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Design and Analysis of Various Thermoplastic for Optimized Ankle Foot Orthosis

S F Khan^{1,2}, I Radzmi¹

¹ Sport Engineering Research Centre, Centre of Excellence (SERC), Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia.

² Faculty of Mechanical Engineering Technology, Universiti Malaysia Perlis, Pauh Putra Campus, 02600 Arau, Perlis, Malaysia.

sfkhan@unimap.edu.my

Abstract. An ankle-foot orthosis (AFO) is the brace that provides the assist and support to the patient with dorsiflexor weakness. However, standard AFO does not provide comfortable fit and is quite heavy for the user. The main objective of this study is redesign the standard AFO based on topology optimization to overcome the problems caused by the standardized AFO. With the computer-aided design (CAD), the AFO is designed based on parameters from the actual size of the adult leg. The thickness and the trim lines were also considered during the design the 3D model. The AFO was simulated with different materials and thicknesses to determine the effect on stress and deflection. Three different thicknesses of AFO; 3mm, 4mm, and 5mm and three different materials; polypropylene (PP), high-density polyethylene (HDPE) and polylactide (PLA) were used in the simulation. Shape optimization technique is used to optimize the material usage in the design of the AFO in order to reduce materials cost and weight. The optimized AFO was compared to the original AFO in terms of strength and flexibility. The 3mm and 4mm average displacement increase to approximately from 23% to 24% to all type of materials during foot flat and heel rise. 4mm model maximum stress decrease by 27% during heel strike, 22% during foot flat, and 20% during heel rise. The weight reduction from the initial AFO model to the optimization AFO model for both 3mm and 4mm thickness is 26% weight reduction and for 5mm thickness, is a 19%.

1. Introduction

An orthosis is an externally applied device used to modify the structural and functional characteristics across part of a person's musculoskeletal system. Each orthosis served the purpose of aligning the body segment, supporting joint motion during person's gait, relieving or redistributing weight-bearing forces, protecting from external stimuli, restoring mobility, and minimizing deformities. Ankle foot orthosis (AFO) is a brace used on the lower leg to support and correct the position of the foot and ankle where the foot inability to lift during walking (ankle dorsiflexion), causing the toes to drag or scrape on the ground [1]. AFO can be used to avoid this weakness from occurring by applying it to the leg or through rehabilitation by strengthening the related muscles.

This study is to evaluate the design of posterior leaf-spring AFO for an individual with dorsiflexor weakness and paralysis treatment. AFO is often customized to the lower limb anatomy of a patient and consists of a thermoplastic material such as polypropylene [2]. Conventional customization by taking imprints increase the time consume and labour cost. An alternative method that can be used is to take the parameter of an individual leg by 3D digitizing. The digitized data is used to design the AFO in computer-aided design (CAD). The various CAD model can be used to design and optimize the AFO. The simulation and analysis of the designated AFO will be done by Finite Element Analysis (FEA). A



numerical model is constructed to analyze the reaction between optimized AFO and original AFO model under physical impacts or load. Kubasad et al. [3] describe an optimization study of 3D model of a single piece passive AFO by using the FEA technique of different materials and thicknesses in both static and dynamic analyses. The AFO was optimized by considering the minimum stress-induced, minimum deformation, and allowable factor of safety (FOS) [3]. Better understanding the effect of geometry, material and production process are needed to prevent the fractures on the ankle region [4].

Structural optimisation is a method that maximize the effectiveness usage of fixed quantity of resources to fulfil a given objective. Three categories of structural optimisation exist namely: shape, size and topology. Topology optimization recommends the best material distribution by continuous iterative calculations based on specified constraints and preserve regions in order to attain excellent structural performance [5]. The shapes generated from topology optimisation are often in organic form. Hence the optimal method of fabricating them is by using additive manufacturing technology. Topology optimisation and additive manufacturing have been used to produce a more efficient materials utilization in the design and reduce the time for fabrication of complex shape [6-7].

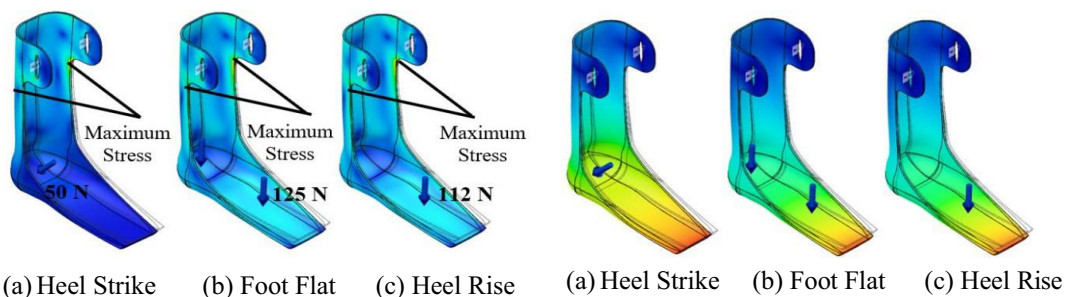
2. Methodology

2.1. Design of AFO

The AFO has a different shape and trim lines from the current AFO model. The AFO is designed with a height of 300 mm, a width of 105 mm, and a length of 250 mm. The AFO has two pinholes for fixed support in simulation.

