^3$ = 220 $kg/m^3$ |
| FlexFoam-iT!® 17 | 1:2 pbv | 100:185 pbw | 0.27 | 93 | 60 sec. | 30 min. | 3.5 times | 17 $lb/ft^3$ = 270 $kg/m^3$ |
| FlexFoam-iT!® 23 FR | N/A | 85:100 pbw | 0.37 | 68 | 90 sec. | 60 min. | 2 times | 23 $lb/ft^3$ = 370 $kg/m^3$ |
| FlexFoam-iT!® 25 | N/A | 1:2 pbw | 0.40 | 63 | 90 sec. | 25 min. | 2 times | 25 $lb/ft^3$ = 400 $kg/m^3$ |

***Mixed Viscosity** (ASTM D-2393)*: 1000 cps  ***Color:*** White  ***Tack Free / Cure Time:*** 2 Hours

* Values measured at room temperature (73°F/23°C)

## *PROCESSING RECOMMENDATIONS*

### *PREPARATION...*

Store and use at room temperature (73°F/23°C). Good ventilation (room size) is essential. This product has a limited shelf life and should be used as soon as possible. Wear safety glasses, long sleeves and rubber gloves to minimize contamination risk. **Because no two applications are quite the same, a small test application to determine suitability for your project is recommended if performance of this material is in question.**

**IMPORTANT:** Shelf life of product is reduced after opening. Remaining product should be used as soon as possible. Immediately replacing the lids on both containers after dispensing product will help prolong the shelf life of the unused product. **XTEND-IT® Dry Gas Blanket** (available from Smooth-On) will significantly prolong the shelf life of unused liquid urethane products.

## Safety First!

The Material Safety Data Sheet (MSDS) for this or any Smooth-On product should be read prior to use and is available upon request from Smooth-On. All Smooth-On products are safe to use if directions are read and followed carefully.

### Keep Out Of Reach Of Children.

***Be careful.*** **Part A** (Yellow Label) contains methylene diphenyldiisocyante. Vapors, which can be significant if heated or sprayed, may cause lung damage and sensitization. Use only with adequate ventilation. Contact with skin and eyes may cause severe irritation. Flush eyes with water for 15 minutes and get immediate medical attention. Remove from skin with soap and water.

**Part B** (Blue Label) is irritating to the eyes and skin. Avoid prolonged or repeated skin contact. If contaminated, flush eyes with water for 15 minutes and get immediate medical attention. Remove from skin with soap and water. When mixing with Part A, follow precautions for handling isocyanates. If machining cured FlexFoam-It!®, wear dust mask or other apparatus to prevent inhalation of residual particles.

**Important:** The information contained in this bulletin is considered accurate. However, no warranty is expressed or implied regarding the accuracy of the data, the results to be obtained from the use thereof, or that any such use will not infringe a copyright or patent. User shall determine suitability of the product for the intended application and assume all associated risks and liability whatsoever in connection therewith.

## APPLYING A RELEASE AGENT...

Urethane foams are adhesive and will stick / bond to many surfaces. **We recommend Ease Release® 2831 to release urethane foam from most surfaces.**

If the release application is particularly difficult (example; releasing urethane foam from urethane rubber), we recommend an application of Universal Mold Release® followed by an application of Ease Release® 2831. **WARNING;** Do not use Universal Mold Release® by itself, or any other silicone based release agents. This will collapse the foam.

## PRE-MIXING & MIXING...

***Pre-mix Parts A & B –*** Stir or shake both Part A & Part B thoroughly before dispensing.

***Measuring – Stop!*** Know the mix ratio of the foam product you are using. Some are by weight and some are by volume. Dispense the correct amounts of Part A and Part B into a large mixing container.

***For Best Results - Pre-Mix Part B after measuring out material –*** although not necessary, pre-mixing Part B using a drill and mechanical mixer (such as a turbine mixer available from Smooth-On) after measuring out and before combining with Part A will yield best results.

***For Best Results - Use a Mechanical Mixer –*** Mix for a minimum of 15 seconds and pour into mold or form.

***Mixing by Hand –*** Stir quickly and deliberately for a minimum of 15 seconds. Make sure that you aggressively scrape the sides and bottom of your mixing container several times. Pour into mold or form.

Be careful not to splash low-viscosity liquid out of container. Remember, these materials cure quickly. Do not delay between mixing and pouring.

## POURING, CURING & PERFORMANCE...

***Pouring & Curing -*** For best results, pour your mixture in a single spot at the lowest point of the containment field and let the mixture seek its level. Allow space in the containment field for the foam to grow as it expands to its ultimate volume. Allow foam to cure for at least 30 minutes before handling. Cure time will be affected by mass and mold configuration.

***Improving Surface Finish & Minimizing Voids With Back Pressure -*** Use a board that will completely cover the mold opening. Using a 3/4" (2 cm) drill bit, drill 3 holes in the board spaced a few inches/cm apart. Make sure that when the board is placed over the mold opening the holes are over the mold cavity and rising foam will be able to make it through. Apply Ease Release® 2831 thoroughly to both sides of the board and into the drilled holes. Mix and pour FlexFoam-iT!® into mold cavity and place board over mold opening. Secure board firmly in place (mold straps may be necessary). As foam rises in the mold cavity, some foam will grow out of the drilled holes. After the foam stops growing, you can let go of the board. Do not handle for at least 30 minutes. After 30 minutes, you can then cut excess material that came through holes and gently remove board and casting.

***Is Your Foam Collapsing? -*** This is a common phenomenon associated with cold temperatures, inadequate mixing or both. **Environment or material too cold?** Warm it up. **Inadequate mixing?** You must thoroughly pre-mix both parts A and B. After combining A and B, mix thoroughly. If using a mechanical mixer, mix for 30 seconds. When hand mixing, mix quickly and aggressively, almost whipping the material.

***Call Us Anytime With Questions About Your Application***
Toll-free: **(800) 381-1733** Fax: **(610) 252-6200**

# Ecoflex-0030 Technical Bulletin

# Ecoflex® Series

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www.smooth-on.com

## PRODUCT OVERVIEW

**Ecoflex**® rubbers are platinum-catalyzed silicones that are versatile and easy to use. **Ecoflex**® rubbers are mixed 1A:1B by weight or volume and cured at room temperature with negligible shrinkage. Rubber also cures without a "tacky" surface. Low viscosity ensures easy mixing and de-airing, or you can choose to mix and dispense using our convenient dispensing cartridges.

Cured rubber is very soft, very strong and very "stretchy", stretching many times its original size without tearing and will rebound to its original form without distortion. **Ecoflex**® rubbers are water white translucent and can be color pigmented with Silc Pig® pigments for creating a variety of color effects. You can also add Smooth-On's Silicone Thinner® to further lower the viscosity. THI-VEX® silicone thickener can be added by weight to Ecoflex® 5 or Ecoflex® 00-10 for brushable aplications. ***Note: THI-VEX® is NOT compatible with Ecoflex® 00-30, Ecoflex® 00-20 or Ecoflex® 00-50.***

***Soft, Softer, Softest . . .*** Ecoflex® rubbers are based on Smooth-On's Dragon Skin® technology and are currently available in four different hardness': Shore A-5, Shore 00-10, 00-20, 00-30 and 00-50. They are suitable for a variety of applications including making prosthetic appliances, cushioning for orthotics and special effects applications (especially in animatronics where repetitive motion is required). **Ecoflex® 5** has a pot life of 1 minute and a demold time of 5 minutes – Available only in dispensing cartridges.

