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### SCAFFOLDS OBTAINED VIA ELECTROSPINNING FROM MIXTURES OF PCL AND PROTEIN WITH POTENTIAL APPLICATION IN TISSUE ENGINEERING

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The electrospinning process is an emerging and relatively easy technique to prepare three-dimensional nanofiber membranes, consequently presenting a large surface area that makes them excellent candidates for several applications. Among them, regenerative medicine stands out because it can take advantage of the intrinsic properties of these nanofibrillar structures to promote cell adhesion and proliferation. These structures are obtained by injecting polymeric solutions (flow rate of 0.4 ml·h<sup>-1</sup>) of synthetic or natural polymers on a collector, applying a voltage of 15 kV. Polycaprolactone (PCL) was selected as synthetic polymer and collagen (Col) and gelatin (Gel) as natural polymers due to their biocompatibility and biodegradability. This project investigates the influence of the composition on the physicochemical and microstructural properties of the final membranes by adding protein (collagen or gelatin) to improve its applicability in the area of regenerative medicine, specifically, in tissue engineering. Thus, different PCL/protein systems were prepared and characterized by FTIR, water contact angle measurements and the images obtained by SEM microscopy. The results revealed that the addition of protein produced more hydrophilic membranes and with a smaller fiber size.

**Keywords:** PCL; collagen; scaffolds; electrospinning; tissue engineering

### ANDAMIOS ELABORADOS MEDIANTE ELECTROHILADO A PARTIR DE MEZCLAS DE PCL Y PROTEÍNA CON POTENCIAL APLICACIÓN EN INGENIERÍA DE TEJIDOS

El proceso de electrohilado es una técnica emergente y relativamente fácil para preparar membranas tridimensionales de nanofibras, consecuentemente presentando una gran superficie específica que las hace excelentes candidatas para varias aplicaciones. Entre ellas, destaca la medicina regenerativa al poderse aprovechar las propiedades intrínsecas de estas estructuras nanofibrilares para promover la adhesión y proliferación celular. Estas estructuras se obtienen inyectando soluciones poliméricas (caudal de 0,4 ml·h<sup>-1</sup>) de polímeros sintéticos o naturales sobre un colector aplicando una gran diferencia de potencial (15kV). Entre los polímeros seleccionados se encuentran la policaprolactona (PCL) como polímero sintético y colágeno (Col) y gelatina (Gel) como polímeros naturales debido a su biocompatibilidad y biodegradabilidad. En este proyecto se investiga la influencia de la composición en las propiedades tanto fisicoquímicas como microestructurales de las membranas finales mediante la adición de proteína (colágeno/gelatina) para mejorar su aplicabilidad en el área de la medicina regenerativa, más concretamente, en la ingeniería de tejidos (o ingeniería tisular). Para ello, se prepararon y caracterizaron diferentes sistemas de PCL/proteína mediante FTIR, medidas de ángulo de contacto del agua y las imágenes obtenidas por microscopía SEM. Los resultados revelaron que la adición de proteínas produjo membranas más hidrofílicas y con un menor tamaño de fibras.

**Palabras clave:** PCL; colágeno; gelatina; electrohilado; ingeniería tisular

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## **1. Introduction**

According to the statistical office of the European Union (2018), approximately 28% of people aged 15-64 in the EU reported a longstanding health problem or a basic activity difficulty, or both. Increasing among people with older ranges of age.(Eurostat - Statistic Explained, 2019)

Orthopaedic appliances are solutions to help patients complete basic activities on their own, being a perdurable alternative in case of suffering from an illness with a non-treatable rehabilitation. Those are usually made of gracious materials, such as Acrylonitrile Butadiene Styrene (ABS), to ensure that they do not cause any armful reaction to the patient.

Orthopaedic appliances are medical devices designed to palliate muscular, skeleton, neuronal issues, while supporting or straightening joints, including those concerned with rehabilitating and preventing injuries, post-operative care, osteoarthritic care.