2.2. Finite Element Analysis of AFO

Polypropylene, high-density polyethylene (HDPE) and polylactide (PLA) are the materials that are applied to the AFO in computer aided engineering module (Table 1). Absolute mesh size is set up to 2.0mm to ensure the result of the simulation is accurate, and the number of the elements and nodes depends on the thickness of the AFO. The value of force exerted is -50N for heel strikes, -125N for foot flat, and -112N for heel rise on the z-plane of the footplate. The forces are taken from the vertical ground reaction force during walking. The result of Von-Mises stress and displacement can be determined from Figure 1 and Figure 2, respectively. The desired thickness and suitable material in designing AFO can be determine from this analysis.



(a) Heel Strike (b) Foot Flat (c) Heel Rise
Figure 1. Stress distribution in polypropylene, 3mm thickness model during three gait phases.

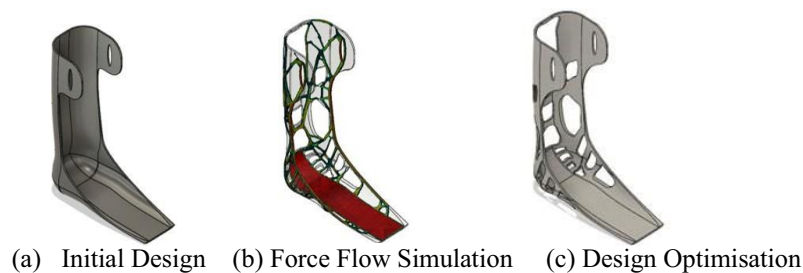
(a) Heel Strike (b) Foot Flat (c) Heel Rise
Figure 2. Displacement in polypropylene, 3mm thickness model during three gait phases.

2.3. Shape Optimization

Shape optimization is selected from the computer aided engineering (CAE) module and all different thicknesses of AFOs are tested to maximum load of 125N. The area which has no load path is removed. However, the total areas removed are different for all thicknesses. Besides, the fillet of 80mm radius is added at maximum stress area to reduce stress at the lateral side of the leg-ankle region, which is the fracture area of the AFO. A comparison between optimized model and original model is carried out to determine the improvement in terms of flexibility and strength of AFO (Figure 3).

Table 1. Materials properties from CAE module

Mechanical Properties	Polypropylene	HDPE	PLA
Young's Modulus (GPa)	1.340	0.911	1.280
Poisson's Ratio	0.39	0.39	0.36
Shear Modulus (MPa)	757.0	320.0	1287.0
Density (g/cm ³)	0.899	0.952	1.252
Yield Strength (MPa)	30.3	20.670	70.0
Tensile Strength (MPa)	36.5	13.780	59.0

**Figure 3.** Shape optimization stages

3. Result and Discussion

The only material that gives the highest amount of the maximum displacement is HDPE, as can be seen from Figure 4. It is expected as this material is the most flexible and desirable choice relative to other types of selected materials, which are more rigid and harder. It is observed that HDPE, polypropylene and PLA produce insignificant maximum stress.

When compared with these three different thickness models, the result from Figure 4 and Figure 5 shows that the value of maximum stress and the displacement decreases as the thickness increase. This trend is similar to other materials.

Table 2 below shows the weight changes from the initial AFO model to the optimisation AFO model in different thicknesses. It can be observed from the table that both 3mm and 4mm thickness experience 26% weight reduction approximately except for 5mm thickness, which is a 19% weight reduction.

