Topology Optimization for Custom Bed-Resting Ankle Foot Orthosis

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Abstract The ankle-foot orthosis (AFO) is a widely used aid for people who suffer from weakness of the dorsiflexion muscles of the ankle due to peripheral or central nervous system problems. Both conditions are caused by a lack of dorsiflexion assistance due to muscle weakness. The mobility of the surrounding joints is affected by the deformity and muscle weakness of a lower limb joint, so corrective measures are required. The aim of this study is, therefore, to observe the effects of a topology optimized AFO model on pressure distribution. The product was designed in Solidworks and subjected to finite element analysis using polylactic acid (PLA) to determine the maximum value of Von Mises stress (VMS) and displacement. The design is then optimized using a topology study to analyze the iteration of the component design that meets a specific optimized target and geometric constraints. The final product is expected to have the desired function of the AFO for bedridden patients.

Keywords Ankle foot orthosis · Topology optimization · Bed-resting

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M. H. A. Hassan et al. (eds.), *Proceedings of the 2nd Human Engineering Symposium*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-99-6890-9_8

1 Introduction

Bedridden is caused by a medical condition such as a stroke, cerebral palsy, brain injury, or spinal cord injury. It is projected that by 2025, 13.4% of Malaysia's population will be over 65 years old [1], and 0.2% of them will be bedridden [2]. Formation of heel ulcers, muscle tension, and stiffness are common issues among the bedridden, but limb support, an active routine, and passive activity can help maintain muscle tone and flexibility. Inactive muscle on a body part can cause muscle shortening and atrophy. Thus, bedridden patients do need ankle foot orthosis (AFO) in order to maintain the position of patients' ankles and feet, relieving or redistributing weight-bearing forces and preventing ankle dorsiflexion [3].

AFOs, which are closely fitted to the anthropometry of the wearer, are ideal for treating patients with lower limb impairments. Despite their low cost, most mass-produced AFOs on the market do not meet the following standards. Existing AFOs that fit individual anthropometry, on the other hand, are costly due to their complicated geometry and require the input of qualified and experienced orthopaedic technicians. The long lead time required to manufacture an orthosis adds to these costs [4]. Many versions of the AFO device have been developed to assist patients with drop foot and gait conditions to regain their normal walking condition [5].

3D printing technology allows manufacturers to overcome these limitations and has been used widely to fabricate assistive devices for people living with disabilities [6]. The benefits of 3D printed AFO encompass fast fabrication, as most traditional orthoses take a long time to make since the individual pieces must be merged manually [4]. Moreover, 3D printing technology also allows high customizability of a product [7]. Also, since the parts can easily be reproduced, refabricating the parts with the very same value can be done at any time [8, 9]. Topology optimization has the potential to significantly improve the performance of structures in a variety of engineering applications. One of the most important aspects to consider while creating a product is the stiffness. Optimization of structure aims to maximise a structure's performance while adhering to multiple conditions like a limited amount of material. Due to the limitation of material resources, impact on the environment, and technological rivalry, all of which demand lightweight, low-cost, and efficient structures, optimal structural design is becoming vital [10]. This study was conducted with the aim of observing the effect of topology optimized AFO model on pressure distribution.

2 Methodology

2.1 3D Scanning of Foot

A point cloud reproduction of the lower leg and foot anatomy of an actual patient must be acquired before anything else can be done to build a custom-fitted ankle-foot orthosis (AFO). This must be done before anything else can be done. Using 3D scanning technology and a Creality CR-scan 01 3D Scanner, this can be performed. In order to construct a single model, many scans had to be manually merged and registered first. This model was then registered globally to improve the anatomical data. After that, the scanned data was kept intact while the noise and outlying areas were mitigated with the use of the CR Studio 2.0 (Shenzhen Creality 3D Technology Co. Ltd.) program. Before it could be imported into Solidworks SolidWorks 2021 (Dassault Systems SolidWorks Corp., USA) for conceptual design, the final stereolithography (.stl) file had to be developed. This was done so that three different ideas could make use of the same-sized foot mold.

