Application of 3D Modelling in The Field of Biomedical Applications for The Construction of Prosthetic Foot

Júlia Inês Garrido Alvarinho & Nuno Soares Domingues

***Abstract*—**Amputees has been a spotlight for several years. After years and years of wars, traffic accidents and diseases, for instance, some citizens seen a part of their body removed as a part of life. Currently, due to the lifestyle that most of the population adopts, there are increasingly younger people undergoing surgical interventions, such as partial or total removal of lower and/or upper limbs. The solution for them is remain with lack of member, have a low cost and non-functionally prothesis or have funding/ economically availability to have ones that are increasingly identical to a healthy limb.

As better the prosthesis is, higher the costs of the equipment and its' integration. This creates an unfair disadvantage for low-income amputees. However, with the growth of technology in this area, it results in the high cost of acquiring them.

The present study aims to know the emerging technologies for the modelling and manufacture of a prosthetic foot and, consequently, the computerized modelling and printing of a prototype. Modeling and simulation were resorted to using the Solidworks software, in which it was printed on a 3D printer in Onyx+Carbon Fibers.

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*:** Prosthesis, Modelling, human gait, prosthetic foot, emerging technologies, finite elements.

I. INTRODUCTION

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 accessible is an important added value.

A. Human gait cycle

Human gait is a very common class of movements in human motor behavior, composed of integrated and complex movements of body segments and is achieved with coordinated movements of body segments in a dynamic interaction of internal forces (muscular and joint) and external forces (inertial, gravitational, and frictional)(Bruniera & Amadio, 1994).

Therefore, whenever the organism performs its movement in a structured way, taking advantage of reaction phenomena, such as external forces, the degree of coordination in locomotion increases (Bruniera & Amadio, 1994).

During human gait, the gait cycle can be divided into two main phases, i.e., the stance phase, in which the foot is in contact with the ground, and the swing phase, during which the foot is in the air (Torricelli et al., 2016).

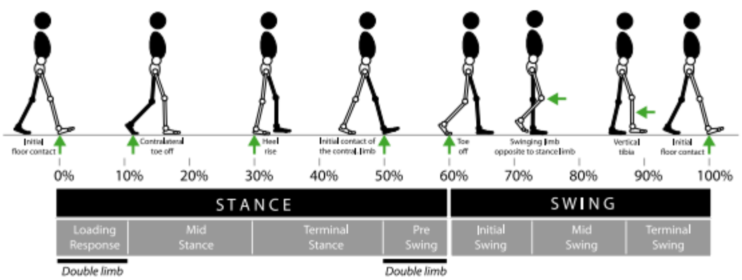

Fig. 1 - Phases of human locomotion and related biomechanical events(Torricelli et al., 2016).

B. Foot-Ankle Complex

The action of the ankle and foot, considering them, has been compared to the rolling mechanism of a wheel, due to the relative movement of the center and pressure between the foot and the ground, it follows a circular path, as described in figure 12. This mechanism was defined as the roll shapes (ROSs) and in the study by MsGeer, it was demonstrated that the ROS is circular, with a radius equivalent to 0.3 times the length of the leg and this is maintained at different speeds of walking and biomechanical conditions(Hansen et al., 2004; McGeer, 1990) Figure 2 shows three instantaneous moments of the stance phase, seen from an observer placed on the foot. The relative motion of the ground and the foot follows a circular path, as it would if the foot were replaced by a wheel.

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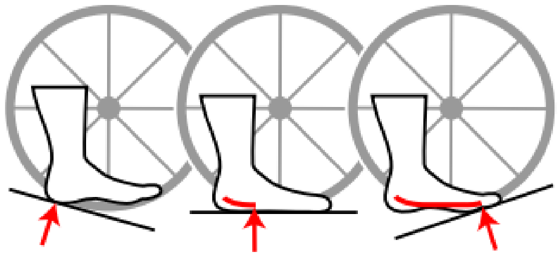

Fig 2 - The wheel-like mechanism of the foot and the resulting scroll shapes (ROS)(Hansen et al., 2004).

