Design and Analysis of a Passive Ankle Foot Orthosis by Using Transient Structural Method

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Abstract. Foot drop is a condition where individuals are unable to lift the foot through the ankle. It results in slap foot after heel contact and toe drag during the swing phase. Ankle Foot Orthosis (AFO) is a mechanical device that supports both the ankle and foot of the individual and guides the movements of the foot to prevent slap foot and toe drag. There are two types of AFOs: Passive AFO and Active AFO. In this work, design and static analysis of a passive AFO to fit a human foot is presented. The static analysis was carried out for AFO made of two different materials (Polypropylene and High-Density Polyethylene (HDPE)) with two different thicknesses (3mm and 4mm). Based on the results obtained from the static analysis, the design of AFO was optimized for shape and thickness. Further dynamic analysis was carried out on the optimized AFO to know its behaviour in walking condition. The results obtained from the static and dynamic analyses showed that the polypropylene AFO was better compared to that of HDPE AFO by generating less stress, deformation, and factor of safety. The proposed AFO can be fabricated and tested for real-time walking conditions.

Keywords: Ankle Foot Orthosis, Finite Element Analysis, Polypropylene, HDPE

1. Introduction
Walking is the human’s most important characteristic of locomotion[1]. It is a voluntary and coordinated activity that involves brain, spinal cord, bones, muscles, peripheral nerves, and different joints[2]. But many people in the world are unable to experience the normal walking activity because of gait disabilities[3]. These gait disabilities are caused due to various neurological diseases (spinal cord injury, stroke, and cerebral palsy), muscular deficiencies (plantarflexion or dorsiflexion muscle weakness), or traumas. The individuals with neurological diseases or muscular deficiencies have either dorsiflexor muscle weakness or plantar flexor muscle weakness or both, which result in reducing their walking ability[4-5]. The individuals with dorsiflexor muscle weakness are unable to lift their foot through the ankle. While walking, they lift their leg higher than the normal to avoid the toe drag. This gait disorder is called steppage gait[6], and it is characterized by foot drop[7]. This gait disability can be compensated by using an assistive device called ankle-foot orthosis (AFO). The AFO is a device
that supports the ankle and foot of the individual to overcome the foot drop condition by guiding ankle dorsiflexion and plantarflexion[8]. AFO is the most commonly used assistive devices (about 26%) among all the assistive devices[9]. These AFOs are classified into passive and active based on controlling mechanisms. Passive AFOs contain only mechanical elements to control the relative motion between the shank and foot parts. Active AFOs contain onboard control system and actuator to control the relative motions of the AFOs.

The AFOs are made from various types of materials, including polypropylene, thermoplastics, carbon fiber, metals, EVA (Ethylene Vinyl Acetate), or combination of similar materials. In the early days, AFOs of a similar shape but different sizes were manufactured so that they would fit a wide variety of patients. However, nowadays, with materials such as Plaster of Paris (POP) and Fiberglass readily available, custom made AFOs are being manufactured. The custom made conventional AFO manufacturing involves casting and making a mold of the patients’ limb by using Plaster of Paris, and then AFO is made around that mold. This method is based on trial and error method and time-consuming[10]. AFOs are designed and fabricated by using 3D scanner and 3D printing technologies are drastically increasing nowadays. These technologies are costly, but efficient. AFOs can be fabricated by 3D printing technology for a wide variety of materials ranging from different plastics to carbon fiber[11-12]. Nowadays, many CAD softwares are available for designing an AFO[13 –14].Recently, researchers are using the CAD softwares to built AFOs virtually and use Finite Element Analysis (FEA) to simulate and optimize the AFO designs[15 –17]. By using the FEA method, one can predict stress and strain distribution induced in the model. This saves the time and cost of fabrication of the real model. FEA method is also used to design and evaluate various assistive devices in orthotics and prosthetics, especially AFOs[18 -25].

This article presents an optimized 3D model of a single piece passive AFO by using the FEA technique of different materials and thicknesses. Both static and dynamic analyses were performed on the AFO to determine the maximum stress, total deformation, and factor of safety (FOS). Static analysis was carried out to know the behaviour of the AFO under static conditions[26]. A novel approach of transient structural method was used for the dynamic analysis of the optimized AFO, which mimic the natural walking condition.

