Macromolecular Symposia

www.ms-journal.de

CAD Optimization of an Ankle Foot Orthosis Using Lattice Structures

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Additive manufacturing technologies have been extensively used in the development of medical products, mainly due to its' complex geometry advantages. Orthoses are among the most common medical devices redesigned for additive manufacturing, as patient specific products. Currently, most of these orthoses are thermoformed from plastic. Advantages of custom and topologically optimized orthosis are mentioned by literature. The aim of this paper is to study the possibility of using lattice structures for the design and development of a functional ankle foot orthosis. The mechanical behavior of an ankle foot orthosis is studied, by optimization using lattice structures, for three different materials, to reduce its weight but also to keep its original resistance. The resulted ankle foot orthosis model is loaded with 500 N, to simulate the real-life value of the force that is applied normally on an actual orthosis. Research results show that the optimum material is PET-G for both 50% and 100% lattice values.

1. Summary

This paper proposes the optimization of an Ankle Foot Orthosis using the Altair Inspire Software to modify its topology and to make it lighter for the user and also to maintain its original structural integrity.

2. Proposal

This paper studies the behavior of an ankle foot orthosis, on which three different materials were applied: polylactic acid (PLA), polyethylene terephthalate glycol (Pet-G), and high impact polystyrene (Z-Hips). The ankle foot orthosis was optimized using lattice structures to reduce its weight but also to keep its original resistance. The resulted ankle foot orthosis model was suppressed under 500 N, to simulate the real-life value of the force that is applied normally on an actual orthosis.

3. State of the Art on Ankle Foot Orthoses

One of the most recommended lower limb assistive devices is ankle-foot-orthoses (AFO). They are designed to fit everyone's foot, leg, and ankle, stopping just before the knee. They are generally constructed of high-temperature plastic and are used to treat a wide range of ailments. Muscle weakness, joint instability, and high muscle tone are examples of these conditions.[1]

AFOs come in a variety of shapes and sizes, with each one tailored to the specific needs of each patient.[2] Solid ankle foot orthoses (SAFOs) are stiff ankle braces that support the ankle without allowing it to move. In comparison to a solid AFO, a DAFO (dynamic foot orthoses) allows the ankle to dorsiflex and plantarflex somewhat.[3] The HAFO (Hinged ankle foot orthosis) is another form of dynamic AFO that is used to limit three-dimensional ankle mobility and the ankle joint's sagittal plane movement.[4] The GRAFO (Ground reaction foot orthosis) is a device that is intended to prevent excessive knee flexion.[5] With the aid of a solid portion positioned just below the knee, this sort of orthosis prevents the knee joint from moving forward. Posterior leaf spring ankle foot orthosis (PLS AFO) improves locomotion quality by controlling plantarflexion during heel strike and swing phase.[6] Traditionally, ankle foot orthoses are manufactured through molding, where the lower part of the leg is casted by producing a positive cast to represent patients' shank, ankle, and foot.[2] The overall weight of an AFO manufactured through these processes is determined exclusively by the materials used. The research of the authors aims at reducing the weight of an AOF while retaining its' functionality.

4. Optimization of Ankle Foot Orthoses

A computer aided design (CAD) model of the actual ankle foot orthosis was realized in OnShape (**Figure 1**). The model was then exported as a *.STEP file to undertake the FEA simulation using the software Altair Inspire.

After the step file was imported in Altair Inspire, in order to keep some functional surfaces of the orthosis, a shell was set. The selected kept surfaces are shown in gray in Figure 1. After the surfaces were selected, using the option Partition, a shell with a thickness of 3 mm was made. Only the portion that is in the shell was modified during the simulation. After the partitions were made two fill methods for lattice structures were selected: 50% and 100% density. Stress scenario involved defining the fixed areas and the main force. A 500 N force was chosen to simulate an estimate of 50 kg of weight. It is important to remember that the

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The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/masy.202100393

DOI: 10.1002/masy.202100393

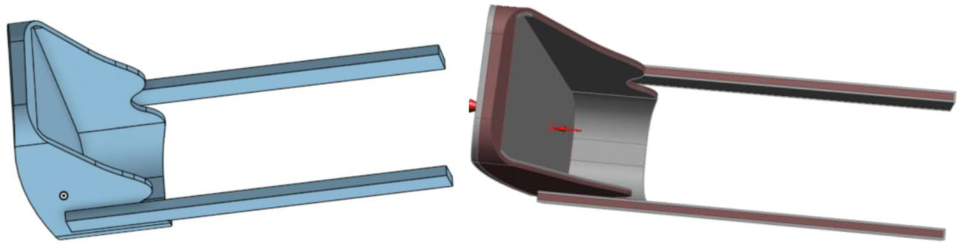

Figure 1. CAD model of AFO and partitioned surfaces (Altair Inspire).