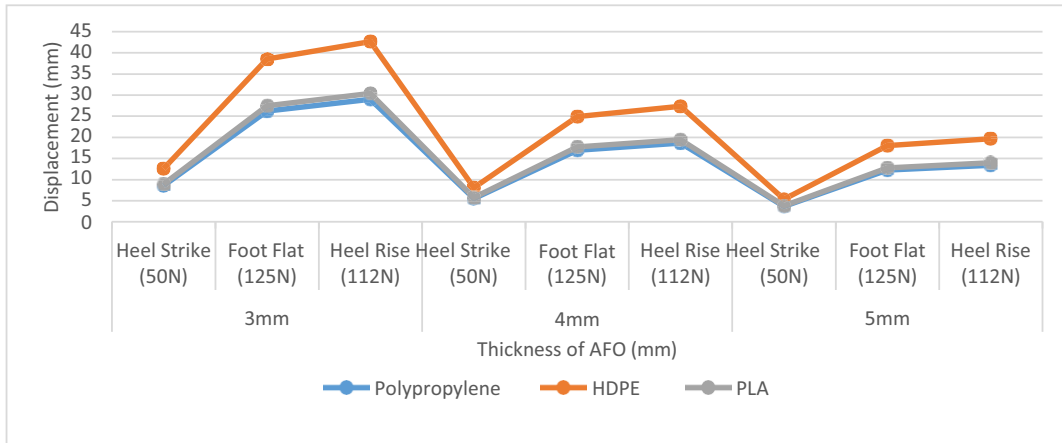


Figure 4. The effect of different materials on displacement

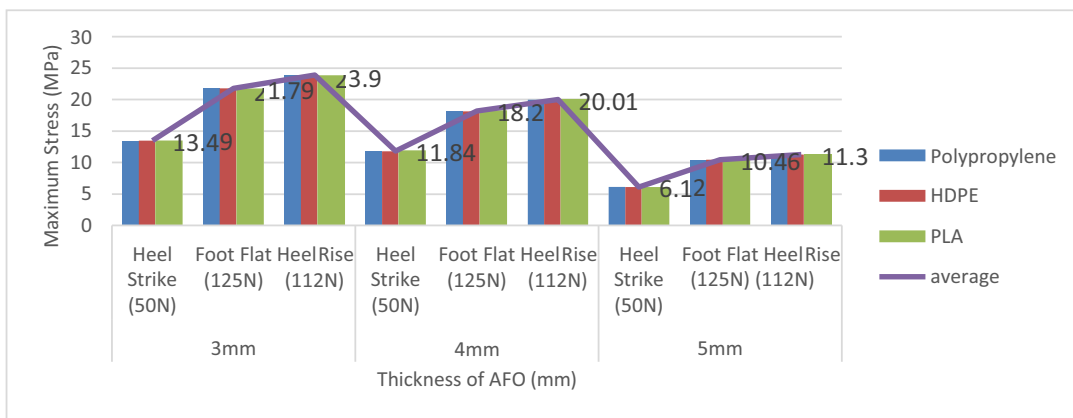


Figure 5. The effect of different thicknesses on maximum stress

Table 2. Weight of AFO comparison

Thickness (mm)	Material	Weight of AFO Before Optimisation (g)	Weight of AFO After Optimisation (g)	Weight Reduction (%)
3	PP	213.339	156.392	26.69
	HDPE	225.916	165.612	26.69
	PLA	297.108	217.80	26.69
4	PP	281.202	206.915	26.42
	HDPE	297.78	219.114	26.42
	PLA	391.618	288.162	26.42

5	PP	347.559	279.423	19.60
	HDPE	368.049	295.896	19.60
	PLA	484.031	389.141	19.60

The maximum stress is compared between optimized AFO and original AFO (Figure 6). During heel strike that is observed from the 3mm thickness, the model shows that maximum stress decrease by 8%. However, the percentage of maximum stress increase by 10% and 9% during foot flat and heel rise respectively. On the other hand, 4mm model shows some decrease percentage values to all simulation which are 27% during heel strike, 22% during foot flat, and 20% during heel rise. Finally, maximum stress results for 5mm model are insignificant as the differences are small enough.

