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Finite element analysis of the CFRP-based 3D printed ankle-foot orthosis

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Abstract

The application of the 3D printing and additive manufacturing in making medical devices have become widespread in the last decades as the opportunity of the technology is rapidly growing. Notably, the Fused Deposition Modeling (FDM) in 3D printing technique has been applied to develop the ankle-foot orthosis (AFO) with different materials and composites. This paper presents a new design and simulation results of a novel orthosis using Carbon Fiber Reinforced Polymer (CFRP). The orthosis for ankle-foot is designed for rehabilitation of the patient from the foot drop disease. The orthosis' shape is modelled to support the backside of the calf. It contributes to the maintenance of the gait cycle. In this paper, two different models of the AFO are compared, namely articulated and non-articulated. The finite-element analysis is done using the ANSYS software, and the results for equivalent Von-Mises stress as well as total deformation are observed and analyzed. Various materials are applied during the numerical analysis, as well as their combinations are tested.

Keywords: Ankle-foot orthosis, 3D printing, Finite-element analysis

1. Introduction

The orthosis is an artificial device that assists externally to support the spine or limbs and to avert any unnecessary movement by the patient. The difference of the orthosis form prostheses is that prostheses completely replaces the part of the body, which is hurt or missing. In contrast, the orthosis helps limbs to recuperate from the injury and to strengthen the proper functionality of them [1]. However, there are a lot of similarities between the orthosis and

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prostheses in different functions. For example, both of the devices are designed to support a specific part of the body to facilitate proper functioning and movement [2]. Besides, both of them share standard design specifications such as lightweight, high compressive and tensile strength; high stiffness is needed to withstand shear stress, high endurance during the impact, low-cost material [3]. The investigation of orthoses is crucial nowadays since, according to Miro et al. [4], the number of researches on the orthosis is much less compared to the number of research papers on the prosthesis. Furthermore, there are a lot of opportunities to discover new things in this specific field. This field can be explored further in detail to improve the performance of the orthosis, specifically ankle-foot orthosis, by making it lightweight, durable, and cheap.

1.1. Ankle-foot orthosis

The Ankle-foot orthosis is the device designed to control and support the motion of the ankle during the foot drop problem. Drop foot is an anatomic paralysis or weakness of the fore section of the bottom leg muscles. The foot drop is described as the issue of disability or hardship to lift the front part of the leg, which causes discomfort during walking. The problem in walking may last a short amount of time or continuously depending on several factors, such as disorder of spinal cord, brain, nerve or muscle, etc. [5]. The AFO (ankle-foot orthosis) helps to treat the disordered gait cycle caused by the foot drop. Regular gait cycle includes the foot strike, when the foot first touches the ground, and foot off, when the foot begins to leave the ground, leading to the swinging phase, when the foot moves forward and doesn't touch the ground for a certain amount of time. In contrast, in the case of foot drop, during the foot strike phase, the foot will rub with the ground instead of just landing the foot portion, and more pressure will be distributed on the leg due to inability of the foot to support the weight of the body during the transitions between phases. In addition, the knee will be extra flexed during the swing phase, since it can't bend dorsally. This kind of movement is called high stepping gait. The AFO device is used by doctors to treat the mild cases of the foot drop disability, which assists the patients to move their foot safely and to improve the walking gait. Usually, the Ankle-foot orthosis is designed in the form of "L", where the vertical part is placed in the rear side of the calf, and the horizontal component is joined to the sole. There are two types of Ankle-foot orthosis: articulated AFO and non-articulated AFO. The articulated AFO has the mechanically adjustable joints at the ankle, which gives the ankles the flexibility of moving the ankle up or down during the gait [6]. The non-articulated AFO is the fixed AFO without any joints, and it restricts any freedom of movement for the ankle. Each type of AFO has its pros and cons. The significant benefit of the articulated AFO is that it doesn't constrain the patient's gait cycle, which provides greater stability and versatility for the bending towards the foot's upper surface and the surface of the sole. On the other hand, it is massive, cumbersome, lacks any comfort with the wearing of the patient's clothes. As for the rigid type of AFO, the structure of it is in contrast to that of articulated ones. The advantage of the conventional AFO models is the lightweight, comfort in wearing with the clothes, and esthetically appealing. However, the gait cycle of the patient doesn't look natural and seems to be limited, since the solid AFO doesn't allow to move the ankle in any direction. In long-period utilization of the rigid AFO, it may cause the rashes and exasperations, since the contact area of AFO with the foot skin is large, and the movement of the foot is not stable compared to the articulated AFO.

