Experimental Analysis of Various Materials on Custom-Fit Ankle Foot Orthosis

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Abstract. Traditional Ankle Foot Orthoses (AFOs) is designed to work for different range of patients. They could not perform comfortable orthotic function arising due to individual differences. This problem can be solved by custom fit AFO’s but the current method involves a lot of manual labor. Rapid Prototyping and reverse engineering can be used on 3-D parts or models designed in CAD software to solve the problem. Through the help of 3-D scanning, customized AFO’s is designed to an individual foot’s anatomy. The scanned data was used to design an AFO structure. The designed structure was virtually tested for different materials and an analysis of the same was done.

Keywords: Ankle Foot Orthosis, Rapid Prototyping, Reverse Engineering, Scanning, Analysis, Experimental analysis.

1. Introduction
Musculoskeletal and Neuromuscular diseases make people lose control over their body limbs such as wrists and ankles. It leads to cerebral palsy (CP), amyotrophic lacteal sclerosis (ALS) and stroke [1]. Focusing on the ankle, it causes great difficulty in walking. The symptoms include foot drop, a gait abnormality which causes involuntary plantar flexion and make raising the front of the foot troublesome due to weakness. In the mechanical engineering industry, the 3D scanning procedure has also been widely used for the inspection and reverse engineering purpose. [2-4]. Due to their complex functions, a lot of consideration has to be put into design of orthosis especially ankle foot orthosis. The major design characteristics include the weight of the orthosis, adjustability, functional use, cost, durability, properties of the materials used, ease of donning and doffing, aeration to avoid skin maceration etc. The review of various techniques for 3D reconstruction of facial structure for craniofacial and aesthetic surgery has also been conducted. The cost-effective solution for a scanning system for body parts based on Microsoft Kinetic sensors has been explained in previously published research paper [5 -7].

The 3D scanning technique are applied in clothing and fashion technology [8]. The 3D scanners are used for acquiring the human body topology for providing comfortable, custom fit, optimized spacecraft seat [9]. Application of 3D scanning technique for clothing industry is also been presented by Ankle Foot Orthoses (AFOs) are used to provide support to the ankle in such cases so as to assist in daily activities. Commercial AFO are broadly classified under two types- a standard general design available in stores with no patient customization and a custom-made AFO designed and fabricated using tedious and time-taking methods of making molds through plasters. However, recent methods involve the use of digital surface capture via 3D scanning and designing a rapid AFO based on the scan [10-12]. Our project aims at studying this method of designing and fabricating a Custom-fit Ankle Foot Orthosis using different materials. Selection of material is important to ensure that the ankle foot orthosis...
provides rigidity and comfort to the patient while allowing certain restricted movements. The design along with the material is also crucial for this. In the context of product development, Rapid prototyping is a widely used practice to create and develop physical parts directly from the digital data [13]. It has been clearly presented what are the different types of processes of virtual modeling to final prototype like fused deposition modeling, laminated object manufacturing, sintering or melting and three-dimensional printing. Chronic ankle instability causes tremors and secondary degenerative problems. The main purpose of this work was to evaluate the usefulness of the ankle arthroscopy for the evaluation and judgment of intra articular pathologies associated with chronic instability.

2. Scanning of the Foot
In order to generate the most accurate data for the 3D scans, a fool proof methodology was followed. It was noticed in the research paper, that the scanner mechanism for the medical application shall been working as a boon [14]. The capture of the human body part is done on a structured glass table light scanner and a computed tomography apparatus is been built. It gives the chance of surround scanning of the human body, using only one scanning head, without changing the body position. As the design required data from below the Knee from the posterior side of the leg and the ventral side of the foot, these parts were covered with talcum powder and probes were attached at fixed distance as shown in figure 1.

![Figure 1. Scanning of the foot being done](image)

The camera locations for the scan were determined by its range and field of view. Since the field of view of the used 3D scanner was less, the locations were chosen such that there were at least 3 probes in a single frame. A white background was also maintained so as to distinguish the patient’s leg from extraneous data.

3. Modeling and Designing of AFO
The scanned data which were obtained was processed with a software called Geomagic Design X. The live capture option of Geomagic was used to capture the data from the 3D scanner. The obtained data was then post processed by using the various tools in Geomagic as shown in figure 2.
The process started with the removal of the redundant data points which include the part of the leg that were not required for the model and also the background data. The probe points were then connected to each other to generate a surface mesh. The individual surface meshes were then aligned using various methods and merged to create rough model of the ankle and foot of the patient’s leg. The surface was then smoothened using required tools and converted in to a STL file to be uploaded in to the CAD software.