However, it is generally believed that ROS reflects the mechanisms humans use to:

i. Transform the passive dynamics of the lower limbs' pendulum into body progression(Gard & Childress, 2001; McGeer, 1990)
ii. Smoothing transitions between opposing poles, thus having direct implications on energy expenditure(Adamczyk et al., 2006)(Adamczyk & Kuo, 2013).

C. Prosthetic foot: Evolution

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 (Versluys et al., 2008).

D. 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 couto, prosthesis and the method of aggregation of the prosthesis to the couto, 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 modeling, 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 et al., 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. Figure 20 shows a synthesis of the stages of the new methods used by orthoprosthesis (Lopes de Almeida, 2018; Nayak et al., 2014).
The most used technologies are:

- CAD modeling, sometimes using finite element methods;
- Reverse engineering that can be done from 3D Scanners;
- 3D printing.

II. METHODOLOGY

Modelling in Solidworks can be done with simple commands, such as the ones illustrated in Table 1.

TABLE I - 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

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

III. RESULTS

Simulation according to the Finite Element Method using the Solidworks has produced the following outputs.

After modeling the prototype in SolidWorks, simulations were carried out based on the Finite Element method in order to observe the behavior 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 you start 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.

However, the Cast Carbon Steel material was used, which presents all the information of the properties present in SolidWorks.
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 millimeters and the minimum size is 2.28633 millimeters, also obtaining 25651 nodes and 15797 elements in the created meshes.

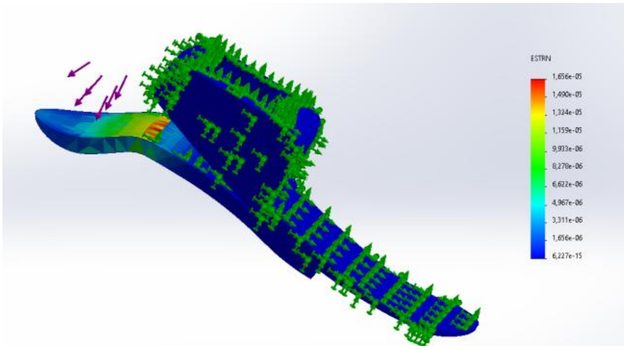

Fig.3 - Deformation at the first contact of the heel with the ground.

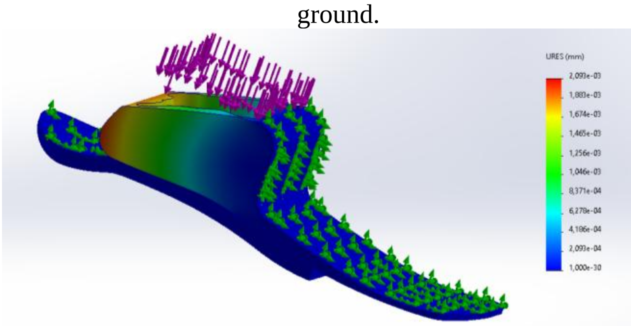

Fig.2 - Displacement in the phase of full support on the ground.

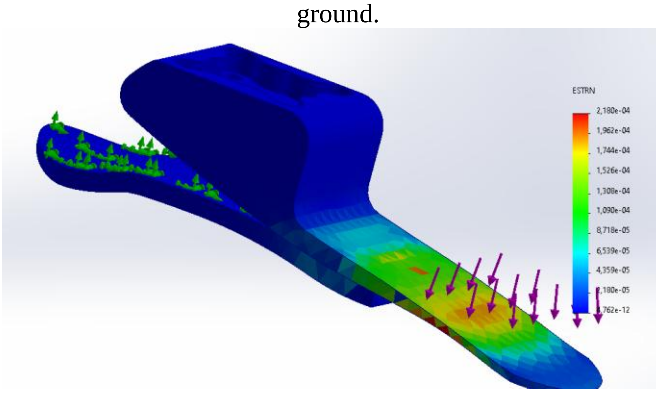

Fig.3 - Tension on the von Mises scale in the final stance phase.

IV. CONCLUSIONS

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.

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