Numerical and experimental analysis of the 3D printed multi-material ankle-foot orthosis

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Abstract. The application of 3D printing in medicine is the major area to concern in the nearest future. Namely, it is convenient to additively manufacture the Ankle-Foot Orthosis (AFO) by fused-deposition modeling 3D printer. AFO is the device, used in medicine, to help the patients rehabilitate from the foot drop disease. The shape of the AFO may vary depending on the leg and foot specifications of the patient. In this paper, three models of the AFO were designed to analyze both numerically and experimentally, those are fracture propagation, stress distribution, and deformation. The regions with the highest stress concentration were altered with the Nylon 12, and this contributed to stress reduction. Three different gait instances were considered for the numerical simulations FEA software. Then, the simplest model to prototype and its modified versions were tested by the compression machine, and the results were compared with the numerical ones. This work demonstrated the significance of the optimization of the multi-material 3D printed AFO’s performance and comfort for patients.

1. Introduction

A multi-material 3D printing makes it possible to create multi-material objects with an enhanced lifespan and performance compared to a single additive manufacturing process. With a multi-extrusion 3D printer, an object can be composed of different materials in different sections to improve mechanical, thermal or other features. Creating an object with improved properties in pre-defined areas in a single manufacturing operation is the most significant advantage of multi-material additive manufacturing. In addition to this, multi-material additive manufacturing can combine similar and dissimilar materials in one continuous process. Owing to these abilities, multi-material 3D printing is a promising manufacturing method for real-world applications [1-2]. Although the multi-material 3D printing is on the infancy yet, many developments of multi-material 3D printers are conducted in terms of print space, cost, functionality, number of hot-ends operating simultaneously, resolution, supported range of materials, control, and extensibility [3, 4, 5]. Apart from this, the further development of the 3D printers into 4D printing occurs by combining the multi-material 3D printing with smart materials [6].

Several types of 3D printing operations exist, such as stereolithography apparatus (SLA), selective laser sintering (SLS), fused filament fabrication (FFF), and laminated object manufacturing (LOM). One of the most widespread and simple types is a fused filament fabrication. FFF creates an accurate product because the plastic filament in FFF is pushed gradually from the nozzle at constant speed. The most common filaments for FDM 3D printing are PLA and ABS. PLA is slower to wear, odorless during printing, easier to reach a flat part, and less susceptible to warp compare to ABS, so it does not require a very hot print bed during printing. At the same time, PLA is more brittle than ABS. Nylon is another material used in 3D printing, which is much stronger, more durable and more versatile than PLA and ABS. Also, it requires much higher extrusion temperature, between 235-270 °C and a heated print bed at 60-80 °C [3]. The material properties of each filament are demonstrated in Table 1.

The objective of the current research is to observe the model of AFO created from PLA for the locations with the highest stress values using the Finite Element Analysis (FEA) method. Afterward,
these locations were substituted with Nylon, which is much harder than PLA. Such modification may improve the total stress resistance of the model and minimize the cost for the used material. To compare the results, the developed AFO was printed by the five extrusion multi-material FDM 3D printer and, finally, tested using the compressor testing machine. External coating of the socket was printed by PLA as a hard material, and internal coating is composed of rubber as a soft material. For the off-load zone (where there are bony protuberances or tendons) and load zone, rubber and PLA are used, respectively, to ensure a comfortable adaptive fit and ideal matching with human limb [7].

2. Methodology

The AFO models were designed in SolidWorks software, which then was imported to the ANSYS Workbench to analyze them in Static structural system for deformation and von-Mises stress behaviors.

2.1. Model design and construction

The three models of the ankle-foot orthosis were designed in SolidWorks 2018 software package. The dimensions were taken for the average human leg sizes. Each model has different parameter values, as well as the client leg type. Their fabrication methods are different, such as; model 1 is dedicated for further 3D printing and compression testing due to its simple geometry compared to other two models as it does not have the lateral foot calf support which cannot be fixed on the compression testing machine. The main motivation of the work was to investigate the fracture of the orthosis and examine their behavior to further improve their performance. The models differ mainly on the parameters such as i) height of the foot support, ii) width of the orthosis, iii) lateral of the ankle, and iv) the arch of the medial plantar and curvature.

2.2. Boundary conditions

The static structural FEA was performed on the three models at different gait instances. As in the research mentioned above, the stress distribution of the three gait instances of the gait cycle at the heel strike, full contact, and heel rise was considered, which are shown in Fig. 1. The components of the force medial-lateral $F_x$, vertical $F_y$, and anteroposterior $F_z$ vary for each case of gate cycle. The tables 1 summarizes the parameter information for gait cycle instances. The force was assigned to the zone with the red color as shown Table 2. Tables 3, 4 and 5 show the simulation results of gait models 1, 2 and 3, respectively.

