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Modelling Techniques and 3d Shapes Acquisition Technologies for Biomedical Application

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ABSTRACT:

The human foot is an element of extreme importance at a structural level, as it provides support and body posture, also allowing locomotion. Its anatomical structure can present different forms and behaviours, varying from person to person. However, it can evolve with congenital anatomical malformations, being the target of severe solutions/treatments, leading to the appearance of several lesions and deformities. Some of the injuries and deformities can be corrected only by resorting to surgery, that is, partial or total removal of the organ, other cases can be mitigated or even avoided if procedures are taken and behaved in everyday life. The proper choice of footwear is one example, but the solution may involve the use of biomechanical devices indicated for each situation.

The present work aims at studying emerging technologies for modelling and manufacturing a prosthetic foot. Prosthetic feet are essential for a lower limb amputee, as this device will allow the patient to walk as naturally as possible.

Modeling and simulation were resorted to using the Solidworks software, in which it was printed on a 3D printer in Onyx+Carbon Fibers.

The simulations carried out in Solidworks, according to the finite element method, indicate that the prosthetic foot developed is not the most suitable to be produced, since at the beginning of the gait it will break and deform with some ease. To this end, the two pieces were joined together, and the thickness increased for later 3D printing.

This project allowed to start the creation of a prototype evaluation methodology and to understand through simulations the defect level of the current model, thus helping the evaluation of future models where it is sought to improve the printing quality and the design of the models.

Keywords: Human Gait, prosthetic foot, emerging technologies, finite elements.

1. Introduction

In Mother Nature, the human being is one of the most developed, distinguished from all creatures, by the ability he must reason and apply it, manipulating what surrounds him.

However, the human brain is the most incredible organ we have and the factor with the greatest weight in distinguishing it from other species(Almeida, 2018).

However, the human foot is an organ that man so much depends on in his daily tasks, to guarantee his autonomy and it is fundamental for human locomotion, as well as for the execution of independent tasks. However, the human foot has a structure with bones, ligaments, muscles, tendons, and nerves, subject to daily efforts and tensions. Deformities, disorders in supporting body weight in static or dynamic situations and pain are the main reasons that lead individuals to seek help from a health professional(Provenzano, 2002).

The absence of a limb, or part of it, may be due to a congenital malformation, or to an amputation, surgical or accidental. Regardless of its origin, this injury results in physical and psychological consequences that affect the amputee's life. The physical consequences are essentially reflected in a marked loss of sensitivity, functionality, and autonomy of the person in handling and interacting with objects and the environment. The psychological consequences come from the loss of capacity, but also from the cosmetic and social impact that the amputation has on the individual(Cordella et al., 2016; Cunha, 2002; Massa, Roccella, Carrozza, & Dario, 2002)

Since the dawn of humanity, prostheses have been used to compensate for this weakness. However, despite the impact that the absence of an upper limb has on the person's life, a considerable percentage of amputees do not regularly use a prosthesis (Childress, 2003; Massa et al., 2002). Therefore, despite technological advances, the solutions currently presented do not fully satisfy the needs of users.

Choosing a prosthesis is a complex process. The poor adaptation of a prosthesis to an amputee implies loss of quality of life and the appearance of other complications due to unbalanced walking. However, commercially available prostheses are generic, not suitable for all amputees and their price is high, not being accessible to some amputees or the national health service. Thus, having the possibility of a prosthesis adapted to an amputee and economically dissuasive is an important added value.

It is in view of the limitations of current conventional prostheses and the needs of their users that the present project work arises to carry out a theoretical study of customizing a prosthesis for the amputee that allows real production at a lower cost is the greatest technical motivation of the present work.

On a personal level, the motivation of the opportunity to learn more about the connection between the medical field and mechanical engineering and learning how to use the Solid Works simulation tool is added.

1.1. Prosthetic foot: State of art

1.1.1. Evolution

From the ancient pyramids to the First World War, the area of Orthoprosthetics has become a sophisticated example of man's determination to do better(Leal, 2011).

The evolution of prostheses takes place from the dawn of time to the present day, combining sophistication with exciting visions for the future. As in the development of any other field of work, some ideas and inventions were worked on and expanded, such as the fixed-position foot, while others fell to the ground or became obsolete, such as the use of iron in a prosthesis(Leal, 2011).

