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SOFT ROBOTIC HAND PROSTHESIS USING REVERSE ENGINEERING AND FAST PROTOTYPING

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ABSTRACT

The present work aimed to develop a soft robotic prosthesis of the human hand using reverse engineering and fast prototyping. This project arises in response to some limitations of the current conventional prostheses, namely aesthetic, mechanical and cost, that fail to fulfil the needs of its users, for example with soft objects. The hand prosthesis design involved the acquisition and processing of a medical image of the user's hand, followed by a modelling process which proved to be highly complex, and finally the obtainment of a real model (by 3D printing) of the prosthesis. The results obtained proved to be satisfactory in the approximation of the hand morphology, low cost and the designed mechanical properties. However, due to some technological limitations (the used 3D printers), and more specifically in the physical conception of the model, its functionality is yet to be proved with the pneumatic control.

Keywords: Soft robotics, reverse engineering, fast prototyping, hand prosthesis.

INTRODUCTION

The human hand can be considered the most used tool by the man in the execution of the daily tasks, and its loss leads to physical and psychological damages. The psychological consequences come not only from the diminution of the motor ability, but also from the cosmetic and social impact that the amputation has on the individual [1]. Regardless of the cause of the absence of a limb (congenital malformation, surgical or accidental amputation), the main way to overcome adjacent difficulties is the use of prostheses [2, 3]. Despite this fact, a considerable percentage of the upper limb amputees do not use a prosthesis regularly, since they do not completely satisfy their needs and desires [1]. After literature review it is possible to determine the main characteristics that the users prioritize in a prosthesis, being these the comfort, appearance, functionality, durability and cost [4].

Although prosthetics have been part of human history for thousands of years, being the earliest records from 2500 BC in Egypt, it have always been very rudimentary and poorly developed at the functional level [5]. Nowadays, the devices are composed of light and functional materials, molded to the patient and with a natural appearance [8]. The advancement of microprocessors, computer chips and robotics lead to the possibility of the amputee returning to his lifestyle. However, while we seek prostheses with more developed technology, which allow to satisfy multiple patients requirements, we also find higher prices [4].

In addition to the importance given to the development of prostheses, it is necessary to understand that for the successful adaptation of the patient to the new artificial limb, elaborate

evaluations on the stump and the method of aggregation of the prosthesis are necessary [9]. The most common method of prosthetic fixation it's by suspension, that requires the usage of a costume made sock. To avoid the process of adjusting the sock to the stump, which can be stressful and exhaustive to an already traumatized patient, emergent technologies have been applied in the design of these component, from which the use of inverse engineering, finite elements and rapid prototyping are highlighted [10, 11]. Although the use of these emerging technologies were first applied to the design of the sock, nowadays they allow the customization of the prostheses in a profitable way, in which the main difference arises at the beginning, where the collection of the form is not the stump but the member of interest [12, 13].

The application of this knowledge can be generalized in 5 steps, carried out throughout the present project: 1 - image acquisition techniques, with the use of medical image technology or 3D scans; 2 - digital processing, with the use of software's such as 3D Slicer[®]; 3 - import to the CAD platform and modelling, using a software like SolidWorks[®]; 4 - static and dynamic mechanical analysis (using finite elements) using software's such as SIMULIA Abaqus[®]; 5 - after iterations of the two previous steps, to obtain the final product, the STL file is exported for fast prototyping using 3D printers. Then, with the techniques applied in soft robotics, it is possible the design and to control the soft prosthesis that responds to the soft needs of the user.

Soft robots are the product of robotics inspired in biology that have the potential to address some of the inconveniences of conventional robotics. They are machines composed essentially of flexible materials that allow high continuous deformations, with high radius of curvature that result in a high complacency during interaction with the medium or the object [14, 16]. Due to their composition they can be lighter, economical and have a good power-to-weight ratio [17]. Thus, during the rapid prototyping step, the model is imprinted with soft materials, which exhibit mechanical behaviour like those observed in biology.

