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NUMERICAL AND EXPERIMENTAL DEVELOPMENT OF AN ENHANCING MOBILITY ORTHOSIS FOR VICTIMS OF LOWER LIMBS TRAUMAS USING HONEYCOMB TYPE SHOCK ABSORBER

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Abstract. *Since the invention of crutches back in World War I, there has been little development on conceptual terms on the mainstream market. Therefore, one of the best-known orthosis for lower limb injuries recovery assistance has kept its archaic design for 100 years. This work aims to design, simulate (FEM) and test a new knee-ankle-foot orthosis (KAFO) concept that would have superior performance, ergonomics, and improved mobility for the user when compared to standard crutches. The central goal was achieved by the thorough investigation of the biomechanics of walking, the use of carbon fiber, 3D-printing and development of a polyurethane honeycomb structure to act as the shock absorber and naturalness of walking. A new concept was developed based on anatomic and engineering inputs, the FEM analyses delivered the expected theoretical results and upon prototyping, difficulties working with the PU part were found and latter improvements on the mathematical model for the shock absorber were done. The final structure delivered the desired weight reduction compared to a standard crutch, superior performance and ergonomics, good mechanical resistance and the ability to free the hands of the patient while recovering.*

Keywords: *Finite Elements Method, Honeycomb Structure, Carbon Fiber, Orthosis, Lower Limb*

1. INTRODUCTION

With the aim of providing mobility improvement to a certain portion of society and the desire of acting with biomechanics, this work aimed to build up a new concept of orthosis to replace the current model of crutch. This century-old concept of orthosis, crutch, was invented over the World War I, and it hasn't had great development ever since. In addition, based on clinical surveys that indicated lower limb fractures as the most frequent ones (Salvo, 2017), an improvement study of this device has become even more relevant.

In order to develop an orthosis to assist patients' locomotion that has had fractures in their lower limbs, which offers superior results to the conventional crutches, this work shows the description of the steps of conceptualization, design, finite element method (FEM) simulations, prototyping, manufacturing and experimental tests of an orthosis that offers greater ergonomics and autonomy for the patient, protecting the injury region to allow a more efficient recovery.

Therefore, it is to be expected the presentation of a concept that fills these requirements and offers better aid to patients during their recovery process. An orthosis is a device that will temporarily or for a lifetime, aid a limb that is weakened by a condition. The device developed in this work targets attend specifically people who have suffered injury on lower limbs (knee, ankle or feet) and will need temporary aid.

2. DEVELOPMENT

2.1 Design e CAD Modeling

Theoretical and empirical studies were carried out to better comprehend the dynamics of the human gait to identify the kinematics, iterations of the different joints, proportions and activation of different parts of the legs for effort distributions and impact absorption, and therefore, to define the best point of support for this new orthosis. The gait depicts the movement of the body's center of mass due to the space, with the lowest energy consumption (Young et al.

2011), where the connection between the hip and the femur is the body's center of gravity, which oscillates vertically in sine wave form, from 30mm up to 40mm - peak to peak (Webster and Murphy, 2011).

Once the measurements of the human leg were obtained (for an individual 1.76m tall, whom was used during ergonomic tests), being 500mm from the ankle to the knee and 450mm from the knee to the femur head, and keeping the concept of free-hands that was set to provide greater autonomy to users by releasing the hands or arms assistance to bear body and gait movement, the main guidance for the orthosis' construction were outlined and it was chosen that the orthosis should be fixed below the thigh, when worn. For such a mechanical request condition, the best angle was also identified for a greater sense of safety when using it, resulting in the curvature and dimensions of the part below (Fig. 1), called "rod", with a function of support, distribution of forces and immobilization of the injury region.

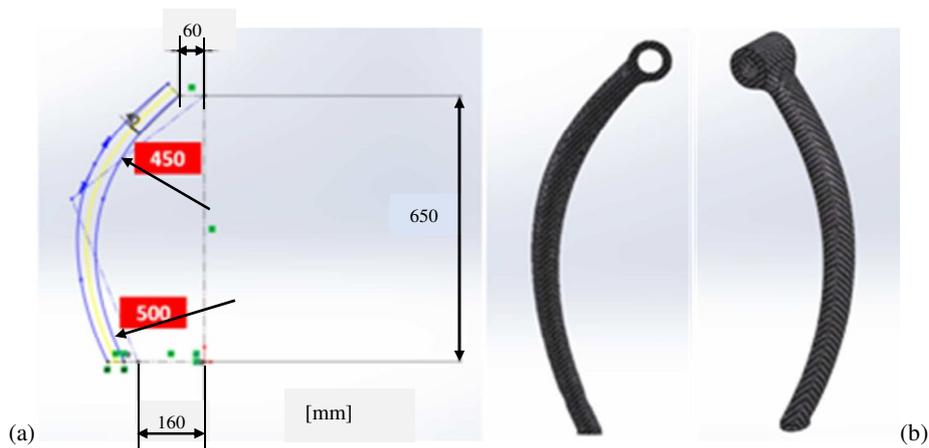


Figure 1. (a) 2D rod model in detail, (b) side view and isometric view of the rod.

