Enhancing 3D Printed Bed-Resting Ankle-Foot Orthosis Design through Topology Optimization

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Abstract: *Ankle-foot orthoses (AFOs) are devices used to support patients with ankle muscle weakness from conditions like stroke or cerebral palsy. This project designs a lightweight AFO for bedridden patients, focusing on engaging the calf muscle and enhancing structural performance while minimizing material use through topology optimization using CAD software, SolidWorks. The study analyzed three materials: Polylactic Acid (PLA), Nylon 6, and Acrylonitrile Butadiene Styrene (ABS). Weight reduction was assessed using Cura software, dividing the AFO into foot and shank models with specific loading and boundary conditions. Five levels of topology optimization (10%-50% weight reduction) were proposed, showing similar weight reduction patterns across materials. However, while weight was reduced, filament usage and printing time were not, as the optimized models required additional support elements during printing. Thus, topology optimization reduces the product's weight but not necessarily filament usage in 3D printing.*

Keywords: Bedridden; Assistive Device, Ankle Foot Orthosis, Topology Optimization; 3D Printing

1. INTRODUCTION

Ankle-foot orthoses (AFOs) are essential medical devices designed to support and stabilize the ankle and foot in individuals with muscle weaknesses, such as those resulting from conditions like stroke, cerebral palsy, spinal cord injuries, or peripheral nerve damage [1, 2]. These devices play a crucial role in enhancing mobility, preventing deformities, reduce pain and improving the overall quality of life for patients [3]. Traditional AFOs are typically manufactured using methods such as molding and casting, which can be time-consuming and offer limited customization [4].

In recent years, the advent of 3D printing technology has revolutionized the field of orthotics, enabling the creation of highly customized, lightweight, and efficient orthotic devices [4, 5]. 3D printing allows for rapid prototyping and fabrication of complex geometries that are difficult or impossible to achieve with conventional manufacturing techniques [6, 7, 8]. The success of 3D printed products typically involves a comprehensive design process to predict their performance, including design reviews, finite element analysis, optimization processes, and adaptability to various engineering fields. [9, 10, 11]. The selection of the best design, parameters, materials can be forecasted earlier to avoid wastage and failure [12, 13]. Among the materials commonly used for 3D printing AFOs are Polylactic Acid (PLA), Nylon 6, and Acrylonitrile Butadiene Styrene (ABS). Each material offers distinct mechanical properties and benefits. PLA is known for its biodegradability and ease of printing, making it a popular choice for prototyping and low-load applications [14, 15]. Nylon 6 is favored for its high strength, flexibility, and durability, making it suitable for applications requiring higher mechanical performance [16]. ABS, on the other hand, offers a good balance of strength, toughness, and thermal stability, making it widely used in various engineering applications [17].

Topology optimization is a computational design approach that has gained significant attention in the field of orthopedic devices [18]. This method involves iteratively removing material from a design space to achieve the desired performance while minimizing weight and material usage [19]. By leveraging topology optimization, designers can create AFOs that are not only lightweight but also structurally efficient [20]. Several studies have demonstrated the benefits of using topology optimization in orthotic and prosthetic device design [21]. For example, Kladovasilakis et al. (2023) applied topology optimization to the design of a tibial implant, resulting in significant weight reduction and maintained mechanical performance [22]. Similarly, Gupta et al. (2020) utilized topology optimization to develop dental implants, achieving optimal structural integrity with weight reduction of 32% to 45% [23].

The objective of this project is to design a lightweight, optimized bed-resting ankle-foot orthosis (AFO) using SolidWorks software and to evaluate its performance with three different 3D printing materials: PLA, Nylon 6, and ABS. The study aims to enhance the structural performance of the AFO while minimizing material usage through topology optimization. The project involves creating initial designs, applying realistic loading and boundary conditions, performing topology optimization, and evaluating the 3D printing parameters using Cura software. The ultimate goal is to propose an efficient, practical solution for bed-ridden patients that

maintains muscle engagement, particularly in the calf muscle, and offers improved patient comfort and mobility.
By integrating advanced CAD software, topology optimization techniques, and modern 3D printing materials, this study seeks to advance the design and manufacturing of ankle-foot orthoses, providing valuable insights for the development of more effective orthopedic devices.