The long road to leg production began around 1500 BC. and it has evolved since then. There were many evolutions from the first peg legs and hand hooks that led to the highly individualized fit present in today's devices. To have a starting point from where the field of prosthetics evolved and where it came from, one has to go back to the time of the ancient Egyptians(Leal, 2011).

Prior to the early 1980s, most prosthetic feet were designed with the aim of restoring basic gait and simple occupational tasks. The most common conventional prosthetic foot is the SACH foot, which has been the industry standard for years. SACH is an acronym for Solid Ankle Cuhioned Heel, which refers to a compressible heel wedge that provides pseudo-plantar flexion after heel strike. Rigid wooden keel provides medium support stability but little lateral movement, being the simplest type of non-articulated foot. The SACH foot is still prescribed frequently (mainly in poorer countries) because it is robust and inexpensive(Versluys et al., 2008).

However, the desire of amputees to practice sport, leading to high demands in athletics, resulted in the development of so-called “energy storage and return” (ESR) feet, these types of prosthetic feet can store energy during posture and returning provide it to the amputee to assist with forward propulsion in late stance. The pioneering ESR foot was introduced in 1981 and was designated the Seattle Foot. The Seattle Foot incorporates a flexible keel within a layer of polyurethane, with the keel flexing when loaded, acting as an elastic spring, returning some of the stored energy to the amputee later in the gait. Other manufacturers followed a similar strategy and incorporated a flexible keel surrounded by foam and/or polyurethane cosmetics(Versluys et al., 2008).

1.1.2. Prosthetic Foot Development: Emerging Technologies

To succeed in adapting the patient to the new artificial limb, it is necessary to have an elaborate study of the residual limb, prosthesis, and the method of aggregation of the prosthesis to the residual limb, as such, technologies were developed that allowed to improve the design of these methods.

Among the emerging technologies, the ones that stand out and are most used in the health area are the use of CAD modelling, finite element methods, Reverse Engineering, 3D Laser Scanner and 3D Printing. These technologies are intended to respond to the low efficiency of the traditional orthoprosthesis process, which requires an extended period and generates waste due to its manual and iterative process(Nayak, Singh, & Chaudhary, 2014; Singh & Pandey, 2016).

These technologies have been developed over the last few decades with the aim of helping the development of products, whether new or just customized, helping to reduce the need for prototypes and, consequently, to reduce the costs and lost time associated with This one(Almeida, 2018; Nayak et al., 2014; Wierzbicka, Górski, Wichniarek, & Kuczko, 2017).

1.1.3. Existing Studies

Since this study will focus more on the production of a computerized prosthetic foot, it was decided to focus more on finite elements, in which a search was carried out for recent studies that used this type of technology in Orthoprosthesis.

In finite element modelling studies, the objective is to implement the non-linear finite element analysis technique for the evaluation of a prosthetic foot and to use finite elements to determine whether the material of the prosthetic foot used is the most suitable for its subsequent manufacture or not(Balaramakrishnan, Natarajan, & Srinivasan, 2020; Hamzah & Gatta, 2018; Um, Kim, Hong, Kim, & Hur, 2021).

The non-linearity of finite element analysis stems from the need to realistically model the prosthetic foot, including the great stresses that the foot suffers(Balaramakrishnan et al., 2020).

In these studies, finite elements were analyzed during the ROS movement, i.e., the movement of the foot from the beginning of heel contact to toe contact, during the stance phase of human gait(Balaramakrishnan et al., 2020; Hamzah & Gatta, 2018; Um et al., 2021).

In the study by Balaramakrishnan et.al, an Ottobock SACH foot was used, being a more conventional foot(Balaramakrishnan et al., 2020).

While in the studies by Hamzah et.al and Kim et.al carbon fiber ESR feet were used, respectively Onyx and wet epoxy carbon fiber fabric(Hamzah & Gatta, 2018; Um et al., 2021).

It was concluded that all prosthetic feet used in the finite element model were successful, proving to be reliable for prosthetic foot design using ROS as the main criterion. However, it was also concluded that the finite element model provides important pre-assessment data about the entire project, saves time and money in development, making correct decisions in the future and helps to develop a specific design for amputees, incorporating conditions of contours applicable in order to arrive at a more appropriate design of a prosthetic foot, which can meet the needs of the patient(Balaramakrishnan et al., 2020; Hamzah & Gatta, 2018; Um et al., 2021).