1.2. Ankle-foot orthosis manufacturing

In the past, the AFOs were usually made of pure leather and wood. As time passes by and the industrial revolution gives the opportunity to apply various techniques and materials, the quality of the AFO production was significantly improved, making orthosis more practical, ecologically sound, and user-oriented [7]. Nowadays, there are three ways to manufacture the AFOs [8], namely,

- fabrication by applying thermoformable polymer sheets
- additive-manufacturing, i.e., 3D printing,
- by using the base of the plaster cast to layup the carbon fiber sheet.

The 3D printing method of AFO manufacturing had become the most popular method in the last decades [9]. By additive manufacturing (AM), various new materials and composites can be applied, such as carbon fiber, ABS, and polypropylene. There are several types of 3D printer that allows us to prototype the AFO, namely FDM (Fused deposition modeling), SLS (Selective laser sintering), and SLA (Stereolithography). FDM is the most used in 3D printing ankle-foot orthosis, since the plastic materials PLA, ABS, etc. exists in the form of the filament. The FDM 3D printing procedure is described as follows: Initially, the 3D model of the AFO is created in CAD software, which is then converted to the STL file and entered into the 3D printer. The plastic filament starts to be heated for further extrusion from the nozzle to the printing bed level-by-level until it reaches the final prototype of its model [10,13]. The application of the 3D scanner to scan the leg of the patient, for designing the 3D model of the patient's personal AFO in CAD software is the massive benefit of 3D printing technique.

Another significant advantage of FDM 3D printing is the high accuracy since the pre-heated plastic filament is accurately extruded from the nozzle keeping the constant speed. The 3D printing speed is high enough, depending on its type, but a lot of researches are conducted to improve its performance. Polylactic acid (also known as PLA) is the plastic filament used in FDM 3D printing, which has no odor and is quickly heated, as well as does not tend to deform compared to Acrylonitrile butadiene styrene (aka ABS). Therefore it does not require a very hot platform during the 3D printing process. On the other hand, ABS is more ductile than PLA, so it gives the ABS-prototype more flexibility. There is one more thermoplastic material commonly used in FDM 3D printing, named Nylon. Nylon plastic is more flexible and durable compared to ABS and PLA, with high stiffness and high chemical resistance, which gives it a great opportunity in various industrial applications. However, nylon requires additional care during the 3D printing procedure. It requires a high heating temperature during extraction from the nozzle and high platform temperature, nearly 240-260℃, and 60-80℃, respectively. Due to its high moist air absorption property, the Nylon prototype requires maintenance in the dry box after the 3D prototyping procedure. Besides, the price of the Nylon filament is high compared to that of the PLA and ABS.

The Carbon fiber reinforced polymer (CFRP) composite is the material composed of reinforced carbon fiber and polymer in a matrix type. It is a very lightweight material, with high strength as the metals have [11]. The CFRP is also has a significant advantage compared to other materials used in AFO manufacturing in terms of aesthetics. Its density ranges between 1500-1600 kg/m3, and tensile strength between 550-1100 MPa [12]. The mechanical properties of CFRP are provided in table 2 [15]. Furthermore, corrosion-resistiveness and fatigue withstanding make the CFRP very durable.

In contrast, CFRP is very expensive, and the manufacturing of the models is time-consuming. In addition, the use of this material in manufacture is non-eco-friendly, since it is almost non-reusable material. The CFRP filaments are not widely used in FDM 3D printing since the pure carbon fiber is costly. Instead of this, reinforced carbon fiber comes in the mixture with the PLA or ABS, which reduces the cost of the filament. Another alternative for using the CFRP in 3D printing is to apply it in the SLS 3D printing, where the CF powder is cheaper than the CF filament. Overall, Table 1 summarizes the properties of all materials used in AFO manufacture.

Table 1. Properties of materials used in AFO

	Material	Advantage	Disadvantage
1	ABS	-Printability -Optimal cost -Good impact resistance -Low production time -Low electricity conductance	-Less chemical resistance -Weaker than other plastics -Non-ecofriendly
2	PLA	-Printability -Stronger than ABS -Good stiffness -Low production time -Lower heating temperature requirement -User-friend	- Less chemical resistance - Less durable -Brittle -Poor impact resistance -
3	Nylon	-Flexibility -Durability -Toughness -Malleability	-High heating temperature -High bed temperature -Moist air absorption