Although of apparent simple geometry, the rod was not design symmetrically all over. Its curvature does not follow a constant radius and the elliptical section also does not have the same radius throughout the entire length of the body. There is a joint that on its bottom extreme serves as the connection point with the next part and the top extreme that allows the connection with the seating through an axis is not centered to the curvature's center line. The design process of this part relied on multiple simulations steps that allowed both ergonomics improvement as mass reduction. Figure 2 illustrates the different versions that were created, simulated and optimized, since the first sketch that was brought to a CAD ambient until the ultimate model to attend the boundary conditions of the product.



Figure 2. Rod versions demonstrating the optimization process.

The boundary conditions of the presented problem were defined to support a body of 80kg weight, where the dynamic effort exerted on the legs during walking of 2.9m/s speed, is about 1,500N (Romanzoti, 2011 and Lebrão, 2007). In addition, the project should guarantee the mass of the orthosis to be lesser than 2kg, aiming to have another clear advantage point against standard crutches, since the average weight of them turns around 2kg (Hatem, 2017).

Still in the development stage of the components, the foot part was responsible for the impact damping system that would enable the vertical displacement of 30 - 40mm, which happens during the human body's gait movement. Once the device aims to be a better ergonomical and anatomical fit than those already available, it should be able to allow a

gait movement as close as the real one. For that purpose, a passive damping system was developed based on the honeycomb concept (Fig. 3), commonly used in airless military tires.

This choice occurred due to the need for the system to be light, resistant, flexible and mainly inexpensive. The foot design was based on the papers written by Umesh and Amith (2016) as well as Aboul et. al. (2015), who analyzed behaviors in a wide variety of honeycomb designs using the numerical simulation software ANSYS Mechanical. In their publication, Pewekar and Gaikwad (2018) shows that the spokes - structures that act as lattices for the polymer - must be strength, to support the demands of traction and compression and also must have a rigid behavior to limit the exaggerated deformation of the structure.

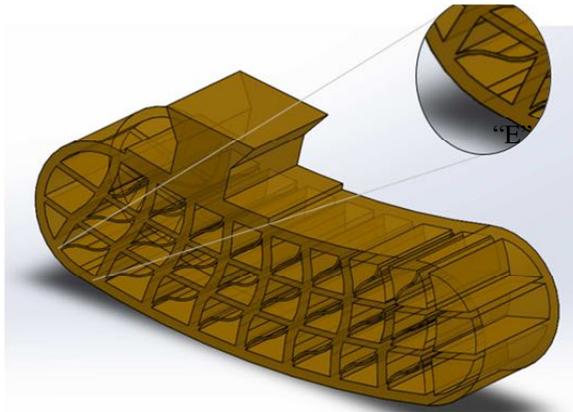


Figure 3. 3D Model of the honeycomb foot. A spoke is shown in detail “E”.

Similar to the rod development process, this part was also improved through multiple steps of numerical simulations using the software ANSYS with results validated through experimental tests. The unusual design was based on the works of Aboul et al. (2015), Umesh and Amith (2016) and Pewekar and Gaikwad (2018), in addition to the commitment of develop a part that actually works like a human foot.

Figure 4 presents the evolution of the foot. It is possible to see a clear change in concept from the first two versions to the 3rd version and further, that is due to the fact that after extensive research, trying to develop a part on the lines of athletic performance prosthetics would cost more and increase the manufacturing complexity. From this point on, polymeric material seemed the best option and finding a structure that would be acceptable was made necessary.



Figure 4. Foot versions versions demonstrating the optimization process.

To allow the functionality of the orthosis, connecting parts have also been designed, simulated and tested. Such as the final CAD models shown on Fig. 5. There is a joint to attach the honeycomb foot to the rod, and another connecting point between the thigh seat and the rod's hub that is assembled through a massive shaft (pivot). The seat and rod are attached to the patient's body using straps commonly used in orthopedics. Therefore the orthosis is composed of four main parts: the rod, the foot, the joint and the seat.