2. Modeling and Results

2.1. Main modelling computer resources

In this phase of the project, the necessary methodology was defined for the analysis of existing technologies for the development of a prosthetic foot, dividing the study into the following points:

- Modeling of the prosthetic foot with the SolidWorks software;
- Study of finite elements in Ansys;
- MatLab
- Additive manufacturing in CATIA software.

2.2. Modeling in Solidworks

From the available software set, it was decided to opt for SolidWorks because it fulfils the objective of the work, it is robust, it has good general acceptance by other authors of studies like this one and ISEL has a full use license.

SolidWorks was developed by SolidWorks Corporation which runs on the Windows operating system and is a 3D CAD (Computer-Aided Design) software(Solidworks, 1993).

SolidWorks is based on parametric computing, creating three-dimensional shapes based on elementary geometric operations. In the program's environment, the creation of a solid or surface starts with the definition of a 2D sketch that is later transformed through an operation into a three-dimensional model. However, this software has a lot of functionality, including specific functions for sheet metal, welded construction, and molds(Solidworks, 1993).

For the creation of the prototype of the intended prosthetic foot, SolidWorks was initially used, to create a three-dimensional model of the same for later printing, for this purpose a single piece was created, so that the device can support the weight of an adult person, in which the mold for the placement of the fixation device is present.

The SolidWorks tools used were those shown in table 1:

Table 1 - Tools used in Solidworks.

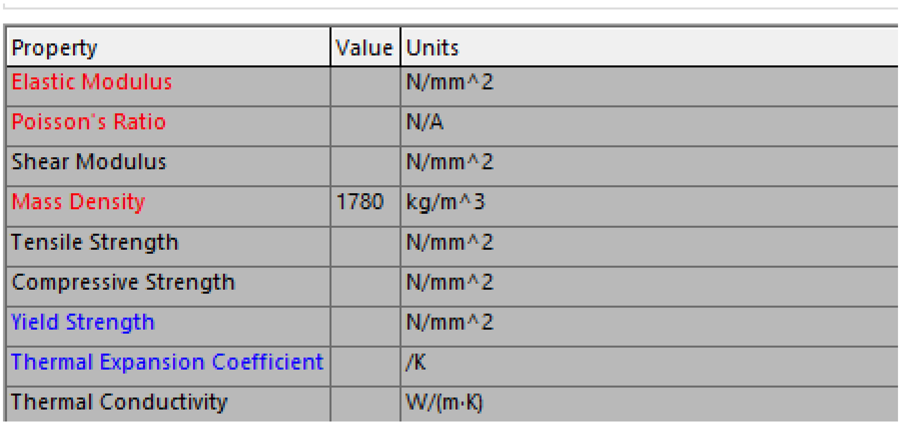
Tools	**Description**
Sketch	Draw 2D sketches of the object
Boss-Extrude	Give volume to sketches
Cut-Extrude	Make cuts on the object
Fillet	Rounded finish on the edge of the part
Mirror Entities	Reproduce copies of a part along an axis of symmetry

2.3. Simulation according to the Finite Element method

After modelling the prototype in SolidWorks, simulations were carried out based on the Finite Element method to observe the behaviour of the foot during the three phases of the ROS: initial contact of the heel on the ground, total support of the foot on the ground and contact only the tip of the foot on the ground.

When starting this type of simulation in SolidWorks, you must choose which material the prototype will be made of. In this software, the material most identical to the material that was used for 3D printing would be Hexcel AS4C with 3000 filaments, but in terms of information on its properties, only the Density value is present, not allowing it to be used for this study, as can be seen in figure 1.

However, the Cast Carbon Steel material was used, which presents all the information of the properties present in SolidWorks, as shown in figure 2.



Property	Value	Units
Elastic Modulus		N/mm^2
Poisson's Ratio		N/A
Shear Modulus		N/mm^2
Mass Density	1780	kg/m^3
Tensile Strength		N/mm^2
Compressive Strength		N/mm^2
Yield Strength		N/mm^2
Thermal Expansion Coefficient		/K
Thermal Conductivity		W/(m·K)

Figura 1 - Properties of Hexcel AS2C with 3000 filaments.