Among the several actuation techniques of soft robotics, it is proposed to use Fluid Elastomer Actuator (FEA), more specifically Soft Pneumatic Actuators (SPAs), which through air pressurization perform movement [17]. The choice was limited by the fast acting, low viscosity, ease of control, market availability, lightness and non-polluting characteristics of the air [18]. Within the types of SPAs, the PneuNet Actuators (PNAs), are the ones of greater interest for the present study, due to its simplicity and customizability. The PNAs are composed of a network of multiple chambers that, when pressurized, interact with one another inducing movement [18, 19]. The trajectory of the movement is influenced by the structural and dimensional characteristics of the actuator. Even within the PNAs, these can have a slow reaction, slow PneuNet Actuators (sPNAs) or fast, fast PneuNet Actuators (fPNAs) [18]. The fPNAs are composed of an extensible upper layer and an inextensible lower layer and, in contrast to the sPNAs, have partially separated chambers, lower thickness and larger area in the inner walls of the chambers. This leads to easier deformation, faster performance and greater energy efficiency [18, 20], which took to its use in this project.

Considering the limitations of current conventional prostheses and the needs of the users, an alternative hand prosthesis is presented in this paper. For the successful development of the present prosthesis, some conditions have been imposed which it has to fulfil, such as certain mechanical properties (lightness, high strength and behaviour), pneumatically controlled like soft robotics systems and an appearance that resemble the human hand, always considering the economic point of view.

This paper is organized as follow: section 2 presents the reverse engineering process of the hand prosthesis. Section 3 presents the actuator models used in this work. In section 4 are shown some simulation and prototyping results. Finally, section 5 presents the conclusions and topics for future work.

REVERSE ENGINEERING PROCESS

The design of the prosthesis was carried out over several steps, with the goal of achieving a functional and aesthetically appealing prosthesis. After the study of the different actuators used in soft robotics and concluding which the most appropriate to fill the needs in the prosthesis to be developed, the practical part of this work lead off. For this, it was used reverse engineering methodologies with the aim of bringing the device closer, as much as possible, to the hand morphology.

Through an imaging examination, computed tomography, it was possible to obtain the necessary information at the image level, of the right hand. These data were later treated in the software 3D Slicer®, where two anatomical models were created, skeletal model (Figure 1-a) and total volume model of the hand (Figure 1-b). Through the first model, the metacarpophalangeal joints can be located, which correspond to the initial flexion point of the actuators and, using the second model, can be obtained the general dimensions that the actuator will have to comply with.

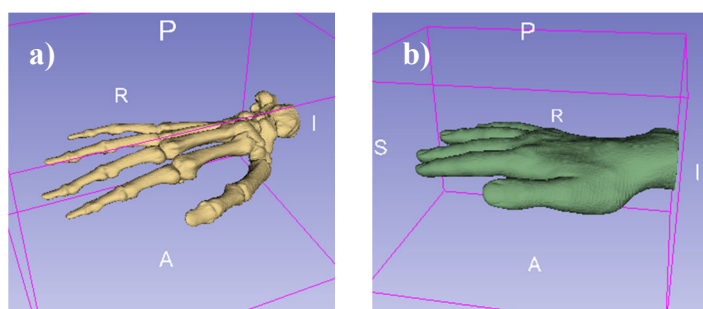


Fig. 1 - Anatomic models: (a) skeletal; (b) hand.

With the two volumes of interest isolated, it was possible to import them into SolidWorks® software, for manipulation and modelling of the actuators (fingers). This complex modelling task involves the isolation of the interest zones for each actuator and the hand palm (Figure 2), correction of the hand natural posture, definition of the actions necessary to each actuator to resemble, as much as possible, the movement of the human hand, and, iteratively between modelling and simulations, a structure that meets all the requirements of the user is reached.

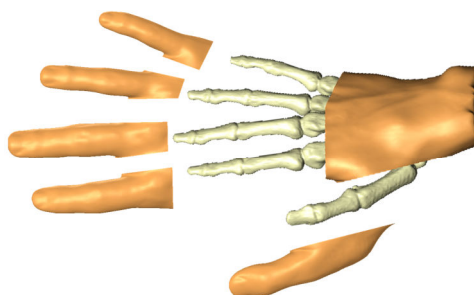


Fig. 2 - Isolation of interest zones.