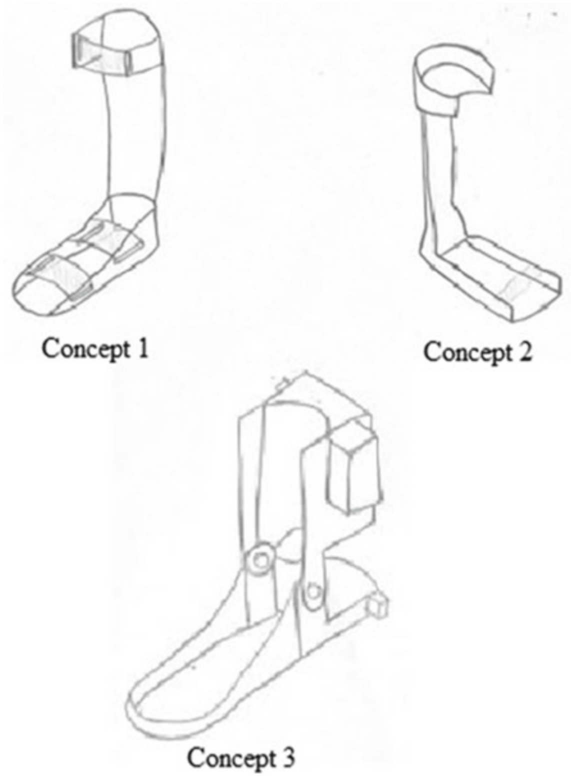
2.2 Conceptual Design of AFO

The idea and concept for creating the desired product were related to existing AFOs. A total of three conceptual designs were sketched and developed using SolidWorks 2021 (Dassault Systems SolidWorks Corp., USA) software based on the 3D scanned foot model. Two of the conceptual designs are solid AFOs, while the other is a foldable AFO. The foldable AFO consists of a separate foot shell and shaft. All three designs have the same function, which is to keep the ankle in a neutral position but allow some restriction of movement to prevent muscle shortening or atrophy. Figure 1 shows the sketches of the design concept of the AFO.

2.3 Topology Optimization

The design has been optimized using topology optimization in SolidWorks 2021 (Dassault Systems SolidWorks Corp., USA) to analyze iterations of the component design that meet a specific optimization objective, namely the best stiffness-to-weight ratio, and its geometric limits are symmetry and thickness control. Symmetry control is semi-symmetric, while thickness is fixed between 0.6 and 1.2 cm. Topology studies are used to define a desired outcome, such as the best stiffness-to-weight ratio, mass reduction, or displacement of a part. With topology-optimized structures, 3D printing allows engineers to overcome the limitations of traditional manufacturing processes and focus on developing lightweight, high-performance structures. The result of the topology study is the best ratio between stiffness and weight. Therefore, the weight reduction is calculated between the original AFO design model and the optimized AFO design model (Fig. 2).

Fig. 1 Design concepts



2.4 *Finite Element Analysis*

Once the design was finalized, finite element analysis (FEA) was conducted using SolidWorks 2021 (Dassault Systems SolidWorks Corp., USA) software, a method of predicting how a product will behave under certain conditions. Polylactic acid (PLA) with Young's modulus of 3500 MPa and Poisson ratio of 0.36 was chosen as the material because it is inexpensive and widely available on the market [11, 12]. The FEA study was performed for each optimized AFO design based on different applied loads, which were determined based on data from previous research work that measured the weight of each part of a human body [13]. The results obtained from the analysis are the Von Mises stress and displacement. Table 1 shows the mean body weight segment of a respective part of the human body.

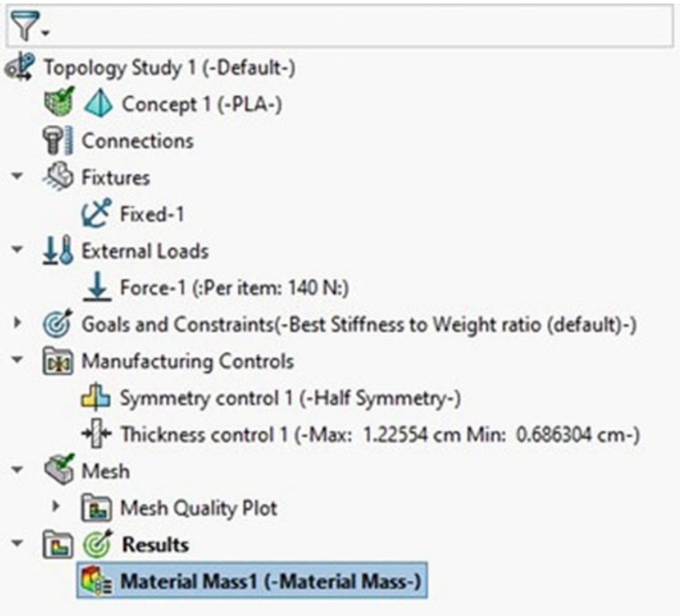


Fig. 2 Parametric settings for topology study

Table 1 Mean body weight segment [13]

Segment	Mass (%)	
	Female	Male
Foot	4.81	4.33
Shank	1.29	1.37

3 Results and Discussion

3.1 Topology Optimization

Figure 3 shows the result of topology optimization of the design to get the best stiffness-to-weight ratio with the manufacturing controls of symmetry and thickness control. The figure shows the area that can be removed to achieve its goal of getting the best stiffness by reducing the mass of the design.