Property	Value	Units
Elastic Modulus	200000	N/mm^2
Poisson's Ratio	0.32	N/A
Shear Modulus	76000	N/mm^2
Mass Density	7800	kg/m^3
Tensile Strength	482.549	N/mm^2
Compressive Strength		N/mm^2
Yield Strength	248.168	N/mm^2
Thermal Expansion Coefficient	1.2e-05	/K
Thermal Conductivity	30	W/(m·K)

Figura 2 - Cast Carbon Steel material properties.

Subsequently, the meshes are created, to analyze the complexity of the geometry, obtaining what can be seen in figure 3. It can be observed that mostly triangular geometries were obtained.

In SolidWorks, we were able to export detailed information about the meshes and, according to this information, the maximum size of the elements is 6.85907 millimetres, and the minimum size is 2.28633 millimetres, we also obtained 25651 nodes and 15797 elements in the created meshes, as shown in figure 3.

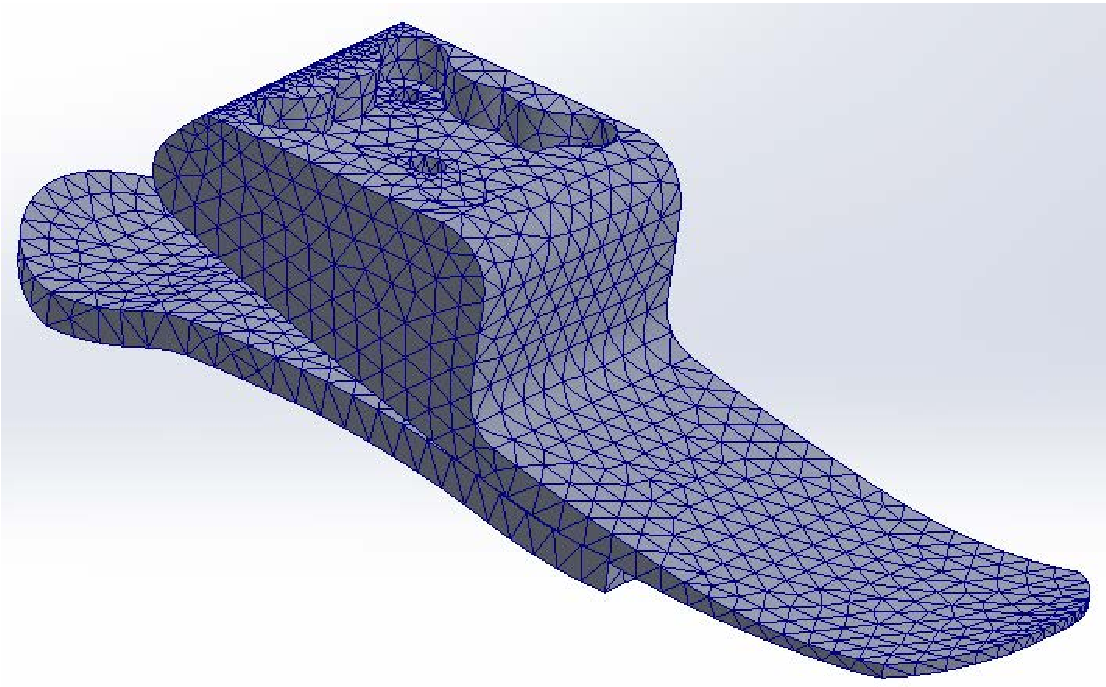


Figura 3 - Designed prototype meshes.

3. Discussion of results and conclusions

In the area of Orthoprosthetics, several factors must be considered when producing a prosthesis or an element of a prosthesis. When manufacturing a component of a lower limb prosthesis, it is necessary to consider the well-being of the patient and the harmony between the residual limb and the prosthesis, so that the medical device fulfils its function, providing an experience pleasant for the amputee and an effective gait that allows them to continue their daily activities(Matos, 2014).

Currently, despite technological advances, there is a large percentage of patients who choose not to use prostheses, which is justified given that current solutions do not meet the needs of their users.

One of the many reasons for the patient to choose not to use prostheses is that in Portugal, there are no Orthoprosthetics companies that are capable of being self-sufficient in the production of prostheses, so that the waiting time and cost for the patient is the lowest. possible.