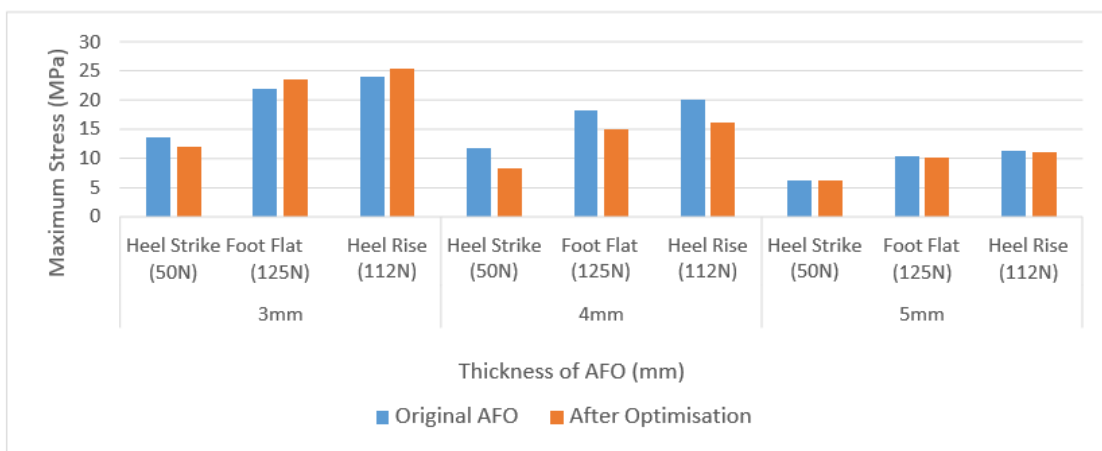


Figure 6. Comparison of maximum stress of AFO models

The displacement of both AFO models is also being compared (Figure 7). It seems that two models which are 3mm and 4mm show similar results in all simulations. The average displacement results for both models increase up approximately from 23% to 24% to all type of materials during foot flat and heel rise. However, 5mm model also increases in average displacement results but the percentage value is approximately 13% to 14% during foot flat and heel rise simulations which are lower than both 3mm and 4mm models. The curious fact is that all type of models shares insignificant displacement result percentage change during heel strike simulation. It can be concluded that the 3mm and 4mm model is the best thickness after shape optimization.

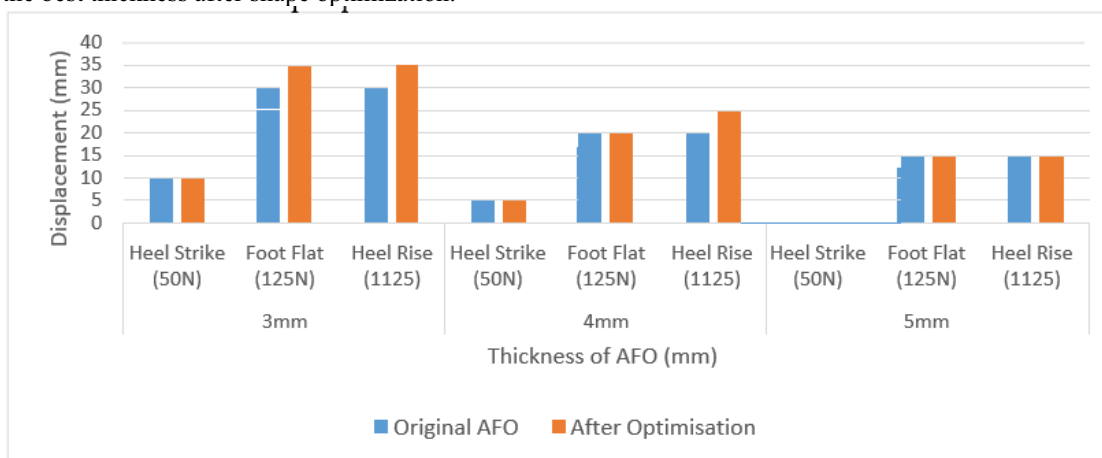
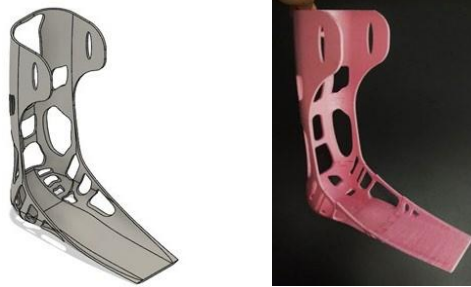


Figure 7. Comparison of displacement of AFO models

The optimised AFO was printed from a fused filament fabrication (FFF) machine (Ender 3). The AFO was sectioned to smaller parts in order to be fitted to the FFF machine. The estimated time from the slicing software (Ultimaker Cura) to print was 14 hours 44 minutes. However, the actual time was 23 hours 44 minutes. The FFF 3D printer took a total of nine hours longer than the estimated. This could be due to the splitting of AFO into a number of parts and shape complexity with lot of curvatures.



(a) CAD Design Optimisation Model (b) Additive Manufacturing Model using FDM

Figure 8. Virtual Prototype to Physical Prototype

4. Conclusion

The suitable material that can provide the highest flexibility and provide enough deformation resistance is HDPE. The 4mm model has a reduction of maximum stress and an increase in total displacement. Even though the volume of this model is reduced but the performance is way better than the original AFO design. Manufacturing by using this 3D printing method is very simple and straightforward, making FDM a good alternative for manufacturing customized orthoses. It is expected that the fabrication time and material waste can be reduced effectively by combining with topology optimization and CAD. By combining the optimization technique with FEA and the manufacturing method of AM, customize AFO can be create to provide comfortable fit and reduce the fatigue associated with weight.

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