## TECHNICAL OVERVIEW

| | Mixed Viscosity (ASTM D-2393) | Specific Gravity (g/cc) (ASTM D-1475) | Specific Volume (cu. in./lb.) (ASTM D-1475) | Pot Life (ASTM D-2471) | Cure Time | Shore Hardness (ASTM D-2240) | Tensile Strength (ASTM D-412) | 100% Modulus (ASTM D-412) | Elongation at Break % (ASTM D-412) | Die B Tear Strength (ASTM D-624) | Shrinkage (in./in.) (ASTM D-2566) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ecoflex® 5** | 13,000 cps | 1.07 | 25.8 | 1 min. | 5 min. | 5A | 350 psi | 15 psi | 1000% | 75 pli | < .001 in./in. |
| **Ecoflex® 00-50** | 8,000 cps | 1.07 | 25.9 | 18 min. | 3 hours | 00-50 | 315 psi | 12 psi | 980% | 50 pli | < .001 in./in. |
| **Ecoflex® 00-30** | 3,000 cps | 1.07 | 26.0 | 45 min. | 4 hours | 00-30 | 200 psi | 10 psi | 900% | 38 pli | < .001 in./in. |
| **Ecoflex® 00-20** | 3,000 cps | 1.07 | 26.0 | 30 min. | 4 hours | 00-20 | 160 psi | 8 psi | 845% | 30 pli | < .001 in./in. |
| **Ecoflex® 00-10** | 14,000 cps | 1.04 | 26.6 | 30 min. | 4 hours | 00-10 | 120 psi | 8 psi | 800% | 22 pli | < .001 in./in. |

*All values measured after 7 days at 73°F/23°C

***Mix Ratio:*** 1A:1B by volume or weight
***Color:*** Translucent
***Useful Temperature Range:*** -65°F to 450°F (-53°C to 232°C)
***Dielectric Strength*** (ASTM D-147-97a)***:*** >350 volts/mil

## PROCESSING RECOMMENDATIONS

***PREPARATION... Safety*** – Use in a properly ventilated area ("room size" ventilation). Wear safety glasses, long sleeves and rubber gloves to minimize contamination risk. Wear vinyl gloves only. Latex gloves will inhibit the cure of the rubber.

**Store and use material at room temperature (73°F/23°C).** Warmer temperatures will drastically reduce working time and cure time. Storing material at warmer temperatures will also reduce the usable shelf life of unused material. These products have a limited shelf life and should be used as soon as possible.

***Cure Inhibition*** – Addition-cure silicone rubber may be inhibited by certain contaminants in or on the pattern to be molded resulting in tackiness at the pattern interface or a total lack of cure throughout the mold. Latex, tin-cure silicone, sulfur clays, certain wood surfaces, newly cast polyester, epoxy or urethane rubber may cause inhibition. If compatibility between the rubber and the surface is a concern, a small-scale test is recommended. Apply a small amount of rubber onto a non-critical area of the pattern. Inhibition has occurred if the rubber is gummy or uncured after the recommended cure time has passed.

**Because no two applications are quite the same, a small test application to determine suitability for your project is recommended if performance of this material is in question.**

To prevent inhibition, one or more coatings of a clear acrylic lacquer applied to the model surface is usually effective. Allow any sealer to thoroughly dry before applying rubber. Note: Even with a sealer, platinum silicones will not work with modeling clays containing heavy amounts of sulfur. Do a small scale test for compatibility before using on your project.

## Safety First!

The Material Safety Data Sheet (MSDS) for this or any Smooth-On product should be read prior to use and is available upon request from Smooth-On. All Smooth-On products are safe to use if directions are read and followed carefully.

**Keep Out of Reach of Children**

***Be careful.*** Use only with adequate ventilation. Contact with skin and eyes may cause irritation. Flush eyes with water for 15 minutes and seek immediate medical attention. Remove from skin with waterless hand cleaner followed by soap and water.

**Important:** The information contained in this bulletin is considered accurate. However, no warranty is expressed or implied regarding the accuracy of the data, the results to be obtained from the use thereof, or that any such use will not infringe upon a patent. User shall determine the suitability of the product for the intended application and assume all risk and liability whatsoever in connection therewith.

***Applying A Release Agent -*** Although not usually necessary, a release agent will make demolding easier when pouring into or over most surfaces. Ease Release® 200 is a proven release agent for use with silicone rubber. Mann Ease Release® products are available from Smooth-On or your Smooth-On distributor.

***IMPORTANT:*** To ensure thorough coverage, lightly brush the release agent with a soft brush over all surfaces of the model. Follow with a light mist coating and let the release agent dry for 30 minutes.

If there is any question about the effectiveness of a sealer/release agent combination, a small-scale test should be made on an identical surface for trial.

## MEASURING & MIXING...

Before you begin, pre-mix Part B thoroughly. After dispensing required amounts of Parts A and B into mixing container (1A:1B by volume or weight), **mix thoroughly for 3 minutes making sure that you scrape the sides and bottom of the mixing container several times.** After mixing parts A and B, vacuum degassing is recommended to eliminate any entrapped air. Vacuum material for 2-3 minutes (29 inches of mercury), making sure that you leave enough room in container for product volume expansion.

## POURING, CURING & MOLD PERFORMANCE...

For best results, pour your mixture in a single spot at the lowest point of the containment field. Let the rubber seek its level up and over the model. **A uniform flow will help minimize entrapped air.** The liquid rubber should level off at least 1/2" (1.3 cm) over the highest point of the model surface.

***Curing / Post Curing -*** Allow rubber to cure as prescribed at room temperature (73°F/23°C) before demolding. Do not cure rubber where temperature is less than 65°F/18°C. **Optional:** Post curing the mold will aid in quickly attaining maximum physical and performance properties. After curing at room temperature, expose the rubber to 176°F/80°C for 2 hours and 212°F/100°C for one hour. Allow mold to cool to room temperature before using.

***If Using As A Mold -*** When first cast, silicone rubber molds exhibit natural release characteristics. Depending on what is being cast into the mold, mold lubricity may be depleted over time and parts will begin to stick. No release agent is necessary when casting wax or gypsum. Applying a release agent such as Ease Release® 200 (available from Smooth-On) prior to casting polyurethane, polyester and epoxy resins is recommended to prevent mold degradation.

***Thickening Ecoflex® Silicones -*** THI-VEX® may be added into Ecoflex® 5 & 00-10 by weight. The recommended maximum amount of THI-VEX® is 2% by weight. ***THI-VEX® thickener is not compatible with Ecoflex® 00-30, 00-20 or 00-50.*** An alternative for thickening Ecoflex® silicones is to add Ure-Fil® 9 or Ure-Fil® 11.

***Thinning Ecoflex® Silicones -*** Smooth-On's Silicone Thinner® will lower the viscosity of Ecoflex® silicones for easier pouring and vacuum degassing. A **disadvantage** is that ultimate tear and tensile are reduced in proportion to the amount of Silicone Thinner® added. ***It is not recommended to exceed 10% by weight of total system (A+B).*** See the Silicone Thinner® technical bulletin (available from Smooth-On or your Smooth-On distributor) for full details.

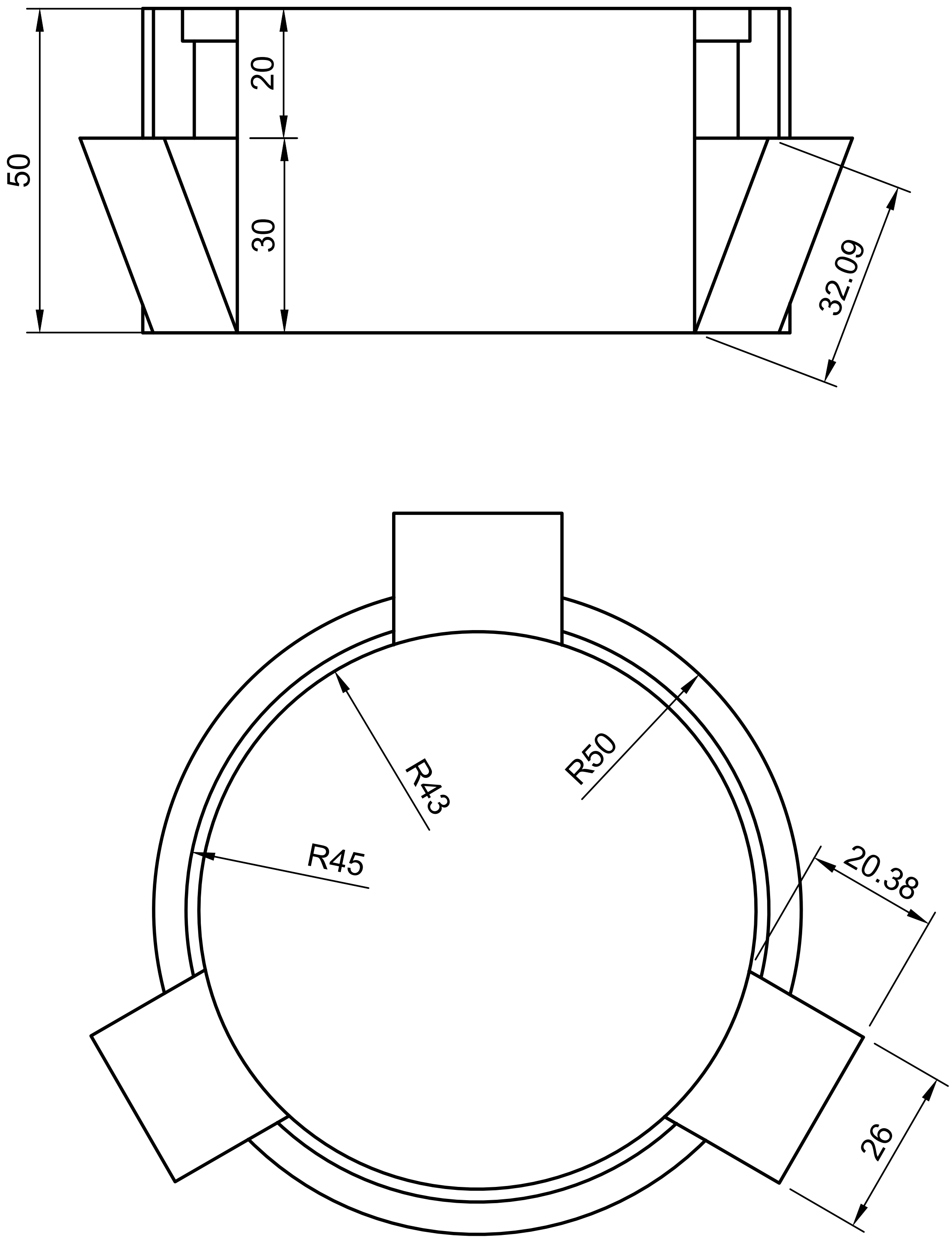
***Mold Performance & Storage -*** The physical life of the mold depends on how you use it (materials cast, frequency, etc.). Casting abrasive materials such as concrete can quickly erode mold detail, while casting non-abrasive materials (wax) will not affect mold detail. Before storing, the mold should be cleaned with a soap solution and wiped fully dry. Two part (or more) molds should be assembled. Molds should be stored on a level surface in a cool, dry environment.