Prior to the iterated simulations, studies were carried out on possible manufacturing materials and processes capable of satisfying the stipulated requirements. The two materials that stood out in the bibliography and were also available in the market, were Elastosil® M4601 and NinjaFlex®, which correspond respectively to the processes of manufacturing molding and 3D printing [12, 18, 21, 24].

Elastosil® is a liquid silicone rubber which, when cured, shows high flexibility, tensile strength and high life time [25]. On the other hand, NinjaFlex® is formulated from a polyurethane thermoplastic and is marketed as a flexible, printable filament, and it stands out for its high flexibility properties, chemical and mechanical abrasion resistance [26]. After material selection and obtaining satisfactory results in the simulations, it was manufactured the prototypes through 3D printing and carried out its experimental validation.

In the molding conception of Elastosil® model, the 3D printing of the molds was made with Poly-Lactic Acid (PLA), in a commercial 3D printer, BEETHEFIRST®, of the company BEEVERYCREATIVE® [27]. Although this printer and material had the main goal of printing the molds, it ended up being used in the manufacture of other essential components to produce the prosthesis, as displayed in Figure 3-a).

In NinjaFlex® model, the Rapid Prototyping was executed by a 3D Prusa+Mendel90 RepRap® 3D printer, with an MKII (Makerbot open source version) and a 20x20 cm² heated plate, that can be seen in Figure 3-b) [28].

The printing parameters for the design of NinjaFlex® models were temperatures of 250 °C for the hot tip and 80 °C for the plate, in all layers, print speed of 30 mm/s, retraction from 6 mm to 20 mm /s and a fill of 20 %. It was also resorted to direct ventilation to help the material cool down and thus improve the print quality, and specialized extruder obtained in the open platform, Thingiverse [29].

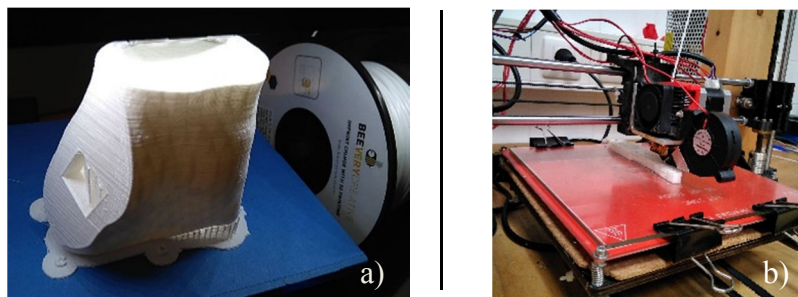


Fig. - 3D Printer's: (a) BEETHEFIRST® printing the palm; (b) RepRap® printing the actuator.

ACTUATOR MODELS

From the five fingers of the human hand, it is possible to distinguish those in which movements may be limited to simplify the models, yet to perform the necessary functions and meet the expectations of the user. To achieve this main idea, it was considered that only the thumb would execute flexion and rotation, while the other fingers would only perform flexion. Considering this, through iterations between modelling and simulation, it was achieved 3 different designs. Two of them correspond to fingers from two to five (index, middle, ring and little fingers), and the third model to the thumb.

When developing the idea of fusing the fPNA with the index finger, it was created a ground model that, despite being almost a direct application of the classical one, due to its specific shape it varies the thickness and highness of the internal walls, along its length. This change was performed after the iterated simulations prove irregularities in the flexion movement.

With the application of two different materials to the ground model, NinjaFlex® and Elastosil®, it was possible to determine each one's limitations and so develop two refined and final designs. In the simulation with NinjaFlex® material, the ground model demonstrated low flexibility and high tensions in between cameras, more specifically in the lateral sides of its base and, in the simulation with Elastosil®, the ground model proved to be highly deformable at low tensions.

Regarding the NinjaFlex® model (final design 1), to correct the problems encountered in the ground model, the sidewalls of the base, located between the inner walls of the actuator, were removed, finishing with that can be seen in Figure 4.