2. Methods

2.1. Obtaining the 3D model of the AFO

Initially, a 3D human foot model shown in figure 1 was downloaded from GRABCAD (www.grabcad.com). For this foot model an AFO was designed as shown in figure 2. This AFO was considered as a reference AFO.
2.2. Static Analysis
For static analysis, the physical situation considered was a person standing upright wearing an AFO with a strap just below his/her knee. The objective here was to find out the stresses induced and the deflection of the AFO under static conditions. Since the person is standing, half of his weight would be taken by each leg, and the force on the AFO would be equal to the same [27]. Since the person wearing the AFO is stationary, load applied were static. This was referred to as static analysis. When applying the forces, it is assumed to be that there is no ground below the AFO and hence no ground reaction forces were applied. The analysis was carried out on the reference AFO with polypropylene and HDPE materials. These materials were chosen because these are widely used to manufacture the AFO [10, 28]. The properties of the materials [13, 29] are given in Table 1. The weight of the person was taken as 55 kg, so a force of 275N was applied on the AFO. The AFO was optimized geometrically based on the results obtained in the FEA method for static condition. For the optimization of the AFO, the reference model was redesigned in two different geometries such as Type I AFO (refer figure 3) and Type II AFO (refer figure 4), and analyses were carried out for two different thicknesses (3 mm and 4mm) and materials (Polypropylene and HDPE). The Type II AFO with 3mm thickness made of Polypropylene Material was chosen as final optimized AFO by considering the optimum maximum stress-induced, optimum thickness of the AFO and factor of safety below 3 [26].

Table 1. Properties of the materials.

| Material  | Elasticity Modulus (GPa) | Poisson’s Ratio | Density (g/cc) | Tensile Strength (MPa) |
|-----------|--------------------------|----------------|---------------|------------------------|
| Polypropylene | 2.4                      | 0.43           | 0.9           | 30                     |
| HDPE      | 1.08                     | 0.418          | 0.958         | 25.7                   |

Figure 3. Type I AFO
Figure 4. Type II AFO

2.3. Dynamic Analysis
The dynamic analysis was carried out on the optimized AFO using ANSYS® software. The dynamic analysis was carried out to know the behaviour of the AFO when the person wearing the AFO walks [30]. As the gait of a person is divided into the stance phase and swing phase, the dynamic analysis was carried out for the stance phase, because a considerable amount of forces act on the AFO during the stance phase, but are almost negligible during the swing phase of the gait, since there is no ground contact. Further, the stance phase is subdivided into loading response, mid-stance, terminal stance, and pre-swing. Similar to Static Analysis, the ground reaction forces were neglected for the Dynamic Analysis. For the analysis, the data was taken from the gait of a 22-year-old normal female...
having weight 55kg [2]. For the analysis, the mediolateral forces were neglected because of their small magnitudes, and only the vertical and fore-aft forces were taken into consideration. Movement of the leg, ground reaction forces, and vertical and fore-aft forces are shown in figure 5, figure 6, and figure 7 respectively.

**Figure 5.** Movement of the right leg in the sagittal plane at 40 ms intervals [2].

**Figure 6.** The ground reaction forces during different stages of the gait [2]  
**Figure 7.** Butterfly diagram showing Vertical and Fore-aft forces at 10 ms intervals [2]

The graph showing the tibia angle with respect to the normal of the ground during the stance phase of the gait is shown in figure 8[31].

**Figure 8.** Variation of ground-shank angle with the stance phase [31]

### 2.3.1. Procedure for the analysis

The dynamic analysis was carried out using the Transient Structural method in ANSYS® Workbench. The analysis was carried out for the four stages of the stance phase, namely loading response, mid-stance, terminal stance, and pre-swing phases. The four stages were given specific time intervals based on the percentage of stance phase they occupy. The stance phase of the subject lasted for 500 ms. The average vertical and fore-aft forces were calculated in the four
different stages from the data above (refer figures 5, 6, and 7). The average angle of the tibia with the normal to the ground was calculated during all four stages (refer figure 8). Finally, the average forces were applied on the AFO according to the tibia angle, and their duration was set according to the corresponding time intervals. The data used during the four stages of the analysis are given in table 2.

