MECHANICAL ANALYSIS OF AN ANKLE-FOOT ORTHOSIS USING FINITE ELEMENT METHOD

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ABSTRACT: Ankle-foot orthosis (AFO) is an externally applied assistive device that encompasses the lower leg, ankle and foot of the human body. AFO is used to control instabilities in the lower limb by compensating for the muscle weakness and aligning the positions of ankle and foot properly. There are many type of AFO which are designed for different biomechanical needs. In AFO design, AFO stiffness is an important parameter that determines the mechanical characteristic of the AFO, and depends on different biomechanical and structural parameters such as trimlines, material type and thickness. The effects of these parameters can be effectively tested in a finite element model of AFO. By doing so, observing the effects of design alterations on the mechanical properties of the AFO can be carried out using FEA (finite element analysis) without conducting an experimental testing of the AFO which would require a high level of cost. A three-dimensional (3D) solid body model of the AFO is required for FEA. However, it is difficult to draw such an object having complex and free-form geometry with a CAD (computer aided design) software. On the other hand, with the advances in the scanning technology, an object with physical free-form geometry can be converted into a 3D CAD model, which enables the object to be mechanically analyzed in the finite element software. In this study, an example involving the mechanical analysis of an AFO is implemented using a finite element software. Results and future directions regarding the mechanical structure of the AFO were also reported.

Key words: ankle-foot orthosis, finite element analysis, 3D optical scan

INTRODUCTION

Many different types of ankle-foot orthoses (AFOs) are available for different biomechanical and clinical aims. They can be generally classified into two categories: articulated (Gao, Carlton, & Kapp, 2011) and non-articulated (Ramsey, 2011). Articulated AFOs contain mechanical joints at the ankle section of the orthosis that allow or limit the range of motion in sagittal plane. Similarly, non-articulated AFOs are used to control of ankle movement and rotation, but they are constructed as a one-piece without incorporation of a joint mechanism. Their design parameters such as material type, material thickness and trimline geometry influence the stiffness of the AFO which is chosen according to biomechanical needs of the patients. Non-articulated AFOs have a rigid character, if the trimlines are anterior to the malleoli. As trimlines are moved to posterior to the malleoli, AFO's flexibility enhances (Harvey, Macko, Stein, Winstein, & Zorowitz, 2008).

The design variables should be carefully evaluated to reach the optimal design. At this point, finite element analysis (FEA) provides an opportunity for designers to predict the behaviors of their product under different loading conditions. So alternative designs can be tried out for their validity and safety using the computer before any model is built (Chandrupatla, 2004). Therefore, FEA reduces the cost and time needed to develop the optimal AFO that inevitably requires design alterations. However, solid body model used in the finite element approach should be properly constructed such that it accurately represents the mechanical structure of the original product hence, it would be possible to have realistic results from the analysis. So the model geometry, boundary conditions, material type, loading conditions and meshing preferences, which are the major components of a finite element analysis, should be defined as accurately as possible to be able to mimic the real-world conditions. The objective of this research was to implement the mechanical analysis of a flexible, non-articulated ankle foot orthosis using finite element method and to compare results of the FEA with experimental results.

MATERIALS AND METHODS

AFO Production

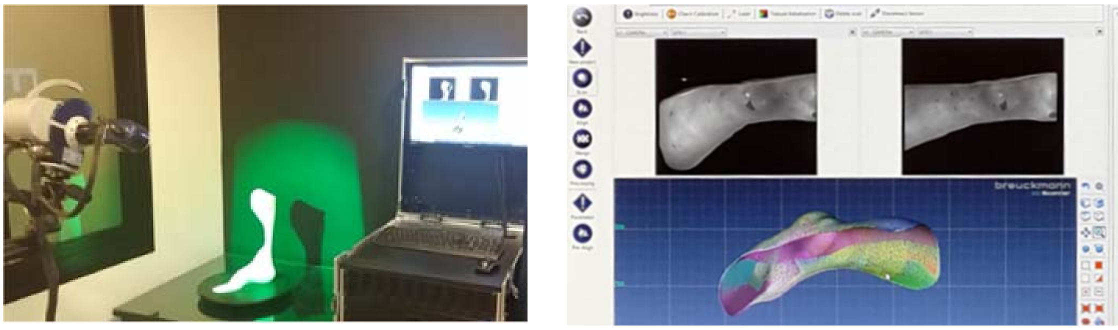
An AFO was fabricated from a polypropylene sheet with 3 mm thickness using the vacuum molding technique (Wilson Jr, 1974) by an experienced orthoptist. In this technique, the polypropylene sheet is heated to its softening temperature in an oven. The polypropylene sheet is then surrounded around a positive mold that produced from a negative mold. In the study, molds were produced according to the lower limb of a patient with spina bifida which is a neurological disease stemmed from the spinal cord malformation and might cause physical and intellectual disabilities that range from mild to severe. The AFO was first trimmed from standard trimline border, so a rigid (solid) AFO was obtained. Then, the AFO was trimmed beyond the standard trimline such that it allowed flexibility under gait conditions (Figure 1).