***Call Us Anytime With Questions About Your Application.***

Toll-free: **(800) 762-0744** Fax: **(610) 252-6200**

The new [www.smooth-on.com](www.smooth-on.com) is loaded with information about mold making, casting and more.

# Gripper parts measures

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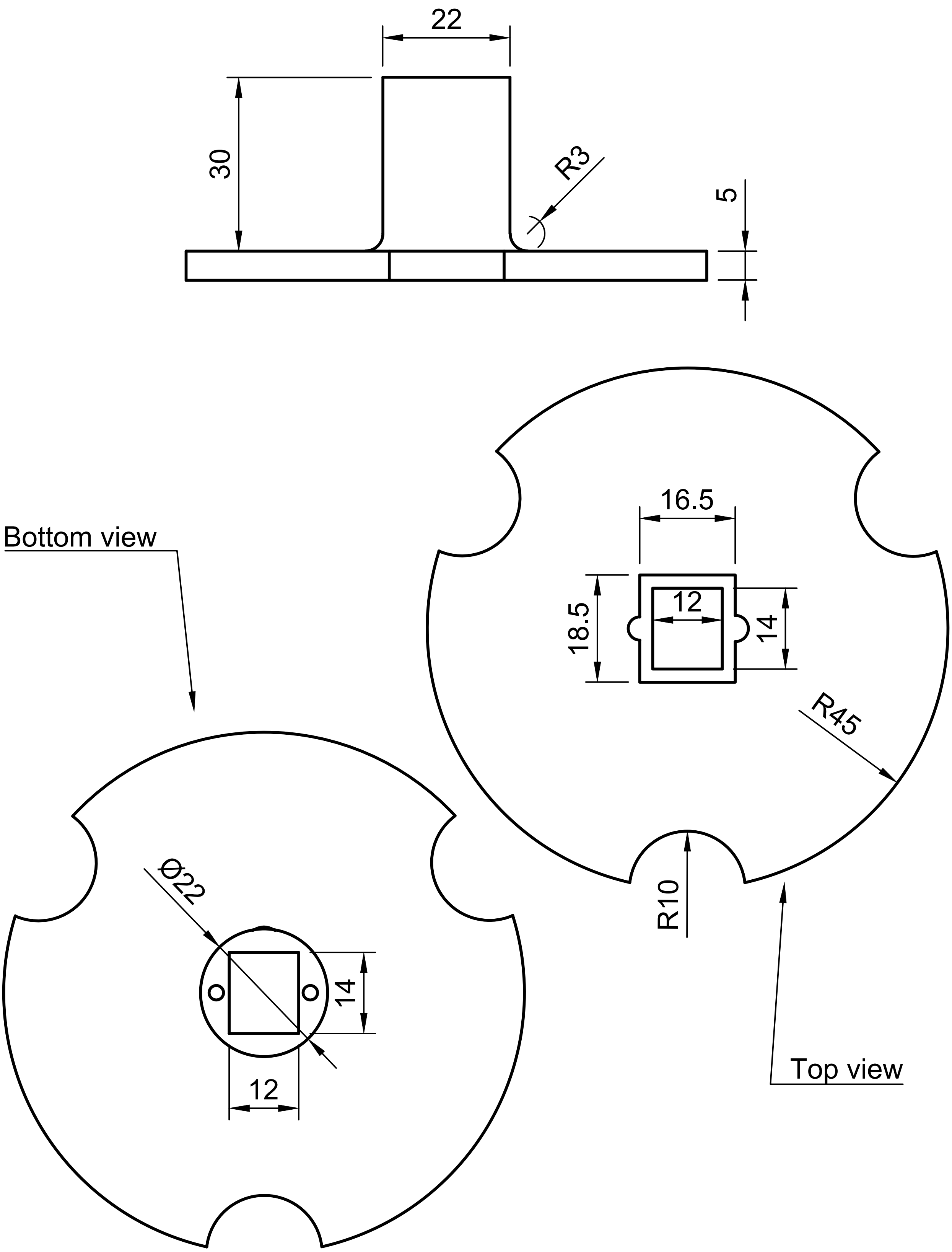


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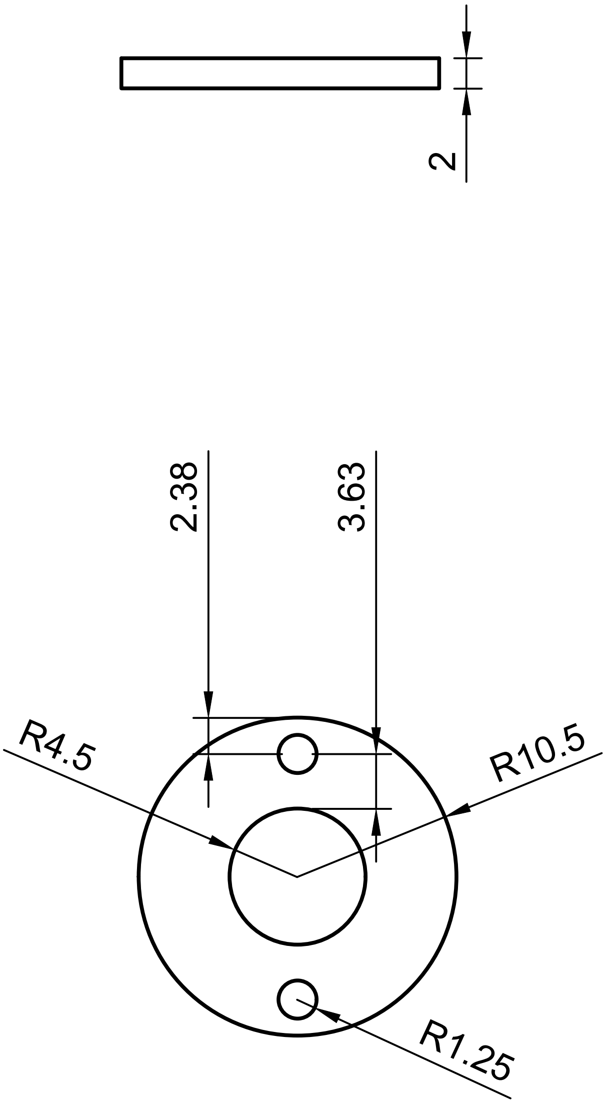


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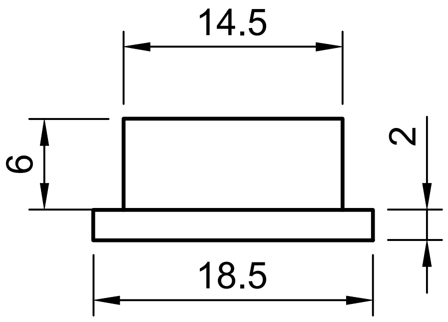