2. MATERIALS & METHOD

The methodology comprises several stages, including initial design, material selection, topology optimization, and evaluation of 3D printing parameters. The entire process was conducted using SolidWorks (Dassault Systems SolidWorks Corp., USA) and slicing software; Ultimaker Cura (Ultimaker 2020), for designing and 3D printing evaluation.

2.1 3D Model of Ankle Foot Orthosis

The initial design of the AFO was created using SolidWorks (Dassault Systems SolidWorks Corp., USA). The design process considered ergonomic and functional requirements to ensure patient comfort and effective muscle engagement. The AFO was divided into two main parts: the foot model and the shank model.
The design of the model was considered for (i) Ergonomic fit for bed-ridden patients, (ii) Proper alignment to engage calf muscles and (iii) Structural support for the foot and ankle.
Three different materials were chosen for this study based on their mechanical properties and suitability for 3D printing: Polylactic Acid (PLA), Nylon 6, and Acrylonitrile Butadiene Styrene (ABS). The properties of these materials are summarized in Table 1.

Table 1. Material properties of the selected materials [12, 13, 15]

	Young's Modulus (GPa)	Tensile Strength (MPa)	Density (g/cm³)
PLA	3.5	60	1.25
Nylon 6	2.8	75	1.14
ABS	2.1	40	1.04

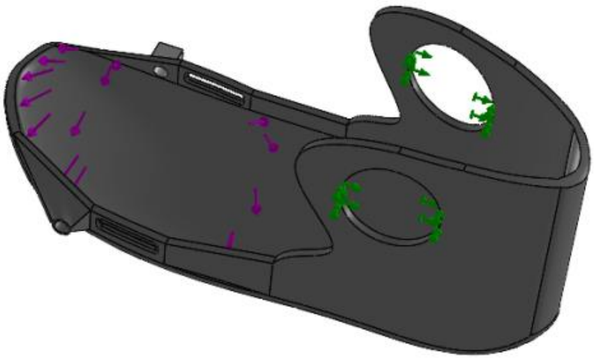
2.2 Topology Optimization Process

The topology optimization by reducing product weight was conducted to minimize the weight of the AFO while maintaining its structural integrity [18, 19]. Solidworks simulation was used to perform the topology optimization process. The steps involved are as follows:

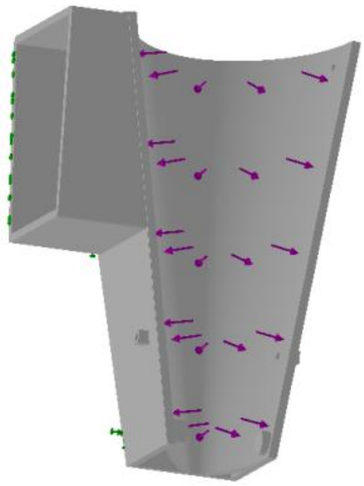
i. Define optimization objectives: Minimize weight while maintaining structural performance.
ii. Apply load conditions and constraints: Realistic load conditions were applied based on typical forces experienced by bed-ridden patients (as shown in Fig. 1)
iii. Run optimization: Use SolidWorks to iteratively remove inefficient areas.

2.3 Evaluation of 3D Printing Parameters

The optimized AFO models were evaluated for 3D printing using Cura software. The total weight and predicted printing time were assessed to determine the efficiency of the optimized designs. Evaluation Criteria to be considered include the total weight of the printed model, predicted printing time, and the need for additional support elements during printing.



(a)



(b)

Fig. 1. 3D model and boundary condition loads for (a) foot and (b) shank models of bed resting ankle foot orthosis.

3. RESULTS & DISCUSSION

The results are analyzed and discussed in terms of weight reduction, structural performance and material efficiency for the three selected materials: PLA, Nylon 6, and ABS.

3.1 Topology Optimization by Reducing Weight

The primary goal of topology optimization was to minimize the weight of the AFO while maintaining structural integrity. The optimization process targeted five levels of weight reduction: 10%, 20%, 30%, 40%, and 50%. Each level was evaluated for the three materials to determine the effects on weight, structural performance, and 3D printing parameters.
Figures 2(a), 2(b), and 2(c) illustrate the optimized models for PLA, Nylon 6, and ABS at the foot and shank parts, respectively.
The optimized designs exhibited significant weight reduction while maintaining structural integrity, as indicated by the similar patterns of weight reduction across all three materials. The reductions were evenly distributed, demonstrating the effectiveness of the topology optimization process in identifying and removing non-essential material.
The design optimization process focused on several key aspects to achieve the desired weight reduction and structural performance. The process had produced designs with simplified geometries, reducing complexity

and potential stress risers. These optimized geometries facilitated easier and more reliable 3D printing, enhancing the practicality of the designs. The optimization process was also performed iteratively, with each iteration refining the design to balance weight reduction and structural performance. This iterative approach allowed for continuous improvement and fine-tuning of the AFO design.