(a) (b)

Figure 1. (a) Rigid and, (b) Flexible AFO Used in the Study

Three-dimensional CAD Model of the AFO

Topometrical three dimensional (3D) scan systems are generally used to measure the dimensions of devices or to convert the physical objects into 3D data (Breuckmann, 2014). AFOs have free-form geometry. So, it is difficult to draw a 3D AFO model with a CAD software. However, scanning technology provides having a complete 3D AFO model for analyzing in a FEA software. An optical 3D scanner (Breuckmann GmbH), that works based on the fringe projection system, was used to digitize the AFO model. It is possible to have highly precise three-dimensional data with this sophisticated method of high-resolution 3D digitization. 20 scanned data was combined and a single point cloud model was obtained. Then the model was converted into a 3D solid body model (Figure 2). In this process, 4000 surfaces were used to be able to represent the real model as proper as possible in regard to the geometrical details. Deviation analysis was carried out for the 3D model with tolerance of 0,1 mm. It was ensured that the all dimensions of the model was below the pre-determined tolerance value.



(a) (b)

Figure 2. (a) Optical Scanning of AFO, (b) Converting the Physical Model of the AFO to a CAD Model

Experiment

The objective of the experiment was to measure the displacement under various loading combinations along the anteroposterior axis between two points, i.e. force application point and a predifined origin point of a coordinate axis. AFO was fixed to a stable structure from its footplate and heel by clamps (Figure 3). Two weight carrier equipments were hung from the rings which were located at the medial and lateral sides of the AFO. Each carrier equipment itself applied a force of 2 N. Later the weights of 10 N, 20 N and 30 N were successively placed on the carrier. Consequently, forces of 4 N, 14 N, 24 N and 34 N were applied to the AFO. The displacement values at each loading level were measured.

4 N 14 N 24 N 34 N

Figure 3. Various Loading Combinations Subjected to the AFO

FEA of the AFO model

Digitized 3D AFO model was imported in a CAD software for the finite element analysis. In the software, planes of the model were arranged according to global *x*, *y*, *z* directions. Polypropylene copolymer material was chosen from software library and defined as a linear elastic material. As for the boundary conditions, the model was fixed from its footplate and heel surfaces which were also immobilized during the experiments by means of fixed joints. Forces were applied from each side where the strap was linked to the AFO (Figure 4). Mesh size was determined around 4 mm considering the detailed surface of the model and a high quality mesh structure was generated using solid mesh type. The mesh structure was consisted of 96883 nodes and 48803 elements.

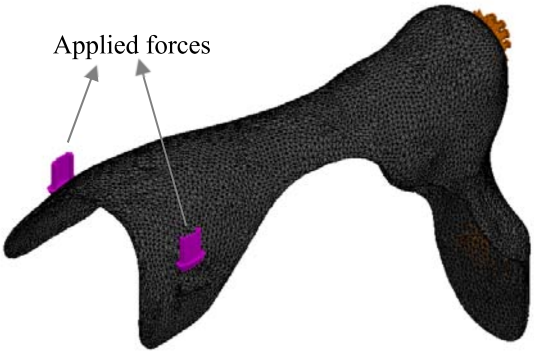


Figure 4. Finite Element Model of the AFO

RESULTS AND FINDINGS

The experimental and theoretical displacement results were shown in the Table 1. Experimentally, loadings of 4 N, 14 N, 24 N and 34 N resulted in 2,5 mm, 7,5 mm, 14 mm and 18,5 mm displacements, along the anteroposterior axis, respectively. Theoretical displacements values obtained from FEA were 2,14 mm, 7,86 mm, 13,65 mm and 18,73 mm for the same loading conditions as the experimental ones. It can be deduced from the last column of the table, which indicates the difference between experimental and theoretical results, that displacement values of FEA are in good agreement with the experimental results.

Table 1. Externally Applied Forces and, Experimental and Theoretical Displacements Values along the Anteroposterior Axis

Applied Forces			Experimental results (mm)	FEA Results (mm)	Difference between experimental and theoretical displacements (mm)
Medial side (N)	Lateral side (N)	Total (N)			
2	2	4	2,5	2,14	0,36
7	7	14	7,5	7,86	0,36
12	12	24	14	13,65	0,35
17	17	34	18,5	18,73	0,23

The graphical presentation of Table 1 was given in Figure 5. It can be observed from the figure that a linear relationship was occurred between the applied forces and displacements over the AFO.