Table 2. Data of time, tibia angle, vertical and horizontal forces acting on the AFO

| Stages           | Duration (ms) | Average Tibia Angle (Degrees) | Average Vertical Force (N) | Average Horizontal Force (N) |
|------------------|---------------|-------------------------------|---------------------------|-----------------------------|
| Loading Response | 61.4          | -11.04                        | 280.69                    | -68.82                      |
| Mid Stance       | 219.3         | 0                             | 501.14                    | -69.01                      |
| Terminal Stance  | 155.3         | 31.43                         | 519.94                    | 69.69                       |
| Pre-Swing        | 64            | 57.4                          | 311.11                    | 97.36                       |

The area of forces applied on the foot part of the AFO is shown in figure 9. The average forces calculated were applied on the foot part of the AFO in the appropriate areas[32 -33]. Since the ground reaction forces are neglected, the above forces and angles must be applied in the exact opposite direction while doing the analysis.

Figure 9. Area of the foot in contact with the ground at different stages [33]

The Transient Structural analysis was initiated in the ANSYS® Workbench. The AFO model was imported in the geometry section. The material and its properties were defined. The duration of the analysis was set to 1000 ms, and the sub-steps were set to 100. The boundary conditions [11, 27, 29] were applied carefully, keeping in mind the angles and time intervals. To ensure that the forces were applied at the correct angles, different coordinate systems were created according to the average tibia angle. Then the Total Deformation, Equivalent (von Mises) Stress, and Factor of Safety options were selected in the Solution section, and the problem was solved. The directions of forces applied during the loading response and mid-stance phases are shown figure 10(a) and 10(b) respectively and the directions of forces applied during terminal stance and pre-swing phases are shown in figure 11(a) and 11(b) respectively.
3. Results and Discussion

The reference model of the AFO was designed around the human foot model, which was obtained from the GRABCAD (www.grabcad.com). This AFO was taken as a reference model to optimize the AFO. To know the behaviour of the AFO in static condition, finite element analysis (FEA) was carried out for the constant load of 275N applied on the foot part of the AFO. For this analysis, two materials were chosen (polypropylene and high-density polyethylene). After the analysis, maximum stress-induced, maximum deformation, and factor of safety was noted by changing the geometrical shape, varying the thickness, and materials of the AFO. As a total, 12 models of AFOs were analysed for static condition. These analyses were carried out to choose the final optimized AFO, which should have minimum stress-induced with less deformation and lower allowable factor of safety. The results of analyses for all 12 models of the AFOs are shown in table 3. The stress induced in the AFOs for polypropylene and HDPE materials with 3mm and 4mm thicknesses are shown in figure 12 and figure 13 respectively. The deformation of the AFOs for polypropylene and HDPE materials with 3mm and 4mm thicknesses are shown in figure 14 and figure 15 respectively. The factor of safety of AFOs for polypropylene and HDPE materials with 3mm and 4mm thicknesses are shown in figure 16 and figure 17 respectively.
Table 3. Properties obtained from static analysis

| Type of AFO | Thickness | Polypropylene | HDPE | 
|-------------|-----------|---------------|------|  
|              |           | Max. Stress (MPa) | Deformation (mm) | FOS | Max. Stress (MPa) | Deformation (mm) | FOS |
| Reference AFO | 3 | 101.8 | 19.5 | 3.94 | 101.3 | 43.3 | 2.53 |
|              | 4 | 61.1 | 10.8 | 4.91 | 61 | 24 | 4.20 |
| Type I AFO | 3 | 92.4 | 87.4 | 3.24 | 108.8 | 428.3 | 2.36 |
|              | 4 | 57.9 | 56.8 | 5.18 | 72.5 | 303.5 | 3.54 |
| Type II AFO | 3 | 114.5 | 20.9 | 2.62 | 115.4 | 268.8 | 2.23 |
|              | 4 | 59.4 | 71.6 | 5.02 | 59.9 | 159.2 | 4.29 |

**Figure 12.** Stress-induced in different models of AFO for 3mm thickness.  
**Figure 13.** Stress-induced in different models of AFO for 4mm Thickness  