There is a considerable variety of orthopaedic appliances that assist patients in many ways, those cover from helping the patient dressing up to allowing them lower trunk mobility.

## **2. Objective**

The principal purpose of this project is to present the design process for an orthopaedic appliance. That must satisfy the requirements that are analyzed in the development of the publication.

## **3. Methodology**

The implemented methodology was a prototype design extensively described by the design researcher and author Engineering Design Methods: Strategies for Product Design, Nigel Cross (1989). Analyse the most common appliances, evaluate the functions they accomplish in pursuance of creating an innovative orthopaedic appliance. The aim of it will be narrowed down to the alimentation processes seeking a final product that allows autonomy and adaptability.

The project itself demanded a prototyped methodology. Implying a first design process, followed from a production procedure and hence the final step; clinical validation and medical tests.

That process has been repeated numerous times, described in the design process section. In order to fulfill the main requirement: design a functional and valid product.

## **4. Orthopaedic appliances**

Orthopaedic devices embrace the medical specialty of orthotics, a field that comprehends all the stages; from design, manufacture, to patient application. These devices are used outside the patient's body and its function is to modify or improve the function and structure of the affected muscles and bones.(Haynes, 2009)

Even though these are not normally placed through medical intervention, it is advisable to have its utilization supervised by a doctor or any qualified professional.

Orthopaedic appliances can be categorized into two subdivisions:

- Upper limb; generally, shoulders collarbones, arms elbows, wrists, hands and fingers
- Lower limb; feet, ankles, knees, and legs.

### **4.1. Materials**

The material selection field includes a wide variety of possibilities. Not only they must fulfill the engineer requirements but also must they allow biocompatibility. Making concepts such as

foreign body reaction (particularly due to wear debris), stress shielding... to be gradually introduced as requirements the design of implantable devices.

The main approach to this subject is the classification between them:

First generation materials were, according to Hench's classification, to achieve a suitable combination of physical properties to match those of the replaced tissue with a minimal toxic response of the host. They were 'inert' so as to reduce the immune response and the foreign body reaction to a minimum. (Jon Goldberg & Kuhn, 2013)

- Second generation materials appear between 1980 and 2000 enhancing the development of bioactive materials' ability to interact with the biological environment to undergo a progressive regeneration while the new implant degrades. (Sunitha Raja & Munirathnam Naidu, 2009)
- Third generation materials are meant to simulate specific cellular responses at the molecular level. (Hench & Polak, 2002) For these biomaterials, the bioactivity and biodegradability concepts are combined to ensure a proper response from the patient.

## **5. Case study**

In the next three decades, the aging of the human population in the industrialized world will increase consistently. The ageing phenomenon is eventually in progress. The improved and upgraded quality of life (QoL) such as medical facility is the main factor of the increasing number of elderly population. Hence, the ageing process caused some decline deterioration effect on the human physical body as well as cognitive ability. Certainly, this phenomenon leads to emotion disappointment and frustration among the elderly. This condition resulted in the limitation in physical ability among the elderly (Bidin et al, 2017). Leading into an augment of the disease related to this population tier. And in the expected consequences, as: elderly people abandonment, malnutrition, home care negligence.

### **5.1. Associated medical framework**

Malnutrition is a common condition in people with any mobility reduction illness. Prolonged malnutrition can lead to the need for artificial nutrition. This latter can be given through two ways, that is, enteral and parenteral (intravenous) tools. In older people especially with dementia, the literature regarding the use of enteral nutrition (in terms of a nasogastric tube or PEG) is contradictory, having some studies failing to report any advantage in survival compared to no treatment. Moreover, the effect of artificial nutrition (particularly enteral) on quality of life is still missing. Finally, the choice of artificial nutrition is also weighted not only by medical reasons but also by ethical and religious beliefs. (Pathak et al, 2014) (Veronese, 2019) The objective of this project is to provide a valid design to assist people that are in an early stage. Preventing or delaying any of the previously listed possible consequences.