Figure 5. (a) Exploded view of the orthosis (CAD model); (b) complete device; and (c) ergonomic test simulation.

2.2 Materials, Simulation and Prototyping

Aiming to meet the criteria of strength, rigidity and mass, during the prototyping period, carbon fiber 0,175kg/m² was applied over the rod and seat parts. Polyurethane (65 Shore A) was used to produce the honeycomb foot and PLA (Polylactic Acid) for connection pieces. The materials have been selected through a study of performance parameters such as the relationship between mechanical strength and density of various candidate materials through the software CES EduPack.

Before the final prototyping, numerical simulations were performed through the software ANSYS - Composite Pre-Post module - for the rod. For the modeling and verification of its safety factor, the failure condition was applied by Tsai-Wu criterion. The results of the main analyzes are presented in Fig. 6, which met the criteria and showed a satisfactory result of resistance and rigidity with a final mass of 0.9kg, maximum deformation of 11.8mm; von Misses equivalent stress of 254MPa and Tsai-Wu maximum criteria of 0.875.

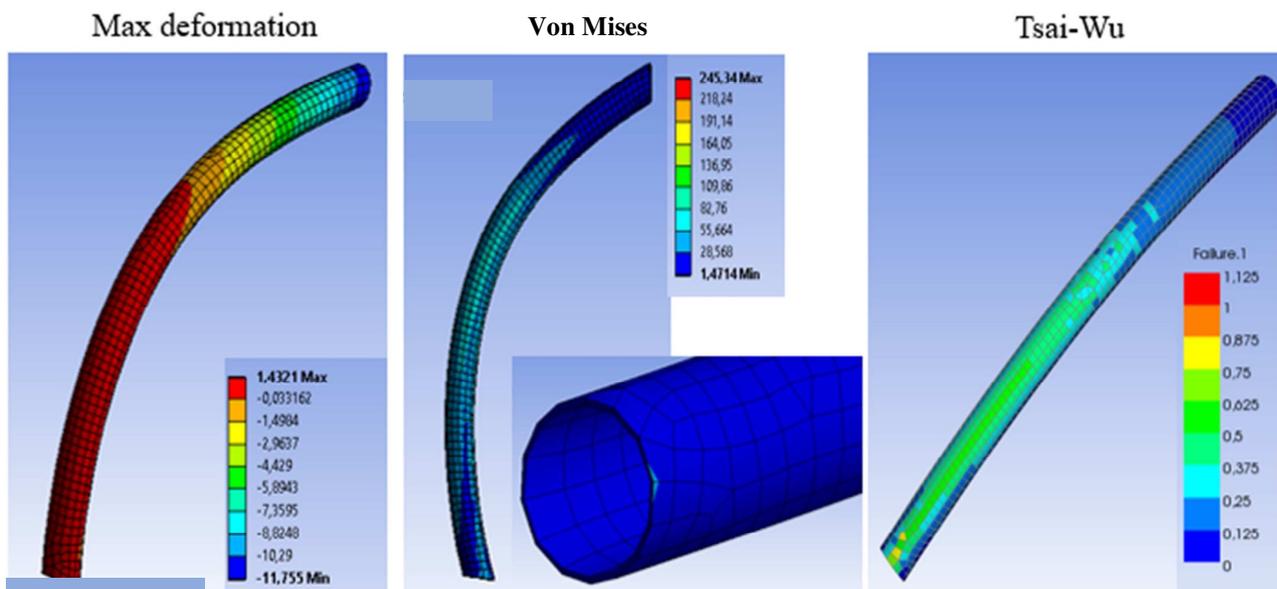


Figure 6. Rod FEM simulation.

The prototyping of the rod was carried out in the materials' laboratory of Instituto Mauá de Tecnologia in two main stages. The first one consisted of printing its "skeleton" in a 3D printer, with PLA material having 10% density, according to Fig. 7 (a), where it is possible to identify the rod was printed in 6 parts due to the limitations of available area inside the printer and the difficulty of depositing the polymeric material vertically following the rod's curvature. This pieces were glued together using an appropriate PLA glue. The second step was the lamination of carbon fiber over the "skeleton" using the manual lamination method that adds the carbon fiber with resin over the desired surface and ending it by applying peelply and infusion bag to absorb the excess resin from the part, Fig. 7 (b), (c) and (d).



Figure 7. Rod prototyping: (a) 3D print model of the 'skeleton' made of PLA, (b) lamination process; (c) application of resin, *peelply*, (d) infusion bag.