Figure 4 shows the design optimization model after the area that can be removed according to the topology study has been removed. The weight of the designs decreases according to what is removed. The weight reduction of the model can be seen in Table 2.

Table 2 shows that concept 3 has the highest weight reduction of 55.89% from its initial weight of 0.560 to 0.247 kg, followed by concept 1, which reduces 17.17%

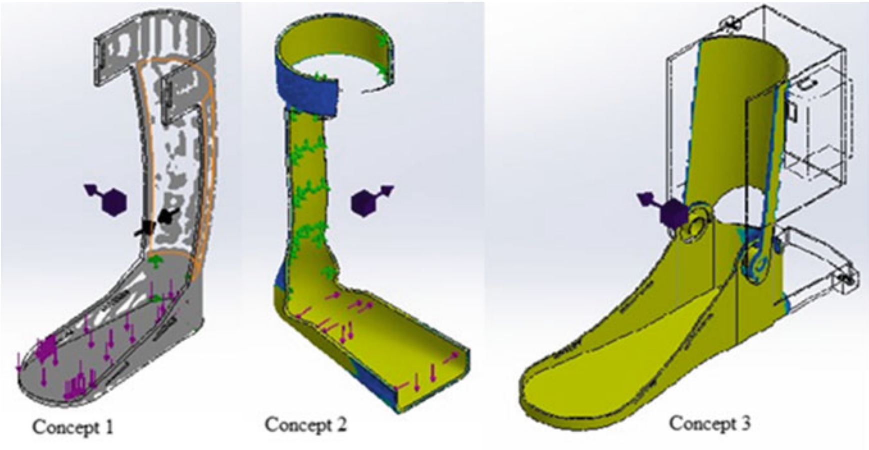


Fig. 3 Result of topology optimization

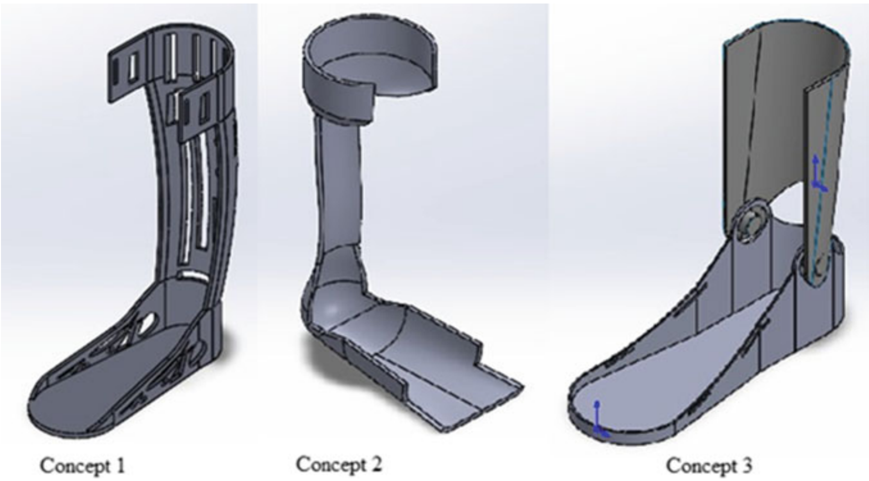


Fig. 4 Design after topology optimization

Table 2 Weight reduction of AFO

Design concept	Weight before optimization (kg)	Weight after optimization (kg)	Weight reduction (%)
Concept 1	0.594	0.492	17.17
Concept 2	0.273	0.259	5.13
Concept 3	0.560	0.247	55.89

of its initial weight of 0.594 kg and is 0.492 kg after optimization. Concept 2 has the most minor weight reduction, with only 5.13% of its initial weight from 0.273 to 0.259 kg. Through topology optimization, weight reduction can contribute to lower production costs, especially when fabrication is done through the 3D printing method [14].