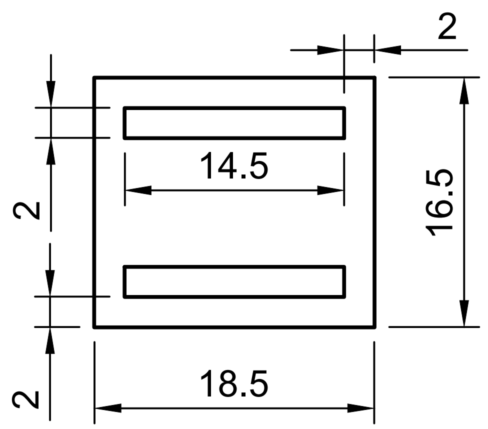


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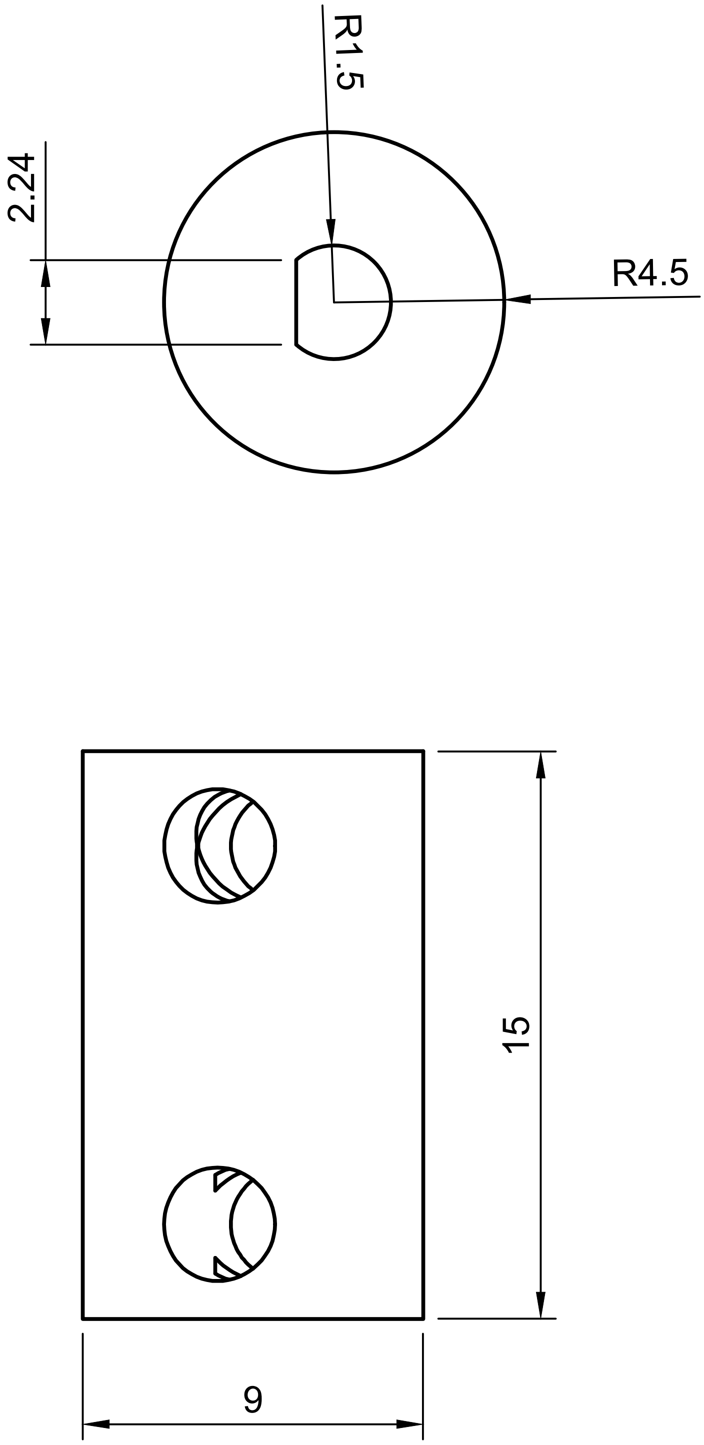


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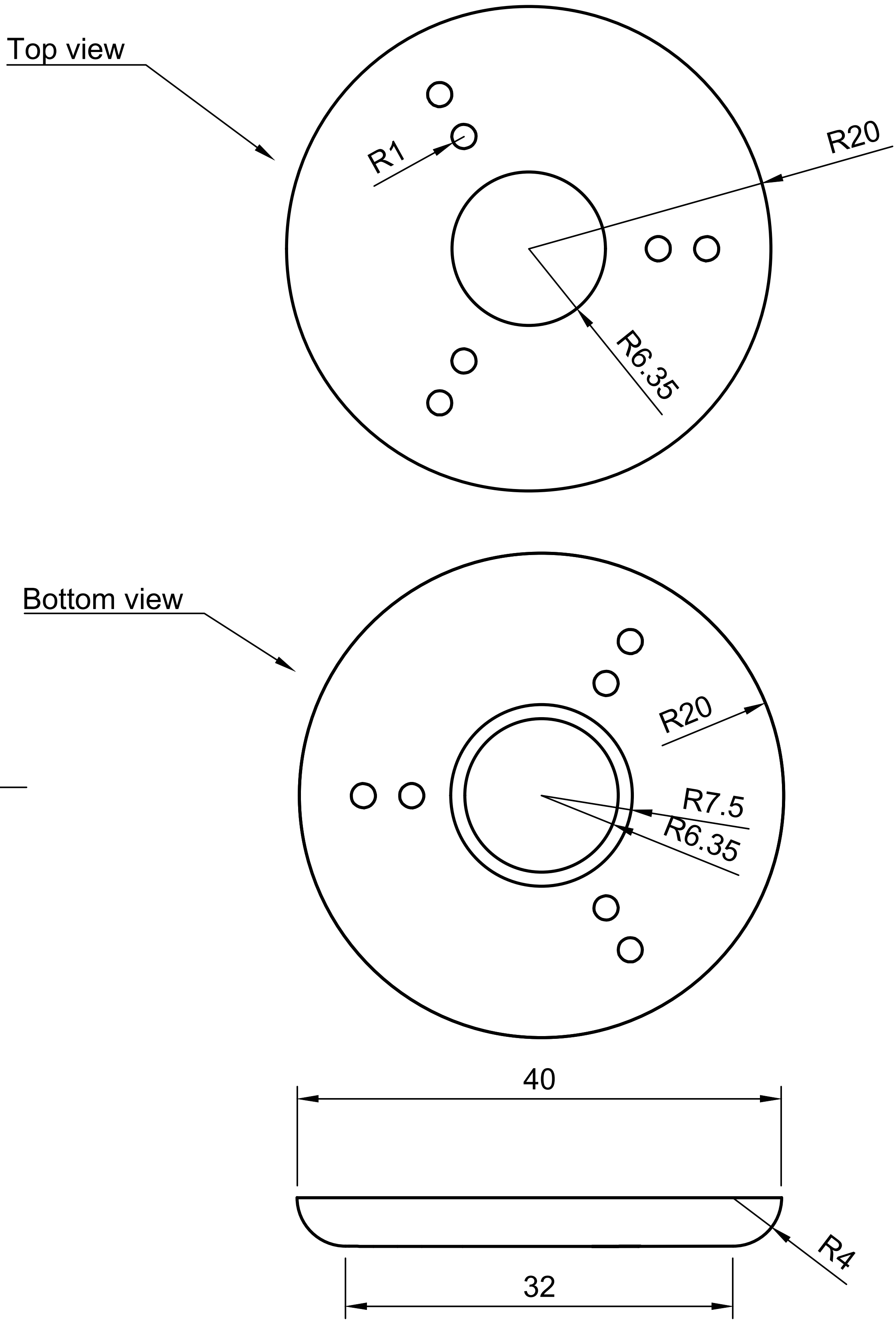