		-Good chemical resistance	-More expensive than other plastics
4	CFRP	-High strength to weight ratio -Lightweight -Suitable aesthetics -Resistance to corrosion -Resistance to fatigue -Durability	-Expensive -Time-consuming manufacture -Not eco-friendly
5	Wood	-Eco-friend material -Resistance to rust -Pleasure with the aesthetics -Satisfactory strength to weight ratio	-Lower elasticity modulus -Lower tensile strength -Variation of the mechanical properties
6	Metal	-High tensile strength -Modular design -Tear-resistance -High heat insulation	-Heavy -Bulky -Energy consuming production -Non-biodegradable -Extraction of chemical waste during production

Table 2. Mechanical properties of standard CFRP

	Characteristic	**Unit**	**Value**
1	Young's Modulus	GPa	70
2	Shear Modulus	GPa	5
3	Poisson's ratio		0.10
4	Ultimate tensile strength	MPa	600
5	Ultimate compression str.	MPa	570
6	Density	g/cc	1.60

2. Methodology

This research aims to investigate and compare the efficiency of the articulated and non-articulated AFO models by conducting Finite-Element analysis in ANSYS software [16]. Additionally, the motivation is to improve the performance of the current models and further experimental investigation of the current and modified AFO models. The CAD models of the AFO were designed in SolidWorks software. The dimensions of the AFO models are illustrated in figures 1 and 2. The numerical analysis was done by using the Static Structural Analysis System in ANSYS Workbench. The applied force values are 3 N in X-direction, 5 N in negative Y-direction, and 490 N in negative Z-direction. Figure 3 shows the regions where the forces were applied and the fixed support as well. These force dimensions, obtained through experimental results as shown in [17], describe the full contact moment in the gait cycle when the sole fully touch the ground. Figure 4 demonstrates the meshing of the AFO, where the mesh size is 5 mm, with the 31904 nodes and 16021 elements.