### **5.2. A utensil for eating assistance**

After analyzing the global view of the orthopaedic appliances. The next step is to focus on the case study. The first approach to this matter is to analyze the most relevant and used products. Then, extract the main features to create one design that merges all of them. (CIAPAT de la OISS, 2019)

**Illustration 1  
Flexible cutlery  
with widening**



**Illustration 2 Adaptable  
belt**



**Illustration 3 Adaptable  
FOAM**



**Illustration 4 Anti-  
vibration electrical  
device**



**Table 1: Discretization and differentiation between different orthopaedic utensils**

	1	2	3	4
Description	Commonly used for both left and right handed, allows bending in both directions. The body is widened to facilitate a proper grip.	This strip allows proper subjection between the user and the cutlery used.	This tool grants a bigger surface for the patient so he can use most of the cutleries.	This stabilizer reduces the vibrations from the patient. It is an electronic tool that uses two motors that stabilise the tool allowing more control for the user to. Also, brings a different way of holding the device.
Main features	-surface finishing -widening -ambidextrously -intuitive.	-strip -different tools usage -different tool position -firm subjection	-adaptability -impact resistance	-vibration reduction -perpendicular subjection position -aims to specific problems
Contrapositions	-difficulty to clean -fatigue break -weak subjection, -different tools required	-difficulty to clean -not intuitive use -weak constitution -difficult for the patient to use itself	-difficulty to clean -no hand-tool subjection -expensive -only allows plane cutlery	-expensive -battery usage -different tools required -no hand-tool subjection
Price (TAX +Shipment)	12,00€	12,45€	45,00€	200,00\$

After the abstract, the main features are shown in the following chart:

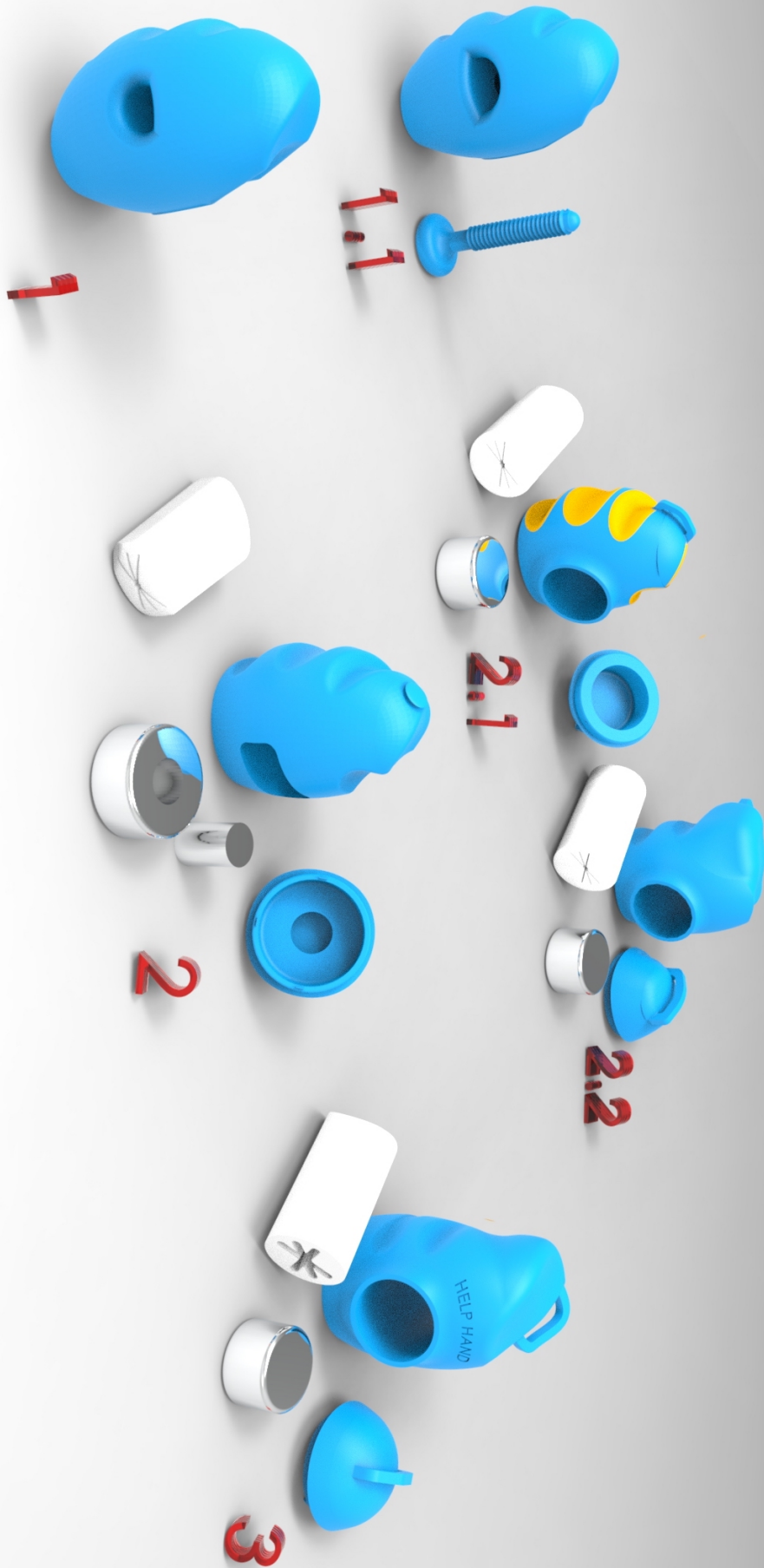
**Table 2 Criterion analyze**

Characteristic	Definition	Technique	Final design implication
Surface finishing	Relative to the product surface	Produced from the replication of the mold surface	Allows improved grip and reduces the chance of slipping
Widening	Augmenting the contact surface between the hand and the product	The 50 <sup>th</sup> hand feminine percentile reflects the size that can accommodate more patients.	To properly accommodate a major number of people it might have different sizes
Ambidextrously	A capacity of being used with both hands	Using symmetry to create different molds	The presented design does not allow ambidextrousness
Vibration reduction	Softening the vibrations produced when the patient uses the product	Can be achieved using electronic devices or mechanical systems	Using a counterweight system and a shock absorber material might
Perpendicular subjection position	A more natural cutlery subjection position is being able to subject the product at 90° from the palm surface	Creating a tool that allows that subjection	The product will reduce the tension in the forearm by providing a more natural subjection
Adaptability	A capacity of using different kinds of cutlery	Using deformable materials	The final product will combine both materials
Impact resistant	Capacity of absorbing the residual energy from impacts without breaking	Both the materials and the shape provide proper resistance	It must resist falls and impacts
Strip subjection	Using a strip is vital in any orthopaedic aid	The strip maintains the device in the right position	There will be a pothook to subject the strip
Bio-compatible	The interaction between the material and the patients	Using materials that do not harm or produce irritation	Any certificate plastic can provide proper characteristics
Suitable for feeding	Non harmful materials	In the eventuality of the product entering in contact with the food the product must prevent any pollution	Any certificate plastic can provide proper characteristics

### 5.3. User analysis

- a. Common user:
  - Reduce timing placement.
  - Reduce weight.
  - Maximize the grip and the subjection.
  - Minimize physical tiredness.
  - Comfortable subjection.
  - Compact, allowing keeping it in reduced spaces.
  - Impact resistance.
  - Trendy, fresh colours.
  - Inexpensive.
  - Stylish.
  - Modern
  
- b. First time users:
  - Intuitive use.
  - Comfortable.
  - Attractive.
  
- c. People that accompanies the user during the meals
  - That it does not occupy space in table
  - That does not make the patient
  - Noiseless use
  
- d. Attendants:
  - Reduce attended need.
  - Easy to place at the patient.
  - Reduce table space
  - Do not trouble fellow patients
  - Usage that does not hurt
  - Easy to wash
  - Easy to storage

Illustration 5  
Design  
process



## 6. Design process

As it has been described in the first section, the prototype methodology demanded many prototypes to be manufactured. To classify the extracted information a data sheet for each prototype and sub-prototype. Beneath is shown the evolution between them:

### 6.1. Prototype 0

**Description:** The 0 prototype was created to test the viability of the solution. Allowing some base ground to build the next solutions. From the first moment, the position between the cutlery and the patient's hand has been one of the most significant improvements for the user.