The STL file of the patient’s leg was uploaded in to the fusion 360 platform under the design window. Using create command a cylinder was created around the patient’s leg from knee to underside of the foot. Using the edit form command the cylinder was adjusted so as to cover the leg as well as the foot of the patient’s leg. The cylinder was pulled down in to the patient’s leg by using the pull command under modify tool box. The unnecessary parts were trimmed away to give the final model of the ankle foot orthosis as shown in figure 3.
4. Analyzing the Design

After studying various papers on analyzing an AFO on ANSYS and studying about the various forecasting on an AFO during use, we proceeded to analyze our design [15-17]. The analysis of the different 3D models was done using ANSYS Workbench Ver.15. The analysis consisted of applying a vertical force of intensity 150 N to the foot plate of two different 3-D models and a horizontal force of 50N to the posterior side on the initial designed model. The test was carried out for three materials: Nylon, Carbon Composite and acrylonitrile Butadiene Styrene (ABS). The various properties of the materials used to carry out the analysis has been mentioned in Table 1. An analysis of the load of lower limbs of occupants in the armored vehicle, which has been demolished due to improvised explosive device charge under the vehicle has been done [18-20]. Analysis of the stress distribution has been conducted, for the forces under different angles to the biomedical axis of a limb has been done.

Table 1. Material Properties

| Material        | Elastic Modulus | Poisson Ratio |
|-----------------|-----------------|--------------|
| Nylon           | 2.4e+009        | 0.39         |
| Carbon Composite| 2.3e+011        | 0.30         |
| ABS             | 2.9e+009        | 0.35         |

From the corresponding stress-strain curves of all three materials, a comparison was made among materials and shown in Table 2. On subjecting the design to the initially mentioned forces, the stresses generated were observed. A stress-strain analysis was also carried out with curves for the three materials being plotted as shown in Fig-4, Fig-5 and Fig-6.

![Figure 4. Stress-Strain Curve for Nylon](image)

![Figure 5. Stress-Strain Curve for Carbon Composite](image)

![Figure 6. Stress-Strain Curve for ABS](image)
Table 2. Stress & Strain Values

| Material          | Maximum Stress [Pa] | Corresponding Strain [m/m] |
|-------------------|----------------------|---------------------------|
| Nylon             | 10156                | 4.2542e-006               |
| Carbon Composite  | 1.5516e+008          | 1.1813e-002               |
| ABS               | 10221                | 3.541e-006                |

From the table, we find that the Maximum Stress is generated the least in the AFO made of Nylon (10156 Pa). On further analysis in the software, we found points where this stress was acting and the stress distribution in the entire AFO as shown in figure 7.

The abstract follows the list of addresses. The abstract text should be indented 25 mm from the left margin. As the abstract is not part of the text it should be complete in itself; no table numbers, figure numbers, references or displayed mathematical expressions should be included. It should be suitable for direct inclusion in abstracting services. Based on the above analysis, a second two-piece AFO was designed (Fig-8). The pieces were connected by a flexible spring made of carbon fiber composite. Such an AFO is known as PDE Modular Spring Composite System AFO.
The advantage of this modified design can be understood by carrying out a stress analysis (Fig-9) on it as was done on the earlier designs. In Design 1, the single piece AFO sees the accumulation of stresses on its lower half and in case of any damage the whole AFO will have to be discarded. But in the 2nd design, all the stresses are taken up by the composite spring and no stress acts on the upper or lower half of the AFO (Fig-8). So, if any damage were to occur due to generation of stress beyond the breaking point, only the spring will have to be replaced and not the entire AFO.

**Figure 9. Stress Distribution in Nylon made PDE Modular Spring Composite System AFO**

In the single piece design, we find that the deformation occurs only in the lower part and has a maximum value of 2.28e-8 m. However, in the two-piece design with metallic spring the deformation is concentrated in the upper part and has a maximum value of 0.053 m (Fig- 10). This shows that the second design is more flexible and will allow certain restricted additional movements to the patient than the single piece AFO while serving all the functions of the original design.

**Figure 10. Comparison of Deformations in both designs – Posterior Leaf Spring AFO (left) & PDE Modular Spring Composite System AFO (right)**
5. Conclusion
From our Single Piece Design, we conclude that the model made of Nylon polymer was the most effective. In this model the critical section was identified at the retro malleolar region next to the ankle trim line with a maximum stress of 10156 Pa with a considerable factor of safety. The maximum strain and deformation were also observed in the same region as shown in figure and were observed to be within safe limits. The considerably low values of deflection and strain point out the lack of flexibility in this model. PDE Modular Spring Composite System AFO: This model makes use of a posterior spring composite system of carbon fiber or any other composite material which absorbs the strain energy to allow more flexibility in the operation of the AFO. The critical section was identified to be the spring with a maximum stress of 1695MPA and a factor of safety of 10. The deflection and strain values were evaluated as shown in the figure and was observed to be within safe limits. This model gives the patient more flexibility and can even be used for athletic activities.

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