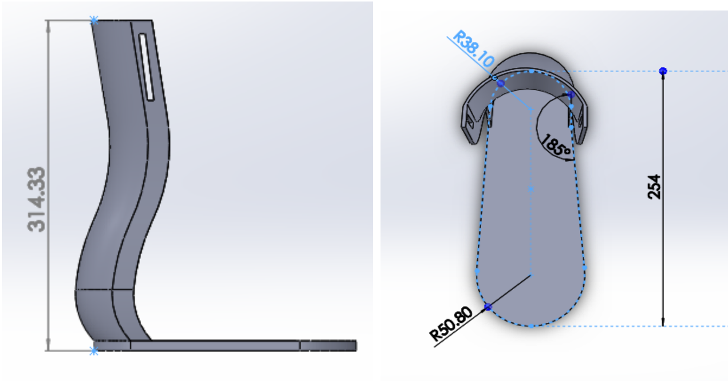


Fig.1. Non-articulated AFO dimensions (a)side-view; (b) top view

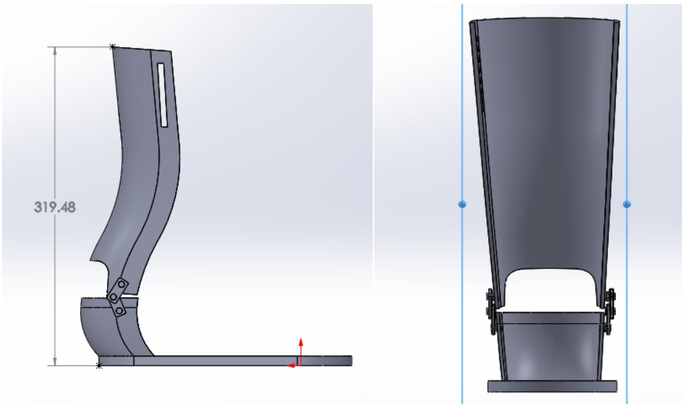


Fig.2. Articulated AFO dimensions (a) side view; (b) front-view

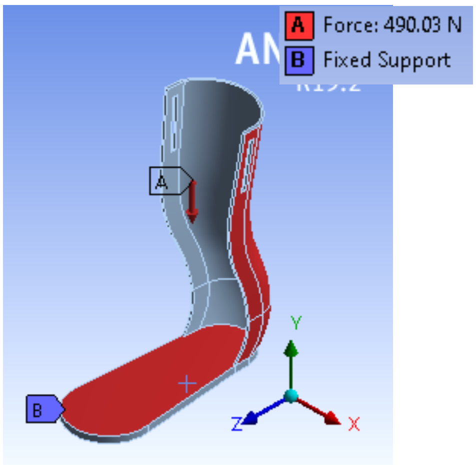


Figure 3. Force applied and fixed support in FEA setting

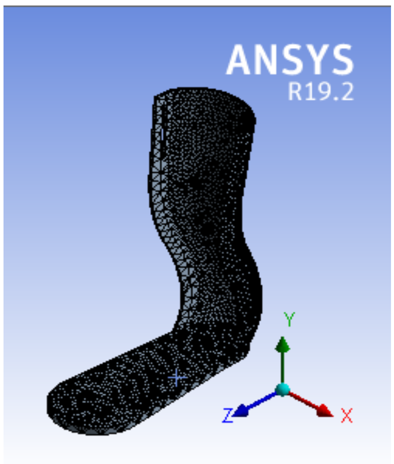


Figure 4. Mesh elements in FEA initial conditions

3. Simulation Results

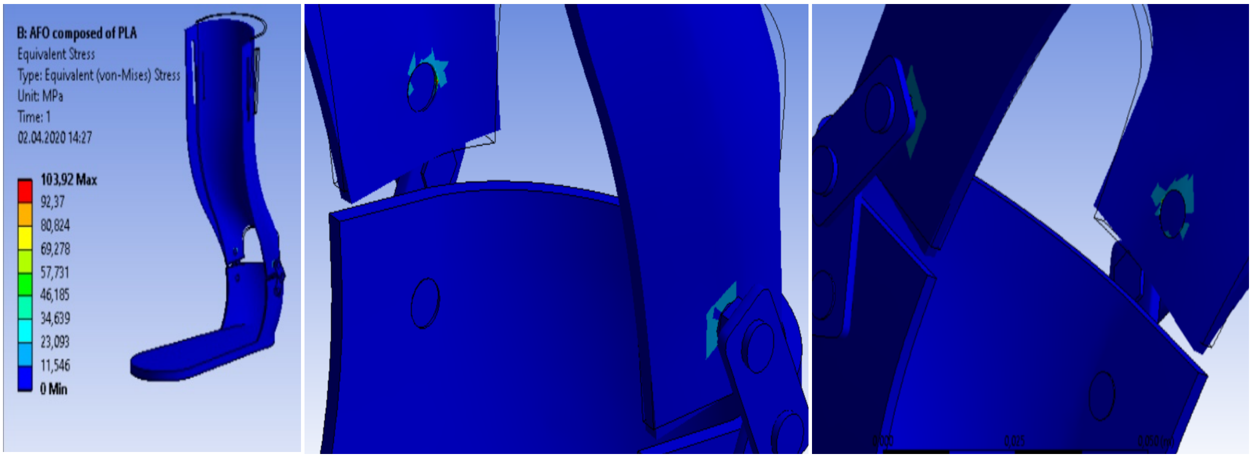


Fig. 5. Stress distribution for articulated model with PLA (a) isometric view; (b) right zoomed view (c) left zoomed view

Table 3. Simulation results for the conventional and articulated AFO model.

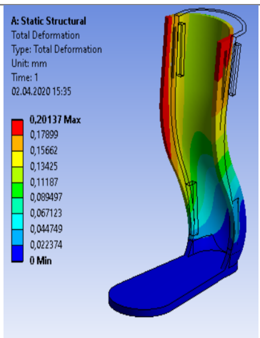
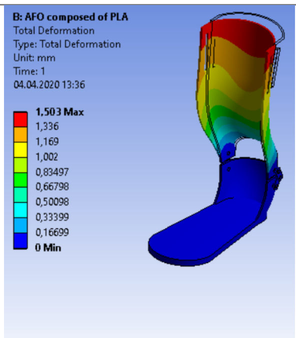
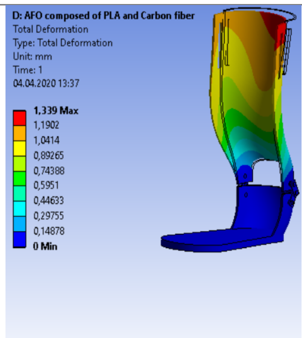
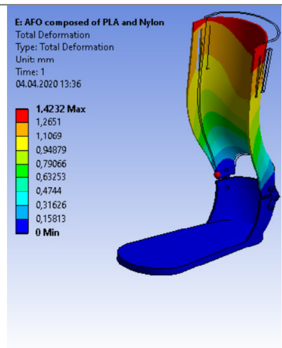
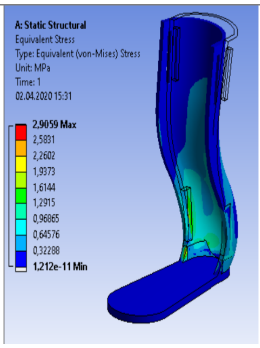
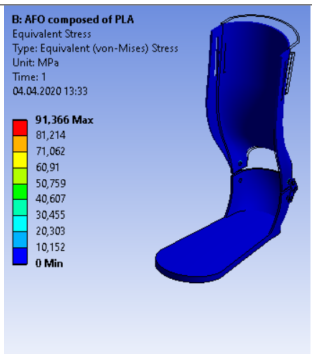
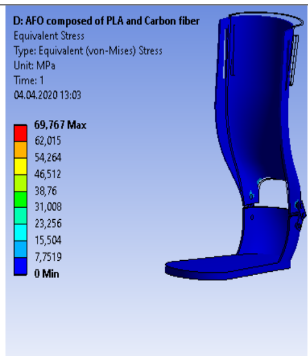
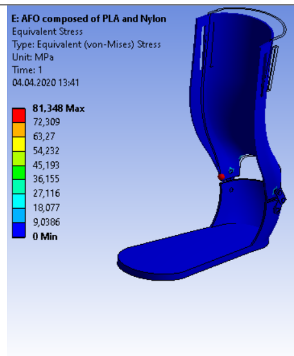
	Model with PLA and Nylon 12	Articulated model with PLA	Articulated model with PLA and Carbon fiber	Articulated model with PLA and Nylon 12
Total deformation				
Equivalent (von-Mises)				