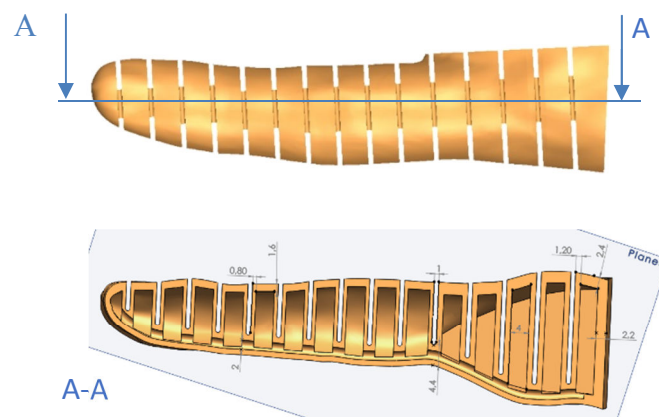


Fig. 4 - NinjaFlex Model.

Referent to Elastosil® model (Final design 2), it was determined that the cuts throughout the model, would be concentrated only in the zones of the finger joints, leading not only to a complete flexion of the actuator, but also to an approximate behaviour to the real finger. As it can be seen in the Figure 5, this model presents nine chambers and the contact walls arise only in the zones of the interphalangeal and metacarpophalangeal joints. In the zones of the interphalangeal joints three cuts were stipulated, and in the metacarpophalangeal two cuts. Finally, it should be noted that, in order to avoid excessive deformations in the actuator, the external walls were modelled with different thicknesses, that is, in the larger chambers that arise in the proximal and middle phalangeal zones, an upper thickness was stipulated to the smaller ones, as shown in Figure 5.

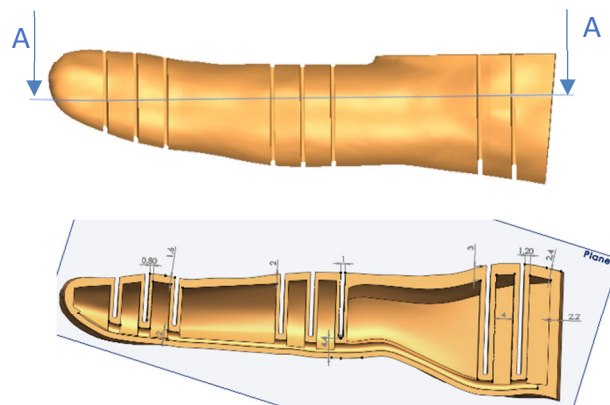


Fig. 5 - Elastosil Model.

With these two models completed and after verification of their results in the simulations, as it can be seen in the ‘Tests and Results’ section, the previously presented manufacturing techniques were put into practice.

For the Elastosil[®] model and as reviewed in the literature, the design of the actuators undergoes a molding process in which the molds are generally fabricated by 3D printing. After this production, it has been found that this is a rather complex process, not having the desired results.

In parallel, 3D printing of the NinjaFlex[®] model was performed and was able to meet the stipulated results. For this reason, NinjaFlex[®] was the material chosen to produce the remaining fingers.

The design created for the index finger has been reproduced for the remaining actuators except, as previously said, for the thumb, which will be explained next. The design of the thumb was modelled with the purpose of moving in different directions. For this, two planes were created, one in the metacarpal zone that induces the rotation movement, and another in the phalangeal zones that induces the flexion (as it can be seen in Figure 6).

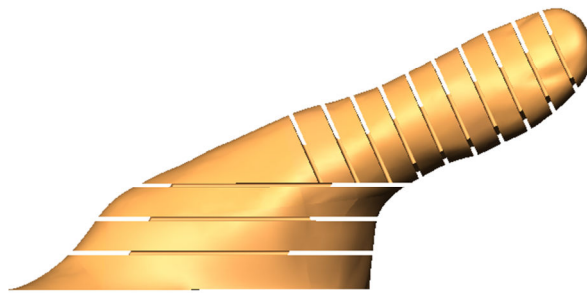


Fig. 6 - Thumb, NinjaFlex Model.