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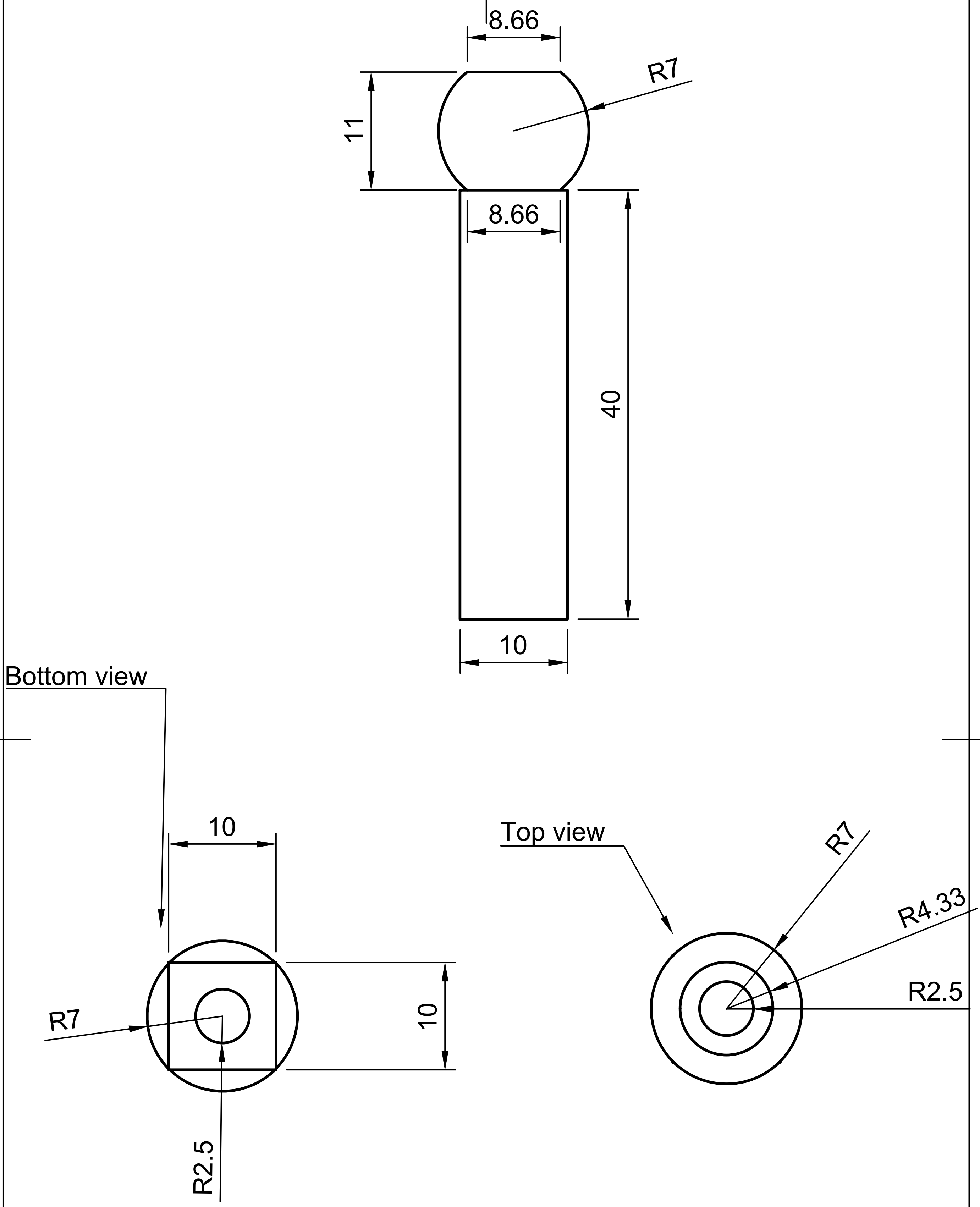


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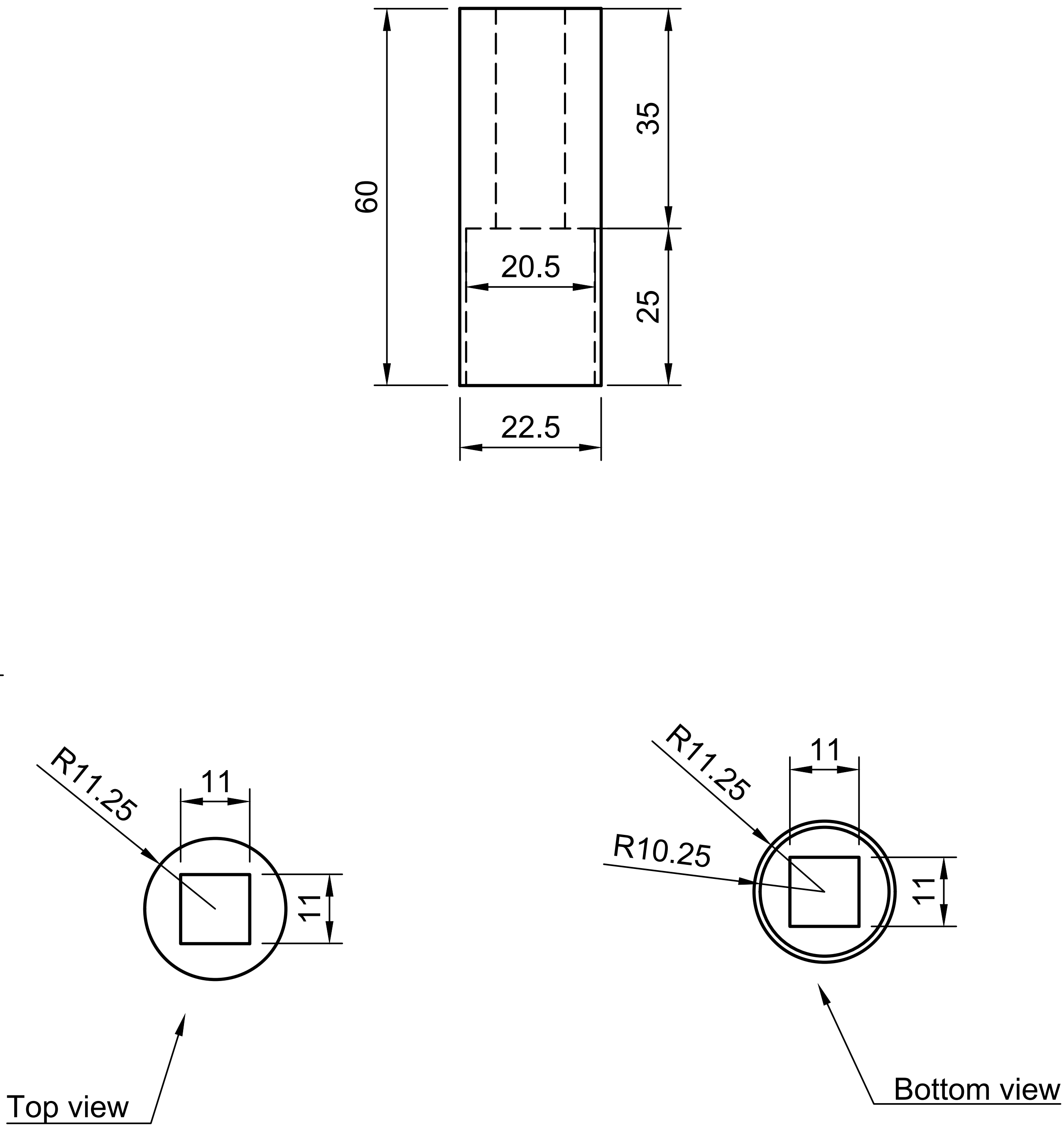