**Configuration study:** It had the exact shape of the hand that it accommodates, granting firm subsection for the patient. The final position originates a 90° degree subsection from the palm to the longitudinal cutlery axis.

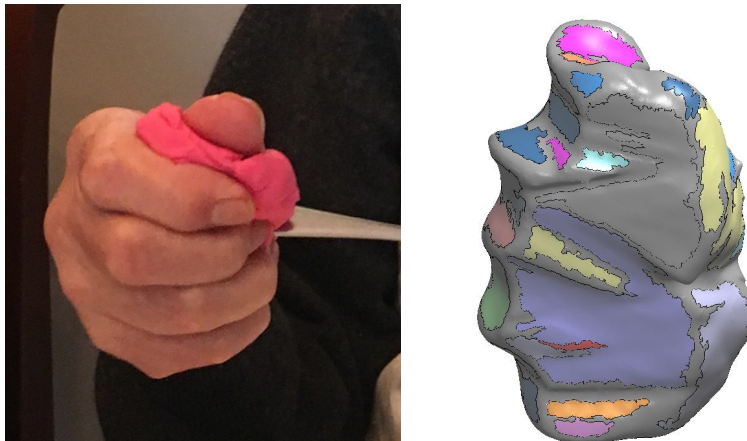
**Material:** Plastic material, that allows mold in different shapes.

**System for cutlery subsection:** The subsection was provided by compressing the material that surrounds the inserted object.

**Main features:** Adaptability, different cutlery subsection, perpendicular subsection, colourful, simple

**Contrapositions:** Cannot be industrialized, cannot be washed, patients need precise instructions to use it, no sanitary procedure.

**Illustration 6: Comparison between the real model and the virtual model**



### 6.2. Prototype 1

**Description:** After testing the prototype 0 -P0-, the following action was virtualizing using a 3D scanner that allows proper measurements.

**Configuration study:** It had an oval shape that helps to comfort the subsection. To provide a right position the prototype had four notches perpendicular along the longitudinal axis locate the middle phalanx of the four larger fingers.

**Anatomic study:** To provide good subsection, the prototype 1 -P1- had the small diameter of 1.7in granting proper grasp to the 50<sup>th</sup> women percentile –the most confining–. (Haynes, 2009)



**Material:** Polylactic acid (PLA) commonly used for 3D printers.

**System for cutlery subjection:** The subjection was provided by friction, inserting the cutlery in a through hole that had a decreasing angle.

**Main features:** First industrial option, optimum size, good grasping, reduced dimensions, adaptability, perpendicular subjection, ambidextrous.

**Contrapositions:** Cutlery subjection and hand-tool subjection loose and insecure, not intuitive use, misunderstanding right position.

### 6.2.1. Prototype 1.1

**System for cutlery subjection:** The subjection was updated with two approaches. The first was one screw, that was screwed towards the longitudinal axis converging in the middle of the hole with the cutlery. The base of it had a larger and knurled cylinder that allowed easier rotation.

The second approach was the hole itself, it had a bigger shape, so it could be easier to accommodate more cutlery inside. Additionally, it had a semi-circular shape in order to fixate the horizontal movement pressing the cutlery to the superior part inside the hole.

### 6.3. Prototype 2

**Description:** After testing the functionality of the P1.1, it was patent that the subjection solution was not effective enough. Additionally, in this stage, it is added a method to hold firm the tool and the hand.

**Configuration study:** This configuration had two materials, preserving the same shape. Also, it had a counterweight system to stabilize the set cutlery-tool. The final design was a two-piece shell with and central elastomeric piece.