After concluding the actuators, it was found the necessity of a structural fixing method between them and the palm of the hand. In the search for a simple method to make this coupling, a fixing part has been developed at the beginning of the actuator. As can be seen in Figure 7-c), this part presents, besides small dents in its exterior to fasten the models, an air chamber that revolves the whole profile, in order to allow the best accommodation of both pieces. It is also possible to check a custom built-in space for quick connect coupling (Figure 7-d) for the connection between the air supply pipe and the actuator.

In the modelling of these parts, it was considered that the dents would appear in the planes of greater solicitation, that for the actuators from 2 to 4 these would be located in the superior and inferior walls, due to the movement of flexion, and in the thumb these would be distributed in all the faces, due to the combined movements of flexion and rotation.

The palm of the hand was possible to be performed after the end of the actuators (set of the finger part plus fixation part). This piece, not having any definite compulsory movement, was designed for a rigid material and therefore, for its production was used 3D BEETHEFIRST[®] printer and PLA filament. As shown in Figure 7-a), this component is hollow to allow passage of the air tubes and reduce its weight, and it's also possible to verify that at its ends, there are specific zones for the fixation of the actuators.

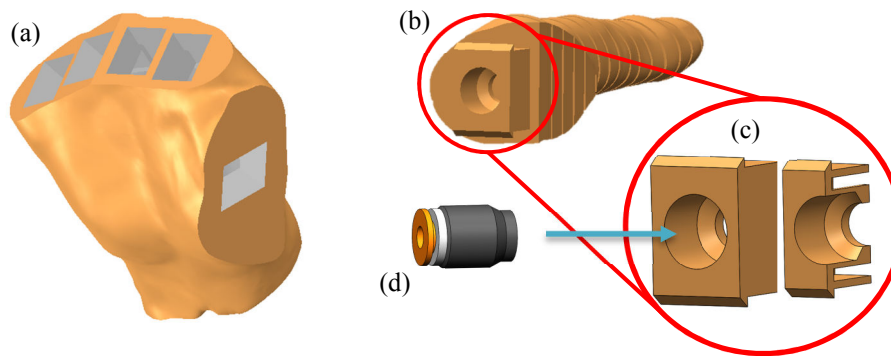


Fig. 7 - (a) Palm; (b) Index actuator; (c) Detailed view of the fixing part; (d) Quick connect coupling.

TESTS AND RESULTS

In the development of the actuators, several simulations were carried out to obtain models capable of satisfying the needs of the user. For this, it was necessary to use the finite element method, that can be executed in CAE software, such as SolidWorks® and SIMULIA Abaqus®.

Since the actuator is made up of a hyperelastic material, which, when in operation, performs high deformations, it is mandatory to use non-linear simulations to obtain accurate results. To carry out a simulation it is necessary its parameterization and this involves the creation of a mesh, characterization of the material and stipulation of the loads, constraints and contact interactions.

For this particular case, it was stipulated a tetrahedric mesh element, characterized the material according to hyperelastic models, stipulation of internal pressures in all of the interiors faces, a fixed geometry in the first face of the actuator and non-penetration condition between the exterior walls of the actuator (Figure 8).

Due to the complexity of contact interactions in non-linear analyses, this simulation has proven to be out of the capabilities of SolidWorks® software. For this reason, it was necessary to use a software with a more robust contact calculation capability, such as SIMULIA Abaqus®.

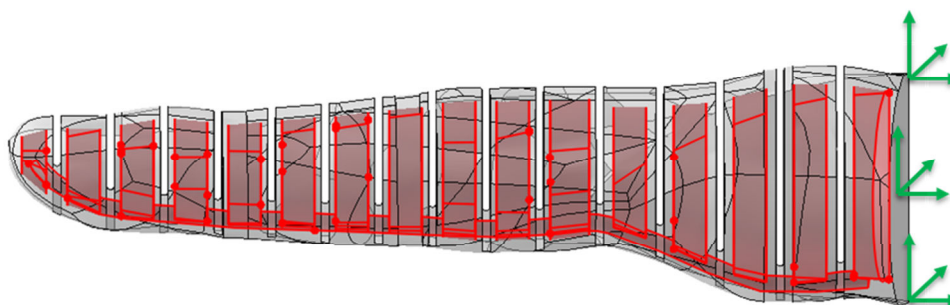


Fig. 8 - Simulation of NinjaFlex® model (red - internal walls; Green - inlay zone).