![Figure 1. Gait instances of the gait cycle. From left to right: heel strike, full contact, heel rise.](image)

| Force elements | HS   | FC   | HR   |
|----------------|------|------|------|
| $F_x$          | -5 N | 3 N  | 7 N  |
| $F_y$          | 50 N | -5 N | -50 N|
3. Numerical simulation

3.1. Numerical results

Table 2. Simulation results for model 1 at each gait instance

| Heel strike | Full contact | Heel rise |
|-------------|--------------|-----------|
| F_z         | -400 N       | -490 Ns   | -300 N    |

Table 3. Simulation results for model 1 at each gait case with the single material (PLA)

|         | Heel strike | Full contact | Heel rise |
|---------|-------------|--------------|-----------|
| Max. total deformation | 2.16 mm | 1.04 mm | 2.66 mm |
| Max. equiv. stress | 7.52 MPa | 6.81 MPa | 8.32 MPa |

Table 4. Simulation results for model 2 at each gait case with the single material (PLA)

|         | Heel strike | Full contact | Heel rise |
|---------|-------------|--------------|-----------|
| Max. total deformation | 9.63 mm | 2.89 mm | 9.31 mm |
| Max. equiv. stress | 2.92 MPa | 2.55 MPa | 2.58 MPa |

Table 5. Simulation results for model 3 at each gait case with the single material (PLA)
3.2. Discussion of the numerical results
The simulation was done for three models at each gait case, and the results are provided in tables 5-7. The maximum deformation and equivalent stress values were summarized as demonstrated in table 5. For each model, the case of full contact instance has the lowest values for both total deformation and equivalent Von-Mises stress. Then, model 1 at full contact case was chosen for further analysis and compression experiments. The region of model 1 where the concentration of the von-Mises stress was the highest, was replaced with Nylon 12. Two modified models are summarized in table N. In addition, these models were also simulated for the full contact instance. From the recorded data, it was found that the maximum deformation for modified model 1 was reduced to 35.7% (from 1.04 mm to 0.669 mm) while for the modified model 2, the reduction was double, about 70.1% (from 1.04 mm to 0.311 mm). Besides, the maximum stress for modified model 1 was decreased for 48.3% (from 6.81 MPa to 3.52 MPa), and for modified model 2 nearly 52.4% (from 6.81 MPa to 2.86 MPa). The replacement of the highest stress zones with the Nylon 12, significantly affected the results, improving the performance of the AFO twice or more under the defined conditions. Besides, since the density of the Nylon 12 is less than that of the PLA, the mass of the AFO was reduced.

4. Experimental results from compression testing

4.1. Experiment set up
The experiment was conducted in a machine dynamics laboratory on the compression testing Tinius Olsen machine. The AFO prototypes were attached to the lower gripper at an angle of 70° to the vertical load. The load was applied to the foot platform of the AFO at the speed of 60 mm/min. Table 6 shows the experimental set-up for three different models.

Table 6. 3D printed prototypes

| Experimental Set-up | Benchmark (PLA) | Modified model 1(PLA+Nylon 12) | Modified model 2(PLA+Nylon 12) |
|---------------------|-----------------|-------------------------------|-------------------------------|
|                     | Image of Benchmark | Image of Modified model 1 | Image of Modified model 2 |

4.2. Experimental results
Table 7 highlights the experimental results of the compression test for the 3D printed ankles.
Table 7. Experimental results of the compression testing

|                       | Benchmark | Modified model 1 | Modified model 2 |
|-----------------------|-----------|------------------|------------------|
| Graph of load vs. deformation | ![Graph 1](image1.png) | ![Graph 2](image2.png) | ![Graph 3](image3.png) |
| Ultimate load         | 505 N     | 183 N            | 237 N            |
| Max. deform.          | 12 mm     | 7.5 mm           | 23.5 mm          |

4.3. Discussion of the experimental results

A practical compression testing was conducted for the three models at the laboratory. Namely, benchmark made of single PLA material, and other two models were the combination of the PLA and Nylon 12 in different proportions. The testing was conducted on the Tinius Olsen compression equipment. Posterior calf enclosure of the orthosis was fixed to the lower gripper of the testing machine, and the movable traverse loading was applied to the foot platform of the AFO under the 70° to the horizontal axis. The graphs of load vs. deformation were obtained from the experiment as illustrated in table 7. The load vs. deformation graph could be converted to the stress-strain curve. However, there was a limitation of the compression machine that could provide only hardcopy of the results, not electronic data. The load-deformation curve behaves similarly to the stress-strain curve. From table 7, it can be seen that benchmark can withstand much greater load (505 N) compared to other models (183 N and 237 N, for modified models 1 and 2, respectively).

On the other hand, modified model 2 had undergone the highest deformation of 23.5 mm. The deformation of the benchmark was about 12 mm, whereas the modified model 1 had deformation of 7.5 mm. The results acquired from the compression experiment are not quite adequate since several factors could affect. Firstly, the density of the infill for each model slightly differs. Therefore, the models with denser infill showed better performance. Secondly, the modified models were printed in combination with two materials, which require the synthesis of the materials at particular temperature. Finally, the performance of the multi-material 3D printer is not ideal as it was expected since it yet needs improvement (in Python) of its printing process algorithm in the future. For future work, it is expected to prototype more models of combined materials of PLA, ABS, and Nylon 12, with different proportions, to further analyze the cost and efficiency as well. Besides, load distribution on the human leg will be determined by applying the pressure-sensitive sheet.

5. Conclusions

In conclusion, the brief review of the multi-material 3D printing and its application in the industry was done. Three models of the AFO were designed and numerically simulated in FEA software. The
results were obtained for the total deformation, equivalent von-Mises stress and equivalent strain. The modified models of the model 1 AFO were developed by replacing the PLA by Nylon 12 at the regions with the highest stress concentration. The results showed considerable improvement in AFO performance, reducing the equivalent stress by nearly 50%, and the total deformation was reduced by 35% and 70% for modified models 1 and 2, respectively. Then, these models were prototyped using the multi-extrusion 3D printing machine, and the compression testing was conducted in Tinius Olsen machine. The graph of load-deformation was obtained from the experiment, and the results were compared. The results were not adequate, as expected in numerical results.

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