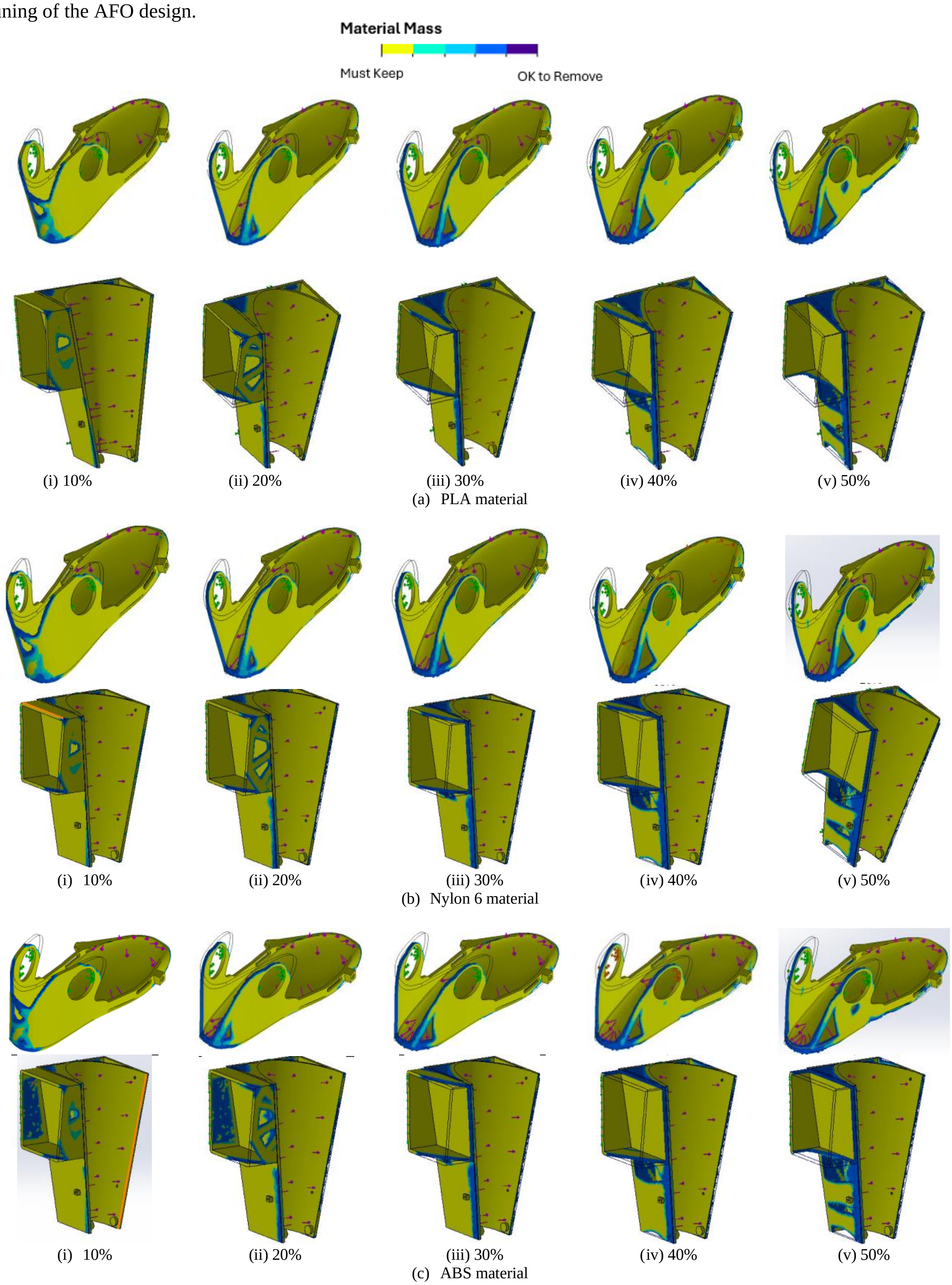


Fig. 2. Topology optimization model for foot (top) and shank (bottom) models by reducing weight at (i) 10%, (ii) 20%, (iii) 30%, (iv) 40% and (v) 50% for three different materials

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3.2 Changes of Printing Filament Usage and Printing Time

Cura software is used to predict the product weight and processing time. The general print settings, including layer height, wall thickness, infill density, infill pattern, and printing speed, are shown in Fig. 3. All models require support elements during the printing process to support overhang angles. To predict changes in printing time and filament usage for different topology-optimized models, all models were set with similar settings.