In the NinjaFlex® model simulation, it was used the hyperelastic model of Ogden that, according to the bibliographic review, is the one that presents greater accuracy of results among the several characterizing models of this material. The mechanical properties of the NinjaFlex® material, with the Ogden's parameters, applied in the simulation, can be visualized in the Table 1 [22, 26].

Table 1 - Mechanical properties of NinjaFlex® [22, 26].

| Properties | | Value | Units |
|--------------------|------------|---------|-------------------|
| Ogden's Parameters | μ_1 | -30.921 | N/mm ² |
| | α_1 | 0.508 | - |
| | μ_2 | 10.342 | N/mm ² |
| | α_2 | 1.375 | - |
| | μ_3 | 26.7911 | N/mm ² |
| | α_3 | -0.644 | - |
| Density | | 1190 | kg/m ³ |
| Tensile Strength | | 4 | N/mm ² |

To realize the pressure control that will have to be done for different grip levels of the hand and to determine the pressure value from which the actuator can perform a full flexion, it was necessary to perform successive simulations in which the pressure was gradually increased (as shown in Figure 9), reaching a final value of about 60 kPa.

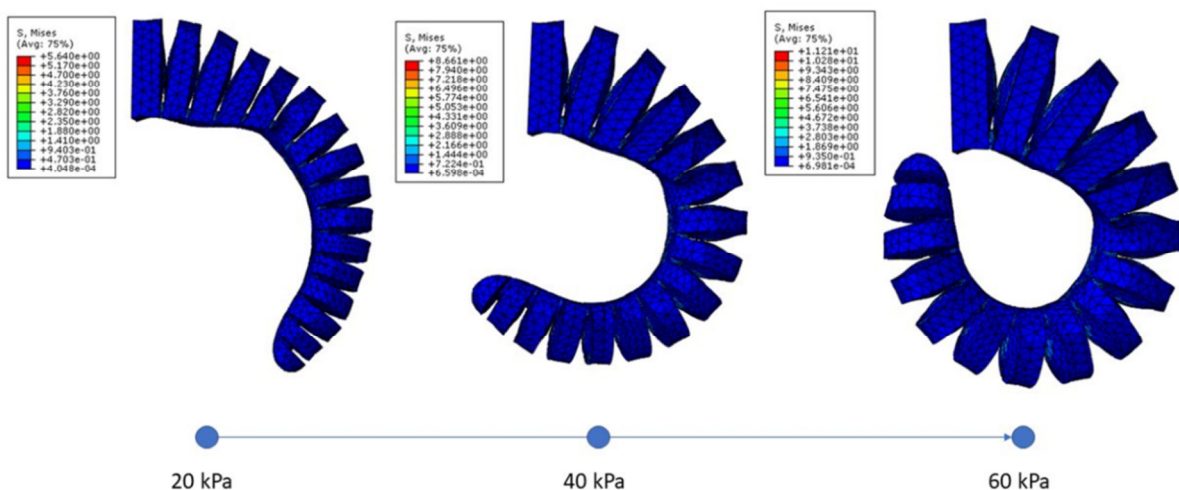


Fig. 8 - Simulation result of the NinjaFlex® model with different pressures.

The results, shown in Figure 10, are the deformation along the actuator when exposed to a pressure of 60 kPa, according to the Von Mises criterion. The different stresses at each point of the actuator can be easily identified by the colour scale shown. By making a more detailed analysis of the obtained values, it can be verified that the maximum tension pointed is of 11,21 MPa. With this and considering that the desired maximum tension limit is 4 MPa, the design of this model could have been rejected. However, in attempting to recognize this value and analysing in detail the zone indicated by the software (detail of Figure 10), the zone with this concentration of tensions didn't match with the expected, because of its location and the tensions around it. In addition to this point analysis, it was also possible to verify that the whole model presents values of tensions below the admitted. This fact led us to consider the value indicated as a numerical error and thus to validate the model.