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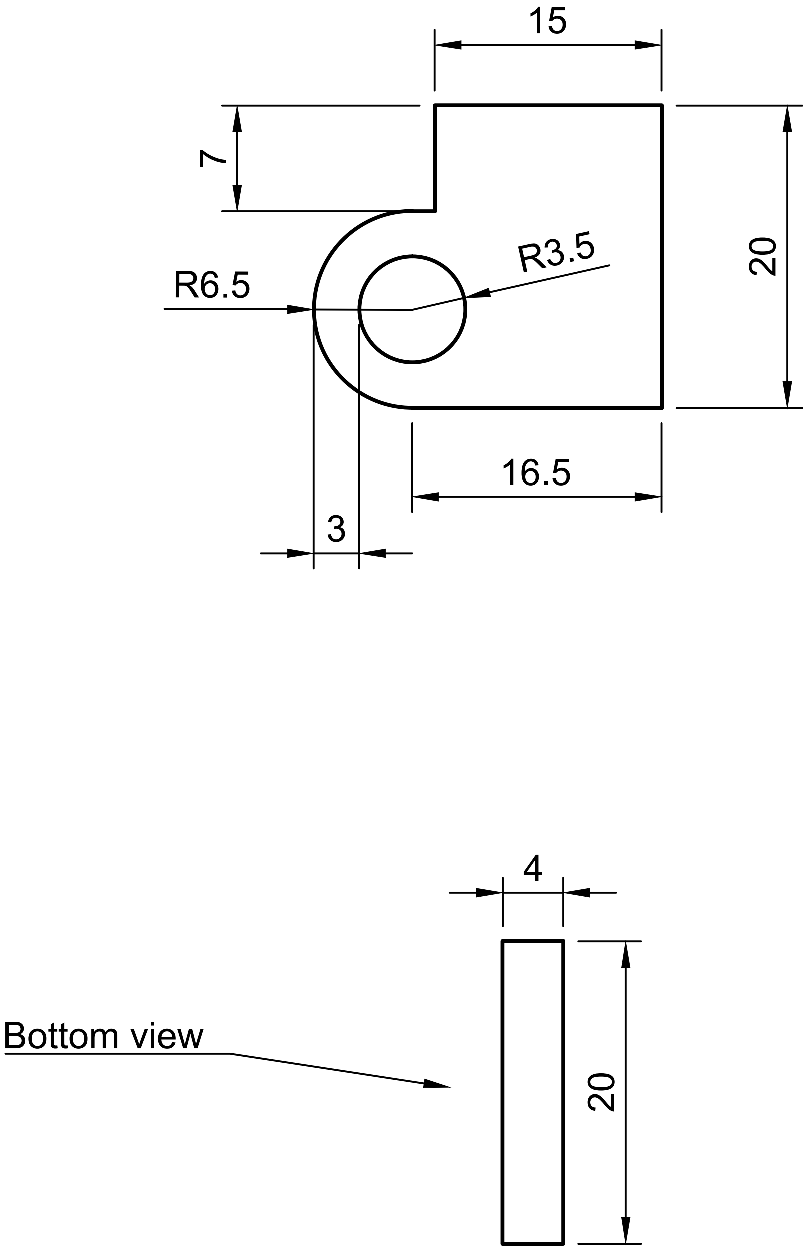


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# Article published

# Hydrogel-Silicone conjunction as epidermal and dermal layers of bio-inspired soft finger skin

Mahmoud Tavakoli[1], João Guilherme Santos[1], João Luis Lourenço[1], Anibal T. de Almeida[1]

***Abstract*— In this article we present an innovative and bio-inspired design of fingers that resembles the physiology of a biological finger. This includes a 3D-printed core to substitute the fingers endoskeleton, a silicon elastomer skin to substitute the elastic and resilient epidermal layer and a hydrogel filling to substitute the dermal layer. The dermal layer in human finger is softer than the epidermal layer and contains a considerable amount of water, and therefore should be protected by the more resilient epidermal layer, that not only protects the underlying layer from mechanical wear, but it also provides a barrier against losing the water. On the other hand, the softer dermal layer helps in better local adaptation of the skin to objects for efficient grasping. The silicone epidermal layer is intended to be elastic, malleable and protects the hydrogel from losing water over the time. The hydrogel filling of the finger is made from sodium polyacrylate and distilled water; the material used as the silicone is Ecoflex 00-30. We successfully implemented a low cost and working prototype of the finger that contains hydrogel, adapts well to different objects, and can be pulled by the integrated tendon. We also show the integration of this finger into a prototype of a soft robotic hand.**

## I. Introduction

One important factor on the quality of the human hand in grasping object is the compliant skin that provides excellent adaptability and contact properties. Human finger, as the most important part of the human hand has always been a source of inspiration. A rigid skeleton, covered by a soft skin provides an excellent combination for grasping actions. The skin itself is composed of a softer, water containing dermal layer, protected by a more resilient epidermal layer, which protects the dermal layer against mechanical wear, and is also a barrier against loosing water (Fig. 1).

Integration of compliance into robotic hands received an increasing attention due to their advantages in providing a better contact condition and a better adaptability to objects, resulting in overall better grasping performance and simplification of the hands as demonstrated in Pisa-IIT hand [1], ISR-Softhand [2], UC-Softhand [3] and SDM hand [4] for prosthetic applications or industrial grasping.

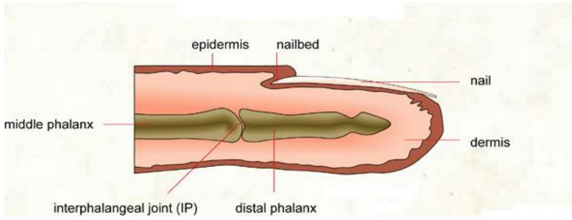



*Figure 1- Longitudinal schematic image of a human finger*

*Figure 2- Previous version of the finger with a 3D printed endoskeleton and a soft skin. Due to the buckling effect the skin required to have a curve profile cut on the joints*

In both cases, the key component of all these hands is their finger design that integrates elastic elements directly into the skin and joints of the fingers. A particular problem in all the previous examples is that islands of soft materials are integrated into a rigid object in contrary to the continuous and uniform soft skin, as it is the case in the human finger. In a previous research [5] we designed and optimized a version of a soft finger composed of a 3D printed endoskeleton and a silicone skin which showed very promising for grasping applications, as shown in Fig. 2. Nevertheless, the silicone skin around the endoskeleton, had to include a curved profile on the joint due to the buckling of the silicone. When the finger is bent, the upper half of the finger skin is stretched, but the lower half is under compression. While silicones have low young´s modulus when stretched, they are not compressible, resulting in buckling of the skin which leads to increasing the required tendon pulling force for flexion of the finger, and therefore larger actuators should be used. To solve this problem, and inspired by the human finger, our new finger embeds a water containing hydrogel that can easily flow inside the more resilient silicone skin, thus providing an excellent analogy with the physiological architecture of the human finger, and also solves the problem of silicone buckling.

[1] Authors are with the Institute of Systems and Robotics of University of Coimbra. mahmoud@isr.uc.pt

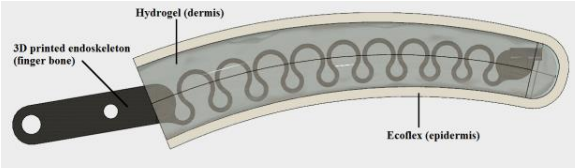



*Figure 3- Longitudinal schematic image of the implemented prototype of the soft finger with a rigid 3D printed endoskeleton, a resilient silicone epidermal layer and a soft hydrogel middle dermal layer*

*Figure 4- 3D Design of finger endoskeleton and the 3D printed part*

In this way the exterior mould of the silicone skin can be formed at arbitrary shapes, making it possible to develop a more anthropomorphic geometry around the endoskeleton. Figure 3 shows the overall finger architecture. The 3D printed endoskeleton was also updated to make it possible to print with the more accessible FDM printers.

## II. Soft Finger

### A. Finger Endoskeleton

The previous version of the endoskeleton [5] used a SLS (Selective Laser Sintering) printer with polyamide material which has excellent flexibility properties. Nevertheless, SLS is not yet as accessible as the Fusion Deposition Modeling (FDM) printers. Therefore, an updated version of endoskeleton was designed which has repetitive circular geometries all over the finger, in contrary to the previous version of the finger which has such structure only on the joint. This geometry then compensates the limited flexibility of the FDM process. The finger endoskeleton is made of acrylonitrile butadiene styrene (ABS) weights in average 5.80 g (Fig. 4). Endoskeleton has nine circular joints with 0.8 mm of thickness. The 0.8 mm was found to be the best trade-off regarding the required tendon pulling force for flexion of the finger, tolerance to the lateral bending and also 3D printing parameters. This was found experimentally among other printed fingers with the thickness of 1, 0.9, 0.8 and 0.7 mm.

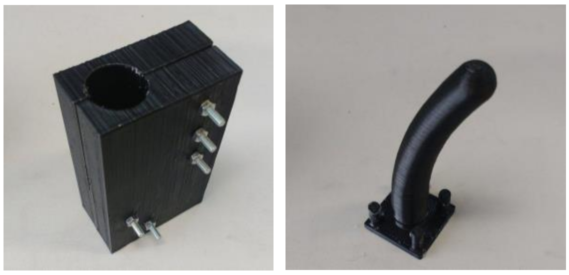
*Table 1- Finger Endoskeleton flexion forces in Newtons*

| **Tested flexions** | **Fingers** | | |
|---|---|---|---|
| | ***Finger #1*** | ***Finger #2*** | ***Finge r#3*** |
| 180º flexion | 7.16 +/- 0.25 | 8.12 +/- 0.29 | 7.50 +/- 0.30 |
| 90º flexion | 3.10 +/- 0.15 | 3.86 +/- 0.30 | 3.94 +/- 0.15 |

The finger width is also decreasing from the joint to the fingertip, for a better tolerance to lateral bending. A string, made of nylon, was inserted along the finger and tied to the fingernail, to work as a tendon to be pulled. The ABS finger was soaked in acetone in order to have a smooth surface finish, shown in Fig. 4. Then, the required forces to bend the endoskeleton finger was tested and studied with an electronic portable dynamometer, as shown in table 1.