As such, to produce the prosthetic foot in this study, Portuguese companies were contacted, with the aim of obtaining existing solutions on the market. As feedback was not obtained from the majority, a small survey was carried out and it was concluded that most Portuguese companies do not sell prosthetic feet individually, having to purchase the transfemoral or transtibial prosthesis in its entirety.

However, one of the companies contacted reported that the most used prosthetic feet are from the following brands: Össur, Ottobock and Streifeneider.

The Össur brand prosthetic feet are mainly ESR feet, made of carbon and which are separated into different families:

- Proprio Foot – has an adaptive microprocessor-controlled ankle for low to moderately active amputees, designed to improve safety by increasing toe clearance in the swing phase and adapting to changes in terrain. It is classified as a prosthetic foot for low to moderate level impact;
- Pro-Flex - They are classified as prosthetic feet for low to moderate impact, more suitable for patients with a calmer physical activity, that is, only for patients who go for walks;
- Balance Foot – They are also classified as prosthetic feet with a low to moderate impact level, however they are the most suitable for patients who are starting to use prostheses and who do not have much confidence in walking, providing the best possible balance;

- Cheetah – These types of prosthetic feet are intended for patients who are dedicated to high competition sports and athletics, since their design is based on the legs of a cheetah providing greater momentum and balance for running or jumping(Össur, 2023).

As for the Ottobock brand prosthetic feet, they are also ESR-type prosthetic feet, but the manufacturing material varies between models, with models made of carbon and others made of glass fibers. However, within the different models of Ottobock prosthetic feet, they also vary in terms of design, including or not the Ankle-Foot complex(Ottobock, 2023).

However, the fiberglass prosthetic feet support a maximum weight of 166 kilograms, showing that it is a prosthetic foot model that can be used during a patient's day-to-day life(Ottobock, 2023).

In the Streifeneider brand, the prosthetic feet are also made of carbon and are of the ESR type, there are only 3 different models Go.Free, Go.Relax and Go.Smart which both include a dynamic and natural gait pattern on various surfaces, basic spring wide for lateral stability, has an extended full contact and has a flexible heel stiffness adjustment by heel wedges. It supports a maximum body weight of 150 kilograms and is intended for everyday use only(Streifeneider, 2023).

This dissertation aimed to identify the technologies and methods for acquiring 3D shapes and the processes of modelling and simulating objects, to be a basis for work and research for the application of prostheses.

Using these technologies, a computerized prosthetic foot was designed, in which the model was based on the ESR prosthetic feet, but a model was idealized in which the keel and the prosthetic foot were together, making a single piece. The final appearance achieved presents a morphology like the real one.

As for the functionality of the prosthetic foot, the simulations carried out in Solidworks indicate that, according to the conditions defined in them – thickness of the prototype and chosen material – that the prosthetic foot developed is not the most adequate to produce, since at the beginning of gear the same that will break and deform with some ease. To this end, the two pieces were joined together, and the thickness increased for later 3D printing.

This project allowed to start the creation of a prototype evaluation methodology and to understand through simulations the defect level of the current model, thus helping the evaluation of future models where it is sought to improve the printing quality and the design of the models.

4. Study limitations and suggestions for future work

This study aimed to simplify the construction of a prosthetic foot, using only Solidworks for computer modelling and analysis of its behaviour during gait movement and using a 3D printer to produce the object. In this process, time and money were saved, which would not have happened if the foot had been produced conventionally.

Regarding the difficulties felt in the development of the project, these involved the multidisciplinary of the system, forcing the recognition of a wide range of areas of study. After the work carried out, the part that proved to be the most challenging was the modelling carried out in Solidworks, since the help of teachers and some research was needed to carry it out.

The remaining difficulties are associated with printing, where there was some difficulty in finding 3D printers that could print with the chosen material - Onyx+carbon fibers -, subsequently having to adjust the parameters to optimize the result of the manufacturing and optimizing the virtual model for efficient printing – increased keel thickness.

Without prejudice to other possibilities, it is considered that it would be interesting and important to continue this line of investigation in the sense of:

- Develop alternative geometries for the prosthetic foot;
- Use of other technologies for its modelling
- The choice of material to use in 3D printing, being more flexible and easier to handle;
- Use the prosthetic foot printed in this study for a functional study, where an amputee would place it;
- Associate thermography in real-time experiments, so that it can later be complemented with the values obtained with the Force sensors.

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