Table 1. Characteristics of chosen materials for optimization.

Characteristics	Pet-G	PLA	Z-Hips
Density	1.18 g cm^{-3}	1.24 g cm^{-3}	1.04 g cm^{-3}
Tensile strength	24 MPa	70 MPa	34.3 MPa
Elastic modulus	2.26 GPa	3.12 GPa	2.26 GPa

orthosis was not designed to be stepped with the whole weight of a person, but to be used as a support in walking.

The chosen materials for the simulations were PLA, Pet-G, and Z-Hips, with their main input characteristics presented in **Table 1**.

5. Results and Discussion

FEA simulations were undertaken, and three types of results were chosen for interpretation: von Mises stress, Principal stress, and Principal strain for each type of material. Graphical results are presented in **Figure 2**.

Based on the obtained FEA results the performance of all three materials was compared. Results are given for high impact polystyrene in **Table 2**, for polylactic acid in **Table 3**, for polyethylene terephthalate glycol in **Table 4**.

Results presented in Tables 2–4 show that PLA and PET-G act identical in all three analysis types. Moreover, the materials have the same performance for both 50% and 100% lattice density. This shows that both chosen materials are reliable and have stable outputs throughout the imposed optimization criteria. Nevertheless, results show that Z-Hips withstand the highest values of stress on the 50% lattice density scenario.

Table 2. Z-Hips FEA results.

Z-Hips	100% Lattice	Von Mises	Min [MPa]	Max [MPa]
			0.0000000005312	0.3356
		Principal stress	Min [MPa]	Max [MPa]
			−0.0145	0.02352
		Principal strain	Min [MPa]	Max [MPa]
			0	0.0004952
	50% lattice	Von Mises	Min [MPa]	Max [MPa]
			0.0000000006857	1.47
		Principal stress	Min [MPa]	Max [MPa]
			−0.0169	0.06398
		Principal strain	Min [MPa]	Max [MPa]
			0	0.0000003867

Figure 2. Lattice optimization results for Z-Hips – 50% density: Von Mises, principal stress, principal strain (left to right).

Table 3. PLA FEA results.

PLA	100% Lattice	Von Mises	Min [MPa]	Max [MPa]
			0.0000000006434	1.43
		Principal stress	Min [MPa]	Max [MPa]
			−0.0175	0.06602
		Principal strain	Min [MPa]	Max [MPa]
			0	0.00002851
	50% lattice	Von Mises	Min [MPa]	Max [MPa]
			0.0000000006434	1.43
		Principal stress	Min [MPa]	Max [MPa]
			−0.0175	0.06602
		Principal strain	Min [MPa]	Max [MPa]
			0	0.00002851

Table 4. PET-G FEA results.

PET-G	100% lattice	Von Mises	Min [MPa]	Max [MPa]
			0.0000000003659	1.43
		Principal stress	Min [MPa]	Max [MPa]
			−0.0175	0.06602
		Principal strain	Min [MPa]	Max [MPa]
			0	0.00003185
	50% lattice	Von Mises	Min [MPa]	Max [MPa]
			0.0000000003659	1.43
		Principal stress	Min [MPa]	Max [MPa]
			−0.0175	0.06602
		Principal strain	Min [MPa]	Max [MPa]
			0	0.00003185

6. Conclusions

The current research proposed a behavior study of a lattice optimized ankle foot orthosis. Altair Inspire software tool was used to modify the product topology and assign two lattice densities, considering an overall weight reduction aim, while retaining mechanical performances under a specific stress scenario. Three materials were used for the FEA simulations. After analyzing each material and its behavior during stress it was concluded that the best option for the ankle foot orthosis is Z-Hips. For this material the 50% lattice structure density is the best choice to withstand the forces that are applied to it. Although with lower calculated values, results also showed that PLA and PET-G could be a viable option if consistency throughout lattice variation is desired. Future developments of this study involve topology optimization of the AFO model in order to reduce more of its weight and keep its resistance, therefore ensuring a better customer compliance when the ankle foot orthosis is used. The resulted model will also be converted to an *.STL file and optimized so that it can be 3D printed, to be tested under real conditions. Due to some software limitations in what concerns the application of the lattice structures properly, the model needs to be printed in order to analyze if under real parameters it behaves similarly with the FEA simulations.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

ankle-foot-orthosis, lattice, optimization, product design

Received: September 28, 2021
Revised: November 4, 2021

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