Fig. 4 compares the total filament used (printing weight), product weight, and printing time for all six models made with PLA material. The foot model (Fig. 4a) indicates significant weight and filament usage reduction at each 10% stage. However, the processing time only decreases by 1–5% with each 10% weight reduction. This is due to the necessity of support elements in the printing process. The new shape of the product still requires additional support during fabrication. A similar pattern is observed in the shank model (Fig. 4b). The larger size of the shank model requires more time to fabricate, with up to 20,062 minutes needed to complete, while the foot model only requires 2,261 minutes to complete for 100% infill.

Although topology optimization successfully reduced the weight of the AFO, the practicalities of the 3D printing process introduced some challenges [12, 13]. Despite the reduction in the overall weight of the AFO models, the printing process still required a significant amount of filament due to the need for support elements. These support structures are essential to ensure the stability and integrity of the complex geometries produced by the optimization process. As a result, the total amount of filament used and the time required for 3D printing increased, offsetting some of the benefits of weight reduction. This highlights a crucial trade-off between achieving a lightweight design and the practicalities of 3D printing. The increased printing time and filament usage due to support structures suggest that while topology optimization is effective in reducing material usage in the final product, it also necessitates careful consideration of the 3D printing process to fully realize these benefits.

Future research could explore methods to minimize the need for support structures, such as optimizing print orientation, using advanced support materials, or employing more sophisticated 3D printing techniques to reduce filament usage and printing time.