3.2 Effects of Different Load

The loads applied are 140, 280, and 560 N. For concept 1, as can be seen in Figs. 5 and 6, the biggest load applied, which is 560 N, has the highest value of maximum VMS with the value of 34.11 MPa, and its maximum displacement is 3.289 mm. The smallest value of maximum VMS is 8.53 MPa, and the displacement is 0.822 mm which is when 140 N is applied to it. When 280 N load is applied, the maximum VMS is 17.06 MPa, and the displacement is 1.645 mm.

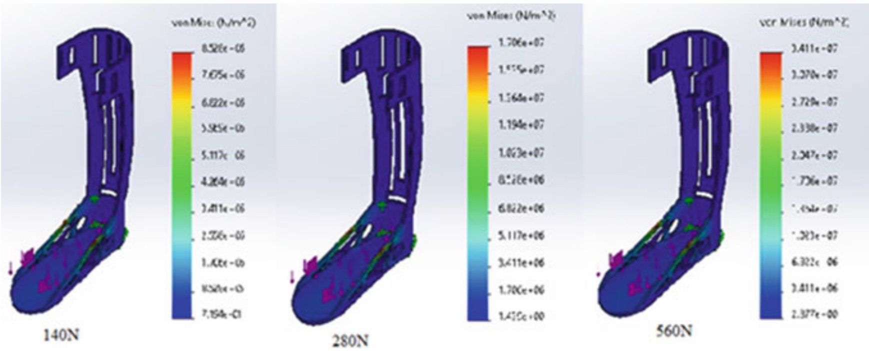


Fig. 5 VMS visual analysis for concept 1

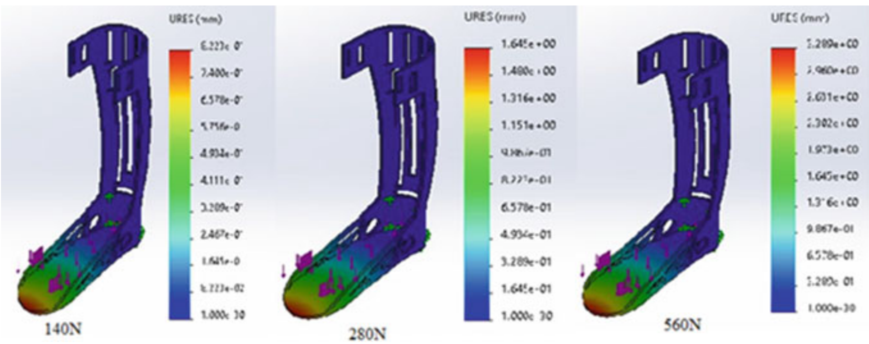


Fig. 6 Displacement visual analysis for concept 1

For concept 2, it can be seen in Figs. 7 and 8 that when 140 N load is applied, the maximum VMS is 16.46 MPa, and the displacement is 0.831 mm. Then, when 280 N is applied, the maximum VMS and displacement increase to 32.94 MPa and 1.646 mm, respectively. The maximum VMS is 65.98 MPa when a 560 N load is applied, and the displacement is 3.232 mm.

As shown in Figs. 9 and 10, for concept 3, the maximum VMS and the displacement when 140 N load is applied are 14.18 MPa and 3.501 mm, respectively. The maximum VMS increases to 28.35 MPa, and the displacement also increases to 7.002 mm when a 280 N load is applied. When the biggest load of 560 N is applied, the maximum VMS is 45.41 MPa, and the displacement is 17.000 mm.

Table 3 shows the values of maximum VMS and maximum displacement for all three concepts when different loads of 140, 280, and 560 N are applied to the foot. As can be seen in Fig. 11, concept 2 has the highest maximum VMS for every load applied, followed by concept 3, then concept 1, which has the lowest maximum VMS compared to the other two. Figure 12 illustrates that concept 3 has the highest maximum displacement compared to the other two concepts, which have a similar value of maximum displacement with only slight differences between those two