**Material:** The hard casing was designed to be made from High-Density Polypropylene (HDPP) and the elastomeric part from Silicon FOAM, both materials were suitable for feeding in case it had fallen into any food. The weight was made from stainless steel 304 to ensure durability. All the chosen materials were both cheap and resistant.

**Weight:** The process design had different variables that led to the final design:

- **Removability:** Allowing different patient to use regarding its needs, e.g. a patient with Parkinson disease normally suffers from tremolos, in that case, he/she will need to add weight to palliate this symptom. Another instance would be a patient with multiple sclerosis, having a reduction in the object weight they can lift, therefore, needing a lighter tool.
- **Position:** Outside the tool -too destabilization, also there was no space-. The top part inside -also there was no space and it was hard to create space-. The final position was at the lower part and inside the tool.
- **Subjection:** The possible solutions were screwed or clipping. Screwing could not offer a great seal, whereas a clip was an industrialized solution that could be implemented.
- **Hand-tool subjection:** Many medical devices are tied with a rubber band made of silicone. That band had on hole in one side and three on the other to allow adjustment.
- **System for cutlery subjection:** To improve the subjection method it is postulated adding an elastomer to provide a solid solution. That also permits multiple cutlery subjection and facilitate the insertion.

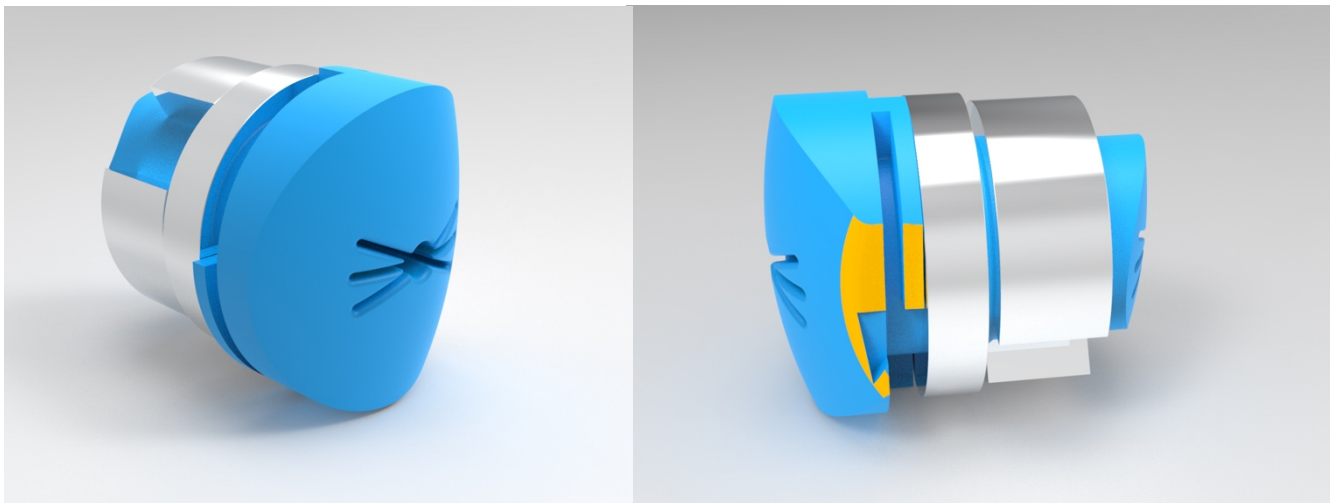
**Manufacturing process:** The first approach was to build a reduced batch made from an industrial 3D printer -probably 3D HP Jet Fusion series 500/300- but after analyzing some

budgets the option was not competitive against plastic injection. Therefore, a 3D printer would have been used for prototyping but it was discarded as a production method. During the manufacturing analyse process has been validated the output angle to provide proper ejection when un moulding the pieces.

**Main features:** Improves subsection both hand-tool and tool-cutlery, using a subsection method makes the device more intuitive, durability, adaptable.

**Contrapositions:** Grabbing the lower part tended to be hard to held when unclipping, the thumb locates too upright difficulty the grasping, the tool lays too up in the hand, the hand-tool subsection was located in the phalanx -which did not provide a firm subsection- also the method was not strong enough.