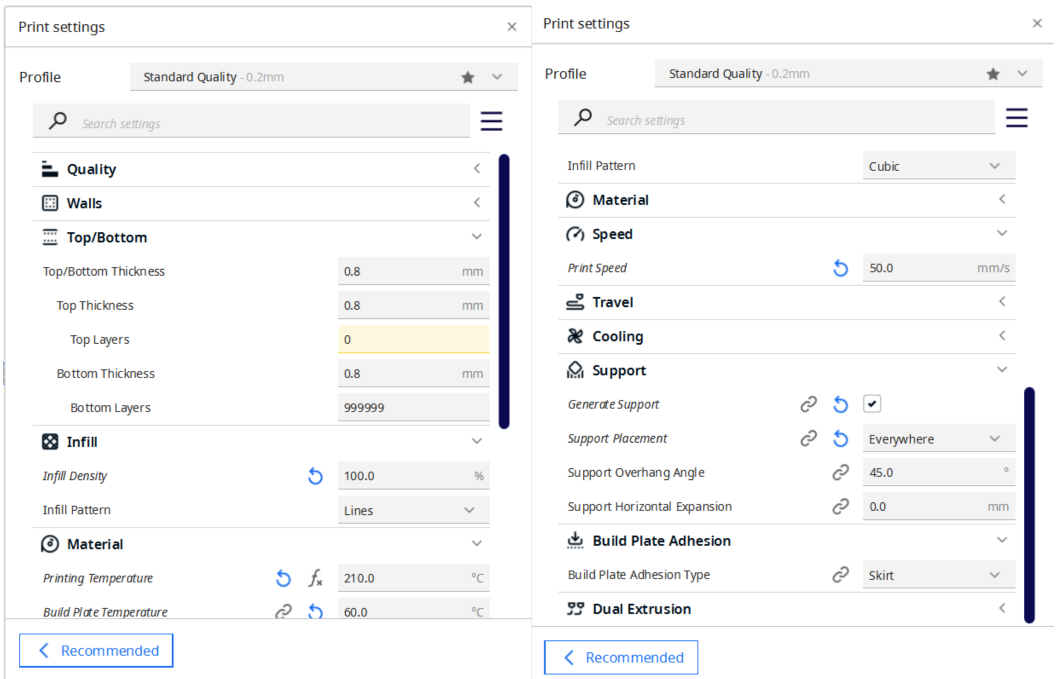
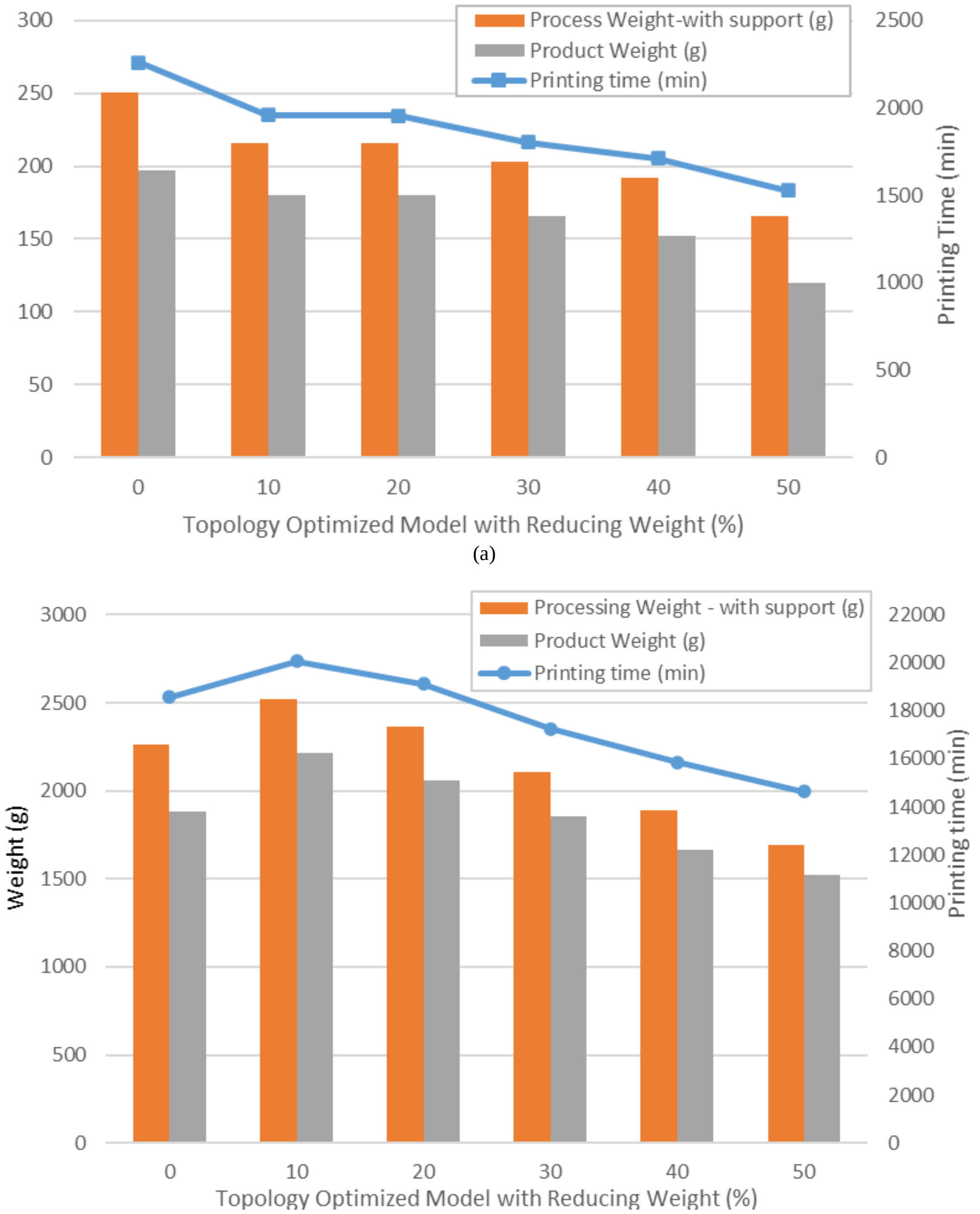


Fig. 3. Parameter setting in Cura software to predict the product weight and printing time



(a)

(b)

Fig. 4. Changes of prototype weight and printing time for (a) foot and (b) shank models with PLA material.

4. CONCLUSION

Topology optimization has proven to be a valuable tool in the design of ankle-foot orthoses, offering significant improvements in weight reduction while maintaining structural integrity. By considering practical fabrication constraints and exploring new materials and techniques, future research can further enhance the efficiency and effectiveness of AFOs. This study provides a solid foundation for the continued development of lightweight, optimized orthopedic devices that improve patient care and mobility.

5. ACKNOWLEDGMENT

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