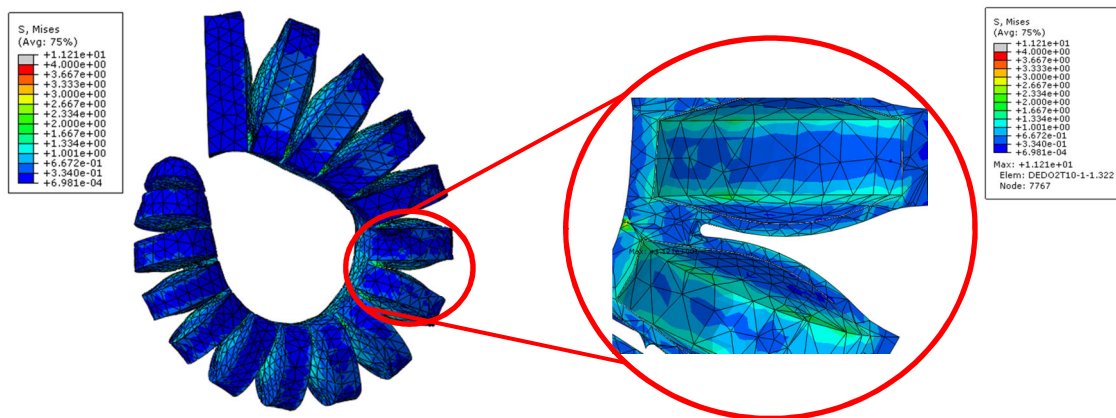


Fig. 10 - Simulation result of the NinjaFlex® model.

In the simulation of the Elastosil® model, it was used the hyperelastic model of Yeoh that, it's used in the bibliography to characterize this material [23, 30, 31]. The mechanical properties of the Elastosil® material, with the Yeoh's parameters applied in the simulation, can be found in the Table 2.

Table 2 - Mechanical properties of Elastosil® [23, 30, 31].

| Properties | | Value | Units |
|-------------------|-----------------|-------|-------------------|
| Yeoh's Parameters | C ₁₀ | 0.11 | N/mm ² |
| | C ₀₁ | 0.02 | N/mm ² |
| Density | | 1130 | kg/m ³ |
| Tensile Strength | | 6.5 | N/mm ² |

Just like in the previous model, in order to determine the pressure value from which the actuator performs a full flexion, it was necessary to perform successive simulations in which the pressure was gradually increased, reaching a final value of about 20 kPa, as shown in Figure 11. These results are the deformation along the actuator when exposed to a pressure of 20 kPa, according to the Von Mises criterion. Again, the different stresses at each point of the actuator can be easily identified by the colour scale shown.

Regarding the results of the Elastosil® model, it can be verified that the obtained deformation is very similar to the flexion of the index finger. Thus, in addition to achieving a natural appearance, it allows a more closed movement, representing an advantage in the action of grasping smaller objects. Since this deformation occurs with low tension values, it does not present fatigue, which would have resulted in a long useful life. Despite all these advantages and as previously mentioned, this model was aborted due to problems related to the manufacture complexity using molds.

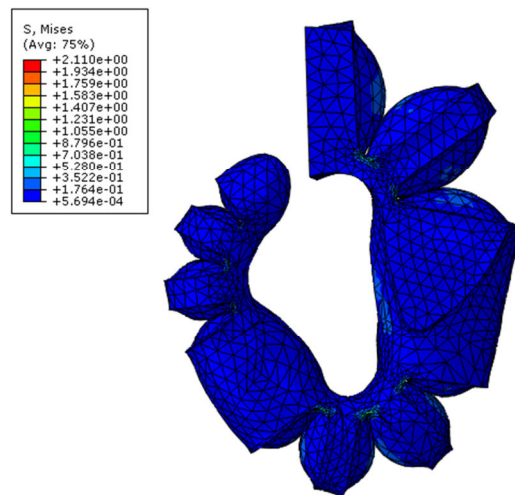


Fig. 11 - Results of the simulation of the Elastosil® model.