### B. Ecoflex

Regarding the epidermal layer of the finger, two molds were printed with respect to the curvy shape of the finger and length, which can be seen in Fig. 5. They are designed in a way to create a 2 mm space between them to thereby create an Ecoflex layer with 2 mm of thickness. The Ecoflex 00-30 is poured inside the main mold, shown in Fig. 5a, and then the shaping mold, shown in Fig. 5b, is placed inside, as shown in Fig. 6. This epidermal layer weights of 9.8 g.



(a) (b)

*Figure 5- Printed molds for the Ecoflex curing: (a) Main mold; (b) Shaping mold*

(a) (b)

*Figure 6- Longitudinal schematic of both molds: (a) 3D design; (b) real picture after curing*

### C. Hydrogel

After the creation of the Ecoflex epidermal layer, Sodium Polyacrylate (SPA) powder is poured manually inside the Ecoflex layer. Then, the finger is inserted in the Ecoflex layer and distilled water is added inside until filled, in order to create the hydrogel as the dermal layer. The reaction of the SPA and distilled water is purely physical, the SPA swells when in contact with water, thus creating the hydrogel, as shown in Fig. 7b.

The hydrogel is an important component for the finger functionality. We experimented a finger with the same geometry fully filled with Ecoflex. Such finger could not perform a full flexion and with a 22(*N*) pulling force could do only a half flexion as can be seen in Fig. 8b. In comparison, the finger filled with Hydrogel could perform a full bend with less than 10(*N*) of force (Fig. 8a and Table 3).

Other option is to use an empty space in the epidermal layer, but also that doesn't work because, when the finger is bended, the Ecoflex layer wrinkles which affects the contact between the object and the Ecoflex skin (Fig. 8c). Therefore, hydrogel is probably the best option as the dermal layer of the soft finger, giving strength, support and flexibility in the movements and grasping actions.

(a) (b)

*Figure 7- (a) Image of SPA in its pure form; (b) Image of hydrogel created by combining SPA and distilled water*

*(a) (b) (c)*

*Figure 8- Full flexion of the soft finger: (a) Finger filled with hydrogel; (b) Finger fully cured with Ecoflex (22(N) was required to make the half flexion) (c) Finger with empty space between the endoskeleton and Ecoflex layer (8(N) was required to do this flexion)*

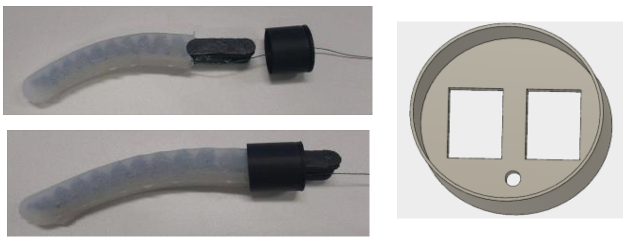


*Figure 9- Little mold printed for final enclosure*

*Table 2- Soft Fingers weight in grams with an error of 0.01*

| | ***Day 1*** | ***Day 3*** | ***Day 8*** | ***Day 10*** |
|---|---|---|---|---|
| Finger #1 | 29.18 | 28.78 | 28.56 | 28.32 |
| Finger #2 | 28.80 | 28.48 | 27.90 | 27.48 |
| Finger #3 | 28.50 | 28.20 | 27.90 | 27.40 |

*Table 3- Soft Finger flexion forces in Newtons*

| **Tested flexions** | **Fingers** | | |
|---|---|---|---|
| | ***Finger #1*** | ***Finger #2*** | ***Finge r#3*** |
| 180º flexion | 9.87 +/- 0.64 | 9.81 +/- 0.98 | 9.80 +/- 1.00 |
| 90º flexion | 5.53 +/- 0.57 | 6.16 +/- 0.30 | 5.26 +/- 0.29 |

### D. Final Assemble

To do the final enclosure, a small mold was printed, with a very thin perimeter, and attached to the finger, as shown in Fig. 9. More Ecoflex is poured inside this little mold with a syringe, and after the curing, the cylindrical wall part is carefully removed with a scissors, so as not to rip the Ecoflex.

One associated problem with hydrogels is that they lose water over time. However, the Ecoflex epidermal layer should act as a barrier against losing of water. To verify this, fingers were weighted during 10 days. As can be seen in table 2, the fingers lose less than 3% of weight after 10 days.

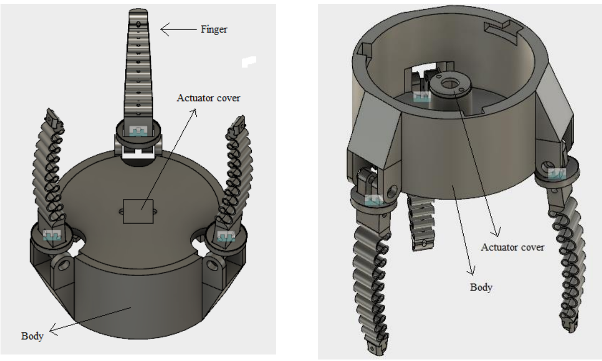
The required force to bend the soft finger was also analyzed, as shown in table 3. Compared to the finger with only endoskeleton that required around 7.5(*N*) for a full flexion, the finger with the Ecoflex and hydrogel layers requires less than 10(*N*), which is around 25% more than the endoskeleton alone. This is significant compared to the full Ecoflex skin that requires 22(*N*) and could not even perform a full closure.

## III. INTEGRATION OF AN UNDER-ACTUATED GRIPPER

In order to test the grasping quality of the soft fingers, a low cost under-actuated gripper was designed, with a mechanism based on the idea of the push base toys, and printed on a FDM printer with polylactic acid (PLA) material. The gripper is composed by a body, where the fingers are attached, as shown in Fig. 10, and is derived with a single actuator that is a dual-shaft micro metal gear motor (Pololu) inside and two covers, to hold the motor inside.

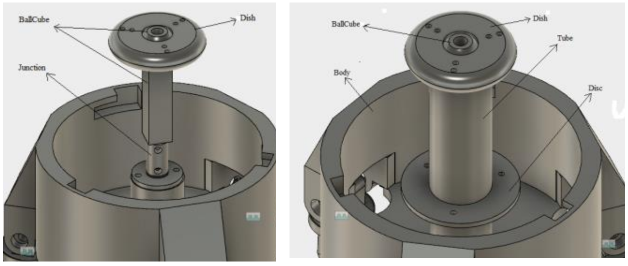
Attached to the motor is a junction to connect it to a threaded shaft, which is inside a piece that we called "BallCube". Around the ball on top is a dish, as shown in Fig. 11a, and this is where the tendons are tied. The squared part of the "BallCube" and also the junction are inside a tube, half squared and half circular, as shown in Fig. 11b. The BallCube slides inside the tube toward up or down directions, making the fingers, respectively, close or open. There is also a disc around the tube in order to align the strings with the dish.

The total weight of the gripper, with the soft fingers integrated, is 285g.




(a) (b)

*Figure 10- 3d design of the first assemble of the under actuated gripper: (a) Top view; (b) Bottom view*




(a) (b)

*Figure 11- Bottom view of the 3D design of the under actuated gripper: (a) second assemble, (b) third assemble*

## IV. Grasping Tests

Some grasping tests, with different objects, were made with this under-actuated gripper, shown in Fig. 12. As can be seen the light-weight and simple under-actuated soft gripper adapts very well to different objects and is able to perform stable grasps on objects with various shapes.

## V. Conclusion

In this article we presented design and implementation of a novel bio-inspired soft finger design that resembles the human fingers physiology, with a rigid endoskeleton, a water containing hydrogel to resemble the dermal layer and a resilient and stretchable Ecoflex layer that resembles the epidermal layer and acts as a barrier to lose of water in the hydrogel. We showed that the finger preserves their water content during several days, and the implemented finger increases the pulling force only around 25%. Finally, we implemented a grasping mechanism with a single actuator and showed grasping of several objects with different geometries with this system. The final prototype weights 285g., and the actuator weights only 10g. Yet, the mechanical structure of the gripper and the geometry of the finger can be further optimized which is among future works.