Table 4. Maximum values of simulation results for a conventional and articulated AFO model.

	Model with PLA and Nylon 12	Articulated model with PLA	Articulated model with PLA and Carbon fiber	Articulated model with PLA and Nylon 12
Max. total deformation	0.2 mm	1.5 mm	1.34 mm	1.42 mm
Max. equiv. stress	2.91 MPa	91.37 MPa	69.77 MPa	81.35 MPa

4. Discussion

The simulation was done for articulated ankle-foot orthosis with PLA material for the full contact instance. From figure 3, it can be noticed that the whole stress is concentrated on the joints of the model. Then the articulated model was modified. The region with the highest concentration of the von-Mises stress (joints) was replaced with carbon fiber. Also, this model was simulated for the full contact instance. These two models were compared with the conventional model composed of PLA and Nylon 12. The simulation results are provided in tables 3 and 4. The maximum deformation and equivalent stress values were defined. From the recorded data, it was found that when the articulated model was modified by adding carbon fiber, the maximum deformation was decreased by 11.9% (from 1.5 mm to 1.34 mm). Besides, the maximum stress was reduced by 30.96% (from 91.37 MPa to 69.77 MPa). However, the maximum deformation of the conventional modified model with Nylon 12 and PLA is lower by 650% (from 1.5mm to 0.2 mm), and the maximum stress is 31.4 times lower than for the articulated AFO with carbon fiber and PLA. So, the conventional model is much more sustainable than the articulated one. Although the articulated model is much more efficient due to its provision of movement flexibility. Thus, it confirms that the articulated AFO requires a very stress-resistant material such as carbon fiber.

By comparing with the modified articulated model with Nylon 12 added instead of carbon fiber, it is seen that the maximum deformation is higher by 5.97% (from 1.34mm to 1.42 mm). The maximum stress for a modified articulated model with Nylon 12 is higher by 16.6% (from 69.77 MPa to 81.35 MPa). It means that the articulated model with carbon fiber is much more sustainable than with Nylon 12. Furthermore, because the carbon fiber density is smaller than that of PLA, the AFO mass has been decreased. Replacing the maximum stress areas with carbon fiber significantly changed the performance, enhancing the AFO's efficiency under the given conditions. The comparison of simulation and its real-life application without CFRP and ABS materials was shown in [18], however, the latter materials couldn’t be applied for 3D printing the AFO and testing of it due to unseen circumstances and lack of opportunity to do so.

5. Conclusion

To summarize, there has been a lack of analysis of the multi-material 3D printing technique and its use in the industry. In the FEA platform, the AFO's articulated models were developed and numerically simulated. The maximum deformation and an equivalent Von-Mises stress were obtained from the results. The modified AFO model was developed by substituting the PLA at the locations with the maximum stress concentration with carbon fiber. The results revealed a major increase in the performance of AFO, which decreased the equivalent stress and total deformation by 30.96 % and 11.9%, respectively. It is observed that the conventional modified model with Nylon 12 is much more sustainable than the articulated model with carbon fiber. Although the articulated AFO prevails the conventional model in motion flexibility, and it is confirmed that for extended durability, the articulated model requires a high-stress resistant material such as carbon fiber. Nevertheless, the articulated AFO with carbon fiber is more stress-resistant than the articulated model with Nylon 12 by 16.6%. From the overall results, it was found that the articulated AFO composed of both carbon fiber and PLA is much more efficient and sustainable than the other.

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