In relation to the honeycomb foot, the results of the nonlinear FEM simulation stayed also within the acceptable range to meet the design requirements, such as maximum deformation of 18.7mm and von Mises equivalent stress value lower than 6.0MPa. The manufacturing was done by the gravity injection process of liquid PU in silicone mold. The mold was produced from a 3D printed piece of the foot, also in PLA. Figure 8 illustrates the numerical simulation results performed for the foot.

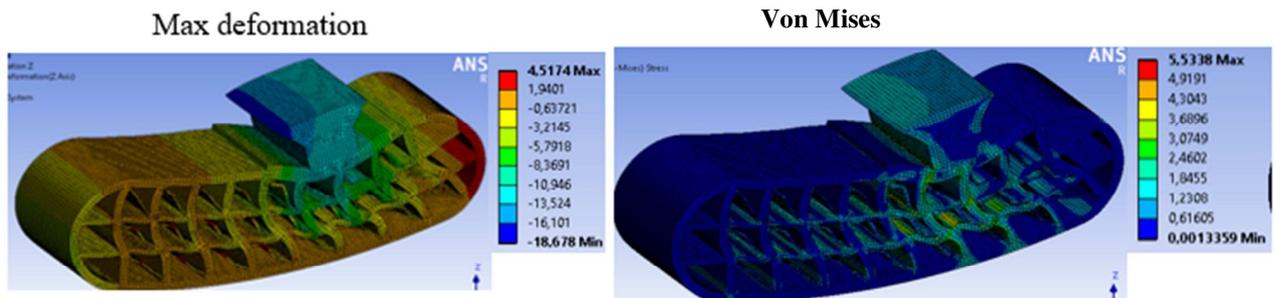


Figure 8. Honeycomb foot: nonlinear simulation in ANSYS.

Although showing satisfactory results on the numerical simulations, the prototyping process of the foot ended up offering additional challenges. As illustrated on Figure 4 previously the foot went through 6 versions, being the 6th the chosen to be manufactured considering the simulations results. The 60mm of width part with its 24 spokes failed during the mold phase, when removing the PLA foot from it caused the mold's rupture according to Fig. 9. It is believed that the excessive friction due to the complex geometry and small spaces between spokes and walls resulted in the mold loss, then simplifying the process would be the best solution. The solution for prototyping was found dividing the 3D printed foot in three equal slices of 20mm and removing all the spokes, and producing another silicon mold according to Fig. 10 (a) and (b), this time reaching successful upon removal from mold.

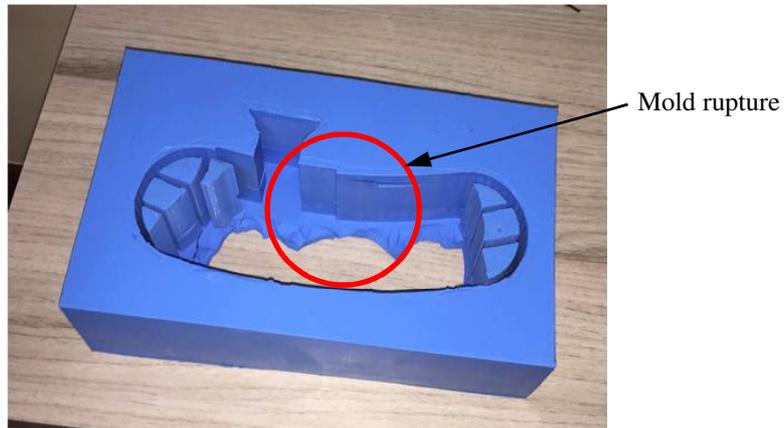
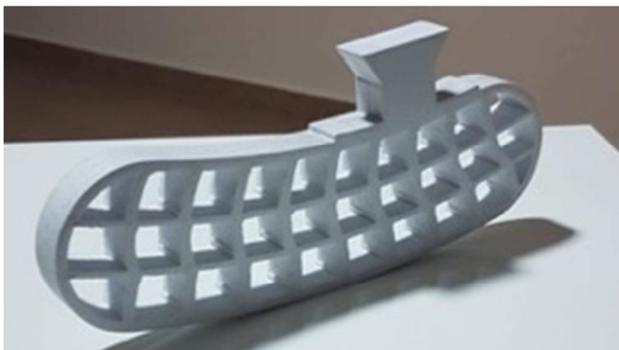
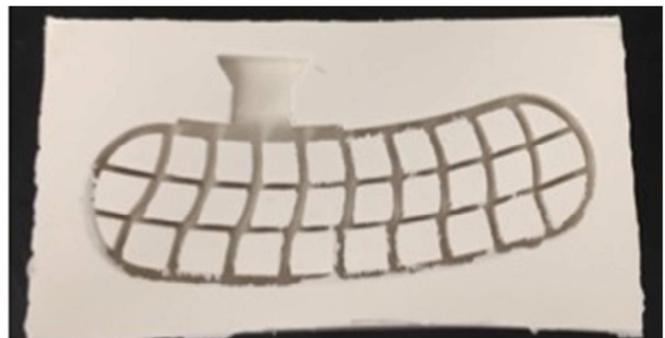