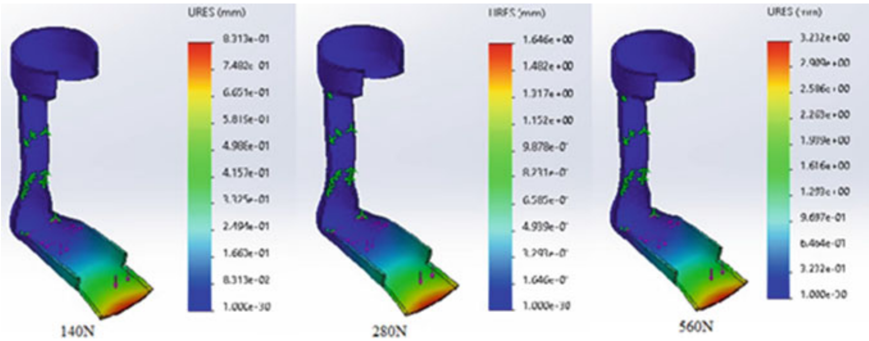


Fig. 7 VMS visual analysis for concept 2

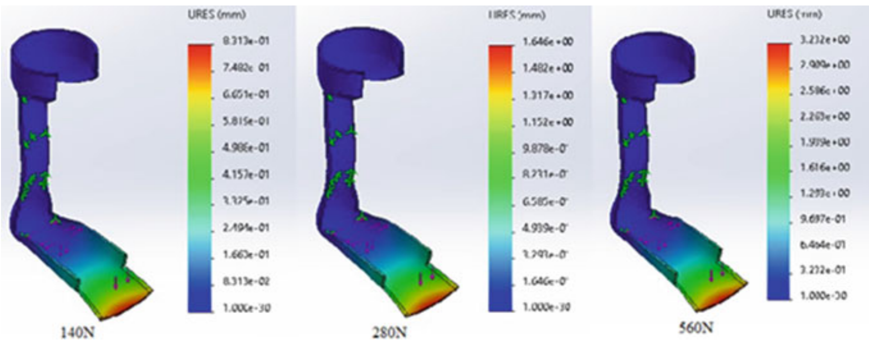


Fig. 8 Displacement visual analysis for concept 2

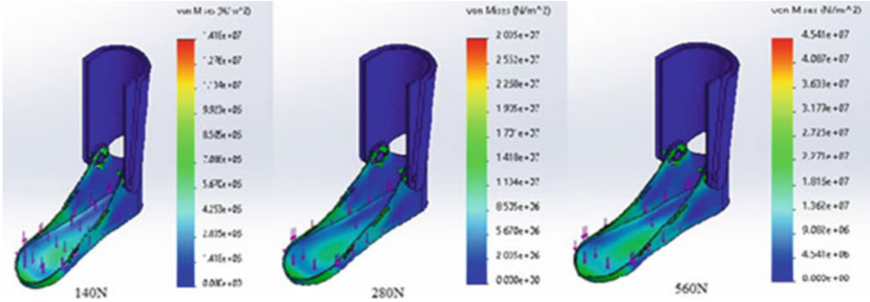


Fig. 9 VMS visual analysis for concept 3

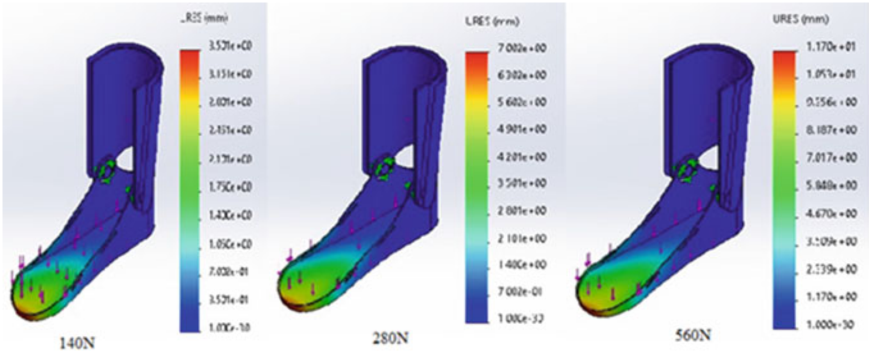


Fig. 10 Displacement visual analysis for concept 3

concepts. From Table 3, it was proven that all designs do not fail upon loads applied as the highest VMS values of all designs do not exceed the yield strength of the material, which is 70 MPa [11]. Concept 2 shows the highest VMS and displacement values compared to other designs, respectively, which are 65.98 MPa and 3.232 mm. This can be caused by the slim design of concept 2, which reduces the ability to distribute the stress and brings down the stiffness. Concept 2 has a property of trimlined AFO, which had been proven by Surmen et al. to have lower stiffness [15].