**Figure 14.** Deformation of different models of AFO for 3mm thickness  
**Figure 15.** Deformation of different models of AFO for 4mm Thickness
By observing the data from table 3, there is no much percentage variation in stress-induced between polypropylene and HDPE. The minimum percentage variation in stress was observed in Reference AFO of 4mm thickness, where stress induced is decreased by 0.06%. The maximum percentage variation was observed in Type I AFO of 4mm thickness, where stress induced is increased by 20.22%. The maximum percentage increase in deformation was observed in Type I AFO of 3mm thickness (79.59% increase). When it comes to the FOS, the percentage variation between polypropylene and HDPE was also calculated. The minimum percentage variation was observed in Type II AFO of 3mm thickness, where FOS is decreased by 14.88%. The maximum percentage variation was observed in Type I AFO of 4mm thickness, where FOS is decreased by (89.57%).

As mentioned above, the AFO was optimized by considering the minimum stress-induced, minimum deformation, and allowable FOS. As seen in table 3, Type I AFO of 4mm thickness with polypropylene material had less stress-induced (57.85 MPa), but results show that the FOS for that model was 5.18, which is not safe. Also, by considering the minimum deformation, Reference AFO of 4mm thickness with polypropylene had minimum deformation of 10.83mm, but it also had a FOS of 4.91, which is not safe. If the minimum FOS was considered, Type II AFO of 3mm with HDPE showed a FOS of 2.23 but failed in stress (115.4 MPa) and deformation (268.75 mm). Finally, Type II AFO of polypropylene material with 3 mm thickness having optimum induce of stress (114.49 MPa), optimum deformation (20.87mm), and FOS of 2.62 was chosen for the dynamic analysis. The finite element simulation of stress-induced is shown in figure 18, and the finite element simulation of deformation is shown in figure 19 for the optimized AFO (Type II AFO).

![Figure 16. Factor of Safety in different models of AFO for 3mm thickness.](image1)

![Figure 17. Factor of Safety in different models of AFO for 4mm Thickness](image2)

![Figure 18. Stress distribution in the AFO](image3)

![Figure 19. Deformation Occurred in the AFO.](image4)
Table 4. Properties obtained from the dynamic analysis of the optimized AFO

|                                | Maximum Stress-Induced | Deformation | Average Factor of Safety |
|--------------------------------|------------------------|-------------|--------------------------|
|                                | 154.14 MPa             | 14.69 mm    | 3.14                     |

Dynamic analysis was carried out on the optimized AFO by considering the real-time force applicable to the AFO with different tibia angles with respect to four subdivisions of the stance phase. The results (refer table 4) show that the maximum stress induced in the AFO was 154.14 MPa around 320ms. The maximum deformation occurred in the dynamic analysis was 14.69mm obtained around 300ms, and the average factor of safety of the AFO was 3.14, which is slightly higher than 3, but satisfactory. The graphical representation of maximum stress v/s time is shown in figure 20, and maximum deformation v/s time is shown in figure 21. The finite element simulation of stress-induced (refer figure 22) and deformation (refer figure 23) are also shown.

![Figure 20. Maximum stress induced v/s Time for Dynamic Analysis](image)

![Figure 21. Maximum deformation v/s Time for Dynamic Analysis](image)

![Figure 22. Stress distribution in the AFO.](image)

![Figure 23. Deformation occurred in the AFO](image)
By observing the results of stress, deformation, and FOS for both analyses, the percentage variations were calculated. The percentage variation in stress between two analyses was increased by 25.72%. The percentage variation in the deformation between two analyses was decreased by 29.611%. The percentage variation in the FOS between two analyses was increased by 16.56%. respectively. The comparison of the parameters of analyses is shown in figure 24.

**Figure 24.** Comparison of Stress, Deformation, and Factor of Safety between Static and Dynamic Analyses for the Optimized AFO

4. Conclusions and Future Work
In this research article, different models of AFOs were analysed for static load conditions with varying shapes and thicknesses for two materials (polypropylene and HDPE). The results showed that the polypropylene material AFO of Type II with 3mm thickness had good capability to withstand the static force. This model was chosen for dynamic analysis using a transient structural method to know its behaviour under real-time walking conditions. In dynamic analysis also, the model showed satisfactory results. This implies that the polypropylene AFO suits good for a person weighing 55 kg compared to HDPE material AFO. In future, this work can be extended for further studies by increasing the static load, fabricating the AFO, and studying it experimentally.

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