Figure 9. First produced mold aiming to manufacturing foot's version 6.



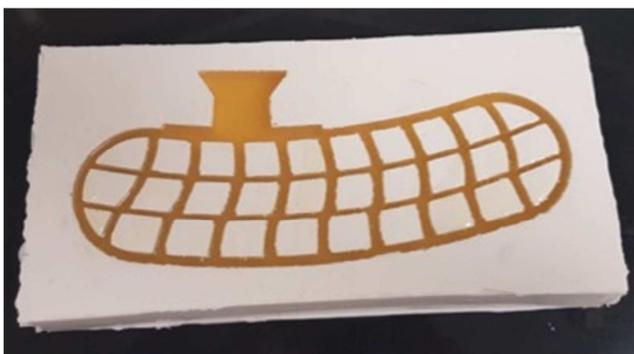
(a)



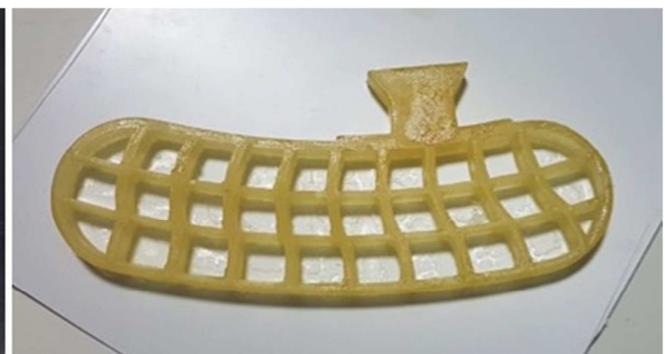
(b)

Figure 10. Second confection of the mold considering the foot made in steps.

After the gravity injection and curation of the PU rubber, the three parts like the one showed at Fig. 11 were glued together using a specific glue for polyurethane. In the next step this foot prototype will be subjected to compression tests in order to validate the deformations obtained during numerical simulations and monitor the shear behavior of the bonded slices.



(a)



(b)

Figure 11. Representation of one third of the foot prototype - version 6.

In relation to the seat and the connection piece (joint) analysis, the FEM simulations presented vertical deformation of less than 0.05mm and a safety coefficient superior of 2.7 for both parts through von Mises criteria. After prototyping all pieces, the orthosis was assembled and submitted to experimental effort tests and ergonomic tests. The rod, the foot, the joint (Fig. 12) and the seat were validated, which withstood a dynamic force of up to 5,000N, approximately 3 times the effort used as the contour condition in this project.



Figure 12. Prototype of the Joint printed using PLA.

For an experimental result of vertical deformation of 28.2mm, a force of approximately 329.5N was applied (Fig. 13), which approximates the values reached in the numerical simulation of the final version of the foot, where the maximum deformation was 30.9mm for the same applied force, reaching a relative error of 8.7%. This result validates the use of the numerical model of the foot, which at a future stage should be complete manufactured to avoid the possibility of failure by shearing between layers.



Figure 13. Foot compression test.

Figure 14 shows the prototype of the orthosis developed and validated in this work. The device was worn and tested during the regular gait movement, as well as going up and down stairs, while entering and leaving a car, was also worn by a heavier person than the project's reference of human and finally tested in terms of convenience as opening doors, ease to wear and remove it from the body and carrying stuff.



Figura 14. Developed prototype named MECHLEG.

3. CONCLUSION

With the aid of ergonomic studies, numerical simulations and laboratory tests, it was concluded that the central objective of creating a concept of orthosis that didn't require the use of the hands to assist in the gait was reached. The final mass of the orthosis was 1.53 kg, and the limit parameters of mechanical resistance and maximum deformations were reached, obtaining positive results in terms of offering better ergonomics, safety, naturalness to walk and autonomy to the user.

4. ACKNOWLEDGEMENTS

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