## Acknowledgment

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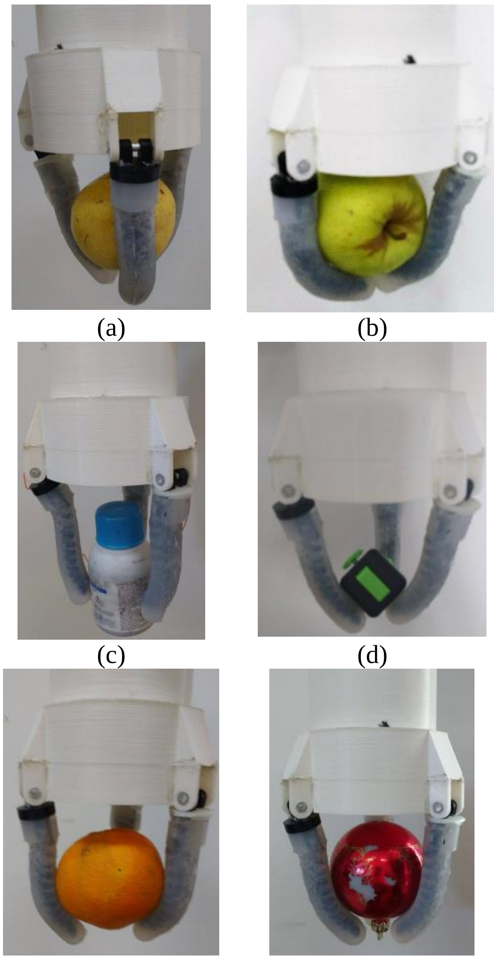

(a) (b) (c) (d) (e) (f)

*Figure 12- Grasping tests with some objects: (a) Peach with 147,56g; (b) Apple with 151,92g; (c) Ink flask with 126,26g; (d) Cube with 35,62g; (e) Orange with 140,24g; (f) Ball with 14,46g.*

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# Experimental Data

| | Finger #1 | Finger #2 | Finger #3 | Finger #4 | Finger #5 | Finger #6 | Finger #7 | Finger #8 | Finger #9 | Finger #10 | Finger #11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 180° Flexion | 8,92 | 7,75 | 6,86 | 7,45 | 6,37 | 5,30 | 6,57 | 6,77 | 7,65 | 7,45 | 6,67 |
| | 9,71 | 6,18 | 6,47 | 6,37 | 6,96 | 5,59 | 6,67 | 6,18 | 7,45 | 7,16 | 6,96 |
| | 8,43 | 7,26 | 6,96 | 6,57 | 5,69 | 5,69 | 6,57 | 6,96 | 7,55 | 7,75 | 7,16 |
| | 7,26 | 6,28 | 6,47 | 6,47 | 7,06 | 6,37 | 6,67 | 6,57 | 7,65 | 7,26 | 7,45 |
| | 6,28 | 5,79 | 6,08 | 6,57 | 7,06 | 5,98 | 6,67 | 6,67 | 7,75 | 7,26 | 7,06 |
| | 7,45 | 6,77 | 7,26 | 6,47 | 7,55 | 7,06 | 7,16 | 6,57 | 7,55 | 7,85 | 7,16 |
| Average: | 8,04 | 6,67 | 6,67 | 6,67 | 6,77 | 5,98 | 6,77 | 6,67 | 7,65 | 7,45 | 7,06 |
| | | | | | | | | | | | |
| 90° Flexion | 2,75 | 2,35 | 1,77 | 2,16 | 2,45 | 2,45 | 2,26 | 3,33 | 2,65 | 3,53 | 2,75 |
| | 0,98 | 2,35 | 1,96 | 2,16 | 2,06 | 2,26 | 2,45 | 2,94 | 3,24 | 3,53 | 3,33 |
| | 2,94 | 2,35 | 1,57 | 2,16 | 2,35 | 2,16 | 2,26 | 2,75 | 3,33 | 3,43 | 2,94 |
| | 2,35 | 2,55 | 1,77 | 2,16 | 2,06 | 2,26 | 2,55 | 2,45 | 3,04 | 3,14 | 2,55 |
| | 2,35 | 2,06 | 1,96 | 2,16 | 1,96 | 2,65 | 2,75 | 2,94 | 2,65 | 2,94 | 2,94 |
| | 2,26 | 2,35 | 2,06 | 2,06 | 1,86 | 2,35 | 2,55 | 2,75 | 2,75 | 2,94 | 2,94 |
| Average: | 2,26 | 2,35 | 1,86 | 2,16 | 2,16 | 2,35 | 2,45 | 2,84 | 2,94 | 3,24 | 2,94 |

**Table 3:** Force required, in *Newton* to do a flexion with the endoskeleton fingers.

| | Finger #1 | Finger #2 | Finger #3 | Finger #4 | Finger #5 | Finger #6 | Finger #7 | Finger #8 | Finger #9 | Finger #10 | Finger #11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 180º Flexion | 10,10 | 11,38 | 12,16 | 13,83 | 8,34 | 10,84 | - | 9,61 | 9,81 | 11,47 | 12,94 |
| | 10,79 | 11,47 | 13,04 | 14,22 | 7,85 | 10,80 | - | 9,71 | 10,49 | 10,89 | 11,57 |
| | 9,81 | 11,57 | 12,06 | 12,75 | 8,34 | 10,78 | - | 10,79 | 10,30 | 10,89 | 11,08 |
| | 9,71 | 11,08 | 12,55 | 13,44 | 7,75 | 10,70 | - | 10,79 | 10,40 | 10,40 | 10,79 |
| | 10,00 | 11,18 | 13,24 | 14,02 | 7,35 | 10,72 | - | 9,51 | 9,61 | 10,30 | 10,79 |
| | 9,02 | 11,08 | 12,85 | 14,51 | 6,86 | 10,67 | - | 10,40 | 10,00 | 10,89 | 10,20 |
| Average: | 9,90 | 11,28 | 12,65 | 13,83 | 7,75 | 10,75 | - | 10,10 | 10,10 | 10,79 | 11,28 |
| | | | | | | | | | | | |
| 90º Flexion | 4,41 | 4,31 | 5,10 | 6,18 | 3,33 | 10,26 | - | 4,41 | 5,69 | 5,39 | 5,69 |
| | 4,22 | 3,82 | 4,81 | 5,69 | 3,63 | 10,25 | - | 4,22 | 4,71 | 5,49 | 5,20 |
| | 4,31 | 4,02 | 4,31 | 5,30 | 3,43 | 10,22 | - | 4,41 | 4,51 | 5,59 | 3,92 |
| | 4,41 | 3,82 | 4,22 | 6,18 | 3,63 | 10,22 | - | 3,82 | 5,79 | 5,10 | 5,59 |
| | 4,31 | 4,12 | 4,31 | 6,47 | 3,33 | 10,24 | - | 4,81 | 5,30 | 5,20 | 5,49 |
| | 4,22 | 4,22 | 4,22 | 5,69 | 3,82 | 10,21 | - | 4,12 | 5,59 | 5,39 | 5,39 |
| Average: | 4,31 | 4,02 | 4,51 | 5,88 | 3,53 | 10,23 | - | 4,31 | 5,30 | 5,39 | 5,20 |

**Table 4:** Force required, in *Newton*, to do a flexion with the experimental soft fingers (Finger #7 broke).

| | 7 mm | 8 mm | 9 mm |
|---|---|---|---|
| 180º flexion | 8,34 | 7,65 | 14,71 |
| | 8,24 | 7,75 | 15,20 |
| | 9,02 | 8,24 | 16,28 |
| | 8,43 | 7,85 | 15,98 |
| | 8,53 | 7,94 | 16,28 |
| 90º flexion | 2,84 | 3,14 | 4,90 |
| | 2,06 | 2,84 | 4,71 |
| | 2,35 | 3,04 | 4,81 |
| | 2,65 | 2,94 | 4,61 |
| | 2,45 | 2,75 | 4,41 |
| 45º lateral flexion | 0,69 | 1,08 | 2,84 |
| | 0,69 | 0,69 | 3,43 |
| | 0,59 | 0,88 | 3,33 |
| | 0,69 | 1,18 | 2,84 |
| | 0,69 | 0,98 | 2,65 |

**Table 5:** Force required, in *Newton*, to do a flexion with endoskeleton fingers with different thickness.