Table 3 Maximum VMS and displacement for each concept

	Concept 1		Concept 2		Concept 3	
Load (N)	Max. VMS (MPa)	Max. displacement (mm)	Max. VMS (MPa)	Max. displacement (mm)	Max. VMS (MPa)	Max. displacement (mm)
140	8.53	0.822	16.46	0.831	14.18	3.501
280	17.06	1.645	32.94	1.646	28.35	7.002
560	34.11	3.289	65.98	3.232	45.41	17.000

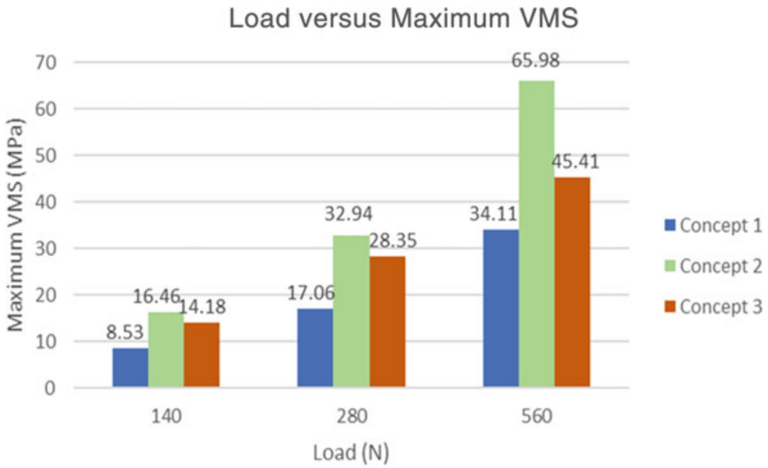


Fig. 11 Load versus maximum VMS for each concept

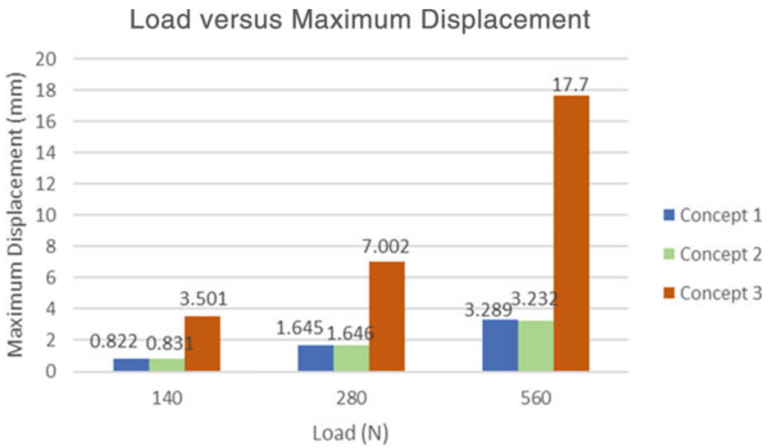


Fig. 12 Load versus maximum displacement for each concept

Trimlined AFO is used to correct abduction or adduction and plantarflexion or dorsiflexion of the foot. AFO stiffness can be affected by the patient's biomechanical conditions, such as the weight and the level of deformity of the patient. For example, for a more flexible AFO, a trimline design needs to be applied at the ankle section; meanwhile, for adduction and abduction correction, the medial and lateral need to be thickened, respectively [16]. In designing and developing AFO, key parameters that need to be considered are the geometrical shape, stiffness, and material type, as these parameters can affect the effectiveness of the AFO [17].

4 Conclusion

The results of the topology optimization show that concept 3 has the highest weight reduction. This is because most of the area that is not loaded can be removed after the topology optimization. The FEA study conducted after optimizing the design shows that the more load applied to the footrest, the higher the value of maximum VMS and displacement. Even though the VMS increases after optimizing the design, the results show that the stress values are still acceptable as they do not exceed their tensile strength of 70 MPa.

Some improvements can be made to the AFO model. For example, the AFO can be made according to the patient's foot size. To obtain the measurements of the patient's feet, a 3D scanner can be used to scan the patient's feet. Also, an automatic mechanism can be installed to help the patient move his ankle quickly. This can be a great help for the patient to avoid weakening or atrophy of the muscles, as a patient who is confined to bed does not use his muscles often. Muscles that are not used regularly degenerate very quickly.

Acknowledgements This study was supported by the Universiti Teknologi MARA, Malaysia, and Universitas Indonesia under the Strategic Research Partnership (SRP) UI-UITM BISA 2021 Grant, Grant No: 100-RMC 5/3/SRP (037/2021). We thank and acknowledge the College of Engineering, UiTM, and our colleagues from Universitas Indonesia, who provided insight and expertise in the research work.

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