**Illustration 7 Interior weight system**



### 6.3.1. Prototype 2.1

**Hand-tool subsection:** The subsection was upgraded to a velcro strap, providing tough fixation

**Manufacturing study:** At the latest phases, the industrialization had become a more relevant factor. To optimize it, one of the changes were: modifying the FOAM silicon subsection to a cylinder shape as it was more common, and it could be produced without specific requirements. Also, making front part straight would reduce the number of production steps and would imply an intuitive use of the tool itself. To provide visual help it had been proposed painting the finger's accommodation.

To effectuate that change there was, at least, four possible manufacturing options: 1<sup>st</sup>: multi-injection, the best way to achieve colouring the device, yet the most expensive. 2<sup>nd</sup>, clamp system to pint using robots, the main contraposition was both the final price and the durability of the solution. 3<sup>th</sup>, two separate pieces that must be assembled lately, that also implied more and more complicated molds. 4<sup>th</sup>, using stickers that would not remain for a long period, therefore making the inversion useless. In conclusion, using a multicolour device would be an interesting advance however, at the current stage it was not a viable modification.

**Weight:** One of the modifications was locating the weight inside the tool, but the idea was inconsistent, as shown in the illustration 7. The system was too complicated, and it would not

implement the self-balance system. The number of weights was reduced to one piece. That would make the tool less complicate.

**System for cutlery subjection:** Cylinder shape, that grants augmented positions to insert the cutlery.

### 6.3.2. Prototype 2.2

**Configuration study:** Remodelling the thumb location.

**Ergonomic study:** The prehensile nature of the hand rests on the thumb mobility. The previous design was restraining it. Relocating the velcro subjection crates a bigger spot for the thumb.

**Impact study:** To ensure that the designed product has a proper lifetime use it has been realized many impact tests using the software “*ESI-GROUP Visual Environment*”.

**System for cutlery subjection:** The ergonomic modification supposed a relocation for the velcro stripe, that meant that the stripe would be attached to the metacarpals instead of the phalanx, providing a firmer subjection.

## 7. Final design

A final design is required to provide a concluding solution to solve the problem.

### 7.1. Prototype 3

**Description:** The last prototype was a refinement of all the previous designs.

**Configuration study:** The body is shaped with two ovals, that grand subjection: one to the four fingers and the other to the thumb.

**Material:** Acrylonitrile butadiene styrene (ABS) for the body as it is a high-end quality plastic. Silicon for the cutlery system subjection to ensure durability and firm subjection, also allows better cleaning, and stainless steel 304 for the weight.

**Prototyping:** The hard body part has been made using a common 3D printer since the final surface finishing was not a relevant. But when printing the molds to discharge the silicone the

*Illustration 8 Final prototype in use*



final surface finishing was relevant, to surpass it has been used an optical 3D printer that uses acrylate.

**System for cutlery subsection:** Using silicone instead of FOAM silicone grants a more durable product. Using an unyielding implies a remodelling the spots where the cutlery was supposed to be inserted.

**Surface finishing:** To provide proper grip for the user, the finishing surface is slightly rugged.

**Main features:** Adaptability to most cutlery, natural subsection, the significant reduction in tremors, number of movements reduced, improve grasping, perpendicular subsection, simplicity, compact, impact resistant, intuitive use, easy to wash.

**Contrapositions:** Any contrapositions observed.

## 8. Conclusions

In conclusion, the main objective, designing an orthopaedic appliance that provides significant improvements in the designated task, has been archived.

there are still many interesting questions unanswered, but this article sits the ground base to reopen a discipline that has been forgotten for many years. An interesting conclusion that can be extracted is that killing ideas is necessary to progress in the development of the design.

The next logical step is analyzing the product in a different way and try to abstain from the technical requirements. Examine the emotions beneath the product and approach it to a more human course. Following the Kansei(Kato & Tsuda, 2016) philosophy.

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