As explained in the previous sections, and after completing the iterative processes of modelling and simulation, the 3D printing of the final actuators and the hand palm have been done. The 3D printing process presented some difficulties, namely the choice of the fingers printing position, the adaptation/adjustments of the printer correct components and parameters associated with the material NinjaFlex®. When defining the printing position, which ideally starts in a flat base, parallel to the printing plane, it was inferred that the only flat face that fulfilled these requirements was the fastener face, being that the rest of the finger presented an irregular and unique shape. However, the use of this face as a basis for printing results in several problems of structural support during the process. These problems arise in the contact walls, which in this printing position, are parallel to the construction plane and have a large area with insufficient support. The 3D printing made in this way would lead to the need to create structural support inside the cams and would increase the defects in the final product, which would compromise its mechanical behaviour.

To avoid all these problems, the actuator was printed horizontally, with the walls perpendicular to the manufacturing plane. This led to the need to create a structural support at the base of the actuator so that the printer would be able to track the irregularity of the finger. While this process has brought improvements to the printing process, it is not free of defects. Due to the flexibility of the material and the temperatures used in the process, a small percentage of the base fuses with the actuator, being necessary to remove it manually, compromising the final aesthetic aspect of the same, as shown in Figure 12-a,b.



Fig. 12 - Printed index actuator a) upper side; b) bottom side.

In the hand palm printing as the material is rigid and contained several flat faces, its manufacture did not reveal adversities, and it's result corresponded to the expected, as can be seen in the Figure 13.

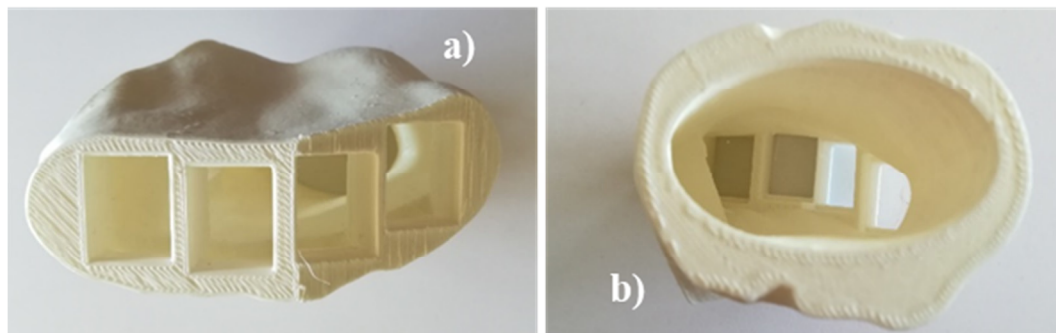


Fig. 13 - 3D printed palm: a) top view; b) bottom view.

Finally, with all the actuators printed, as well as the hand palm, it all could be assembled as shown in Figure 14. Due to all the work previously described, it was possible to obtain a final prototype that is similar to the original hand.



Fig. 14 - Hand prosthesis assembled, next to the original hand and a 2 € coin for size reference.

CONCLUSIONS

Since there is record, man tries to fill the loss of a limb with the use of devices that allow greater autonomy or that restore some of the natural appearance. This work proposed a new soft robotics hand prosthesis using reverse engineering and 3D printing. These techniques have enabled the development of a prosthesis in a sustainable way that could respond to the functional and cosmetic needs of the user.

In this project the prosthesis was obtained by reverse engineering, using fast prototyping technology and following a soft robotic approach, where the actuators (fingers) are soft and controlled using pneumatic energy. This approach could be a good alternative to the more electronic and complex conventional electromechanical prostheses. After being printed, the prosthetic hand demonstrated satisfactory results at the aesthetical level, but it still needs tests to prove its functionality.

The hand prosthesis developed is inexpensive and will have a relatively simple control system when compared to prostheses on the market. However, since the used 3D printers still do not print the NinjaFlex[®] material with the necessary finishing quality, the actuators (fingers) obtained still show some leaks when pressurized. For this reason, it will be necessary in future to improve the printing quality. With the advancement of 3D printing technology this problem will be solved naturally.

At this time, the research group is already building the pneumatic control system for the hand prosthesis obtained and soon we will have results regarding its functionality with an electropneumatic control like that used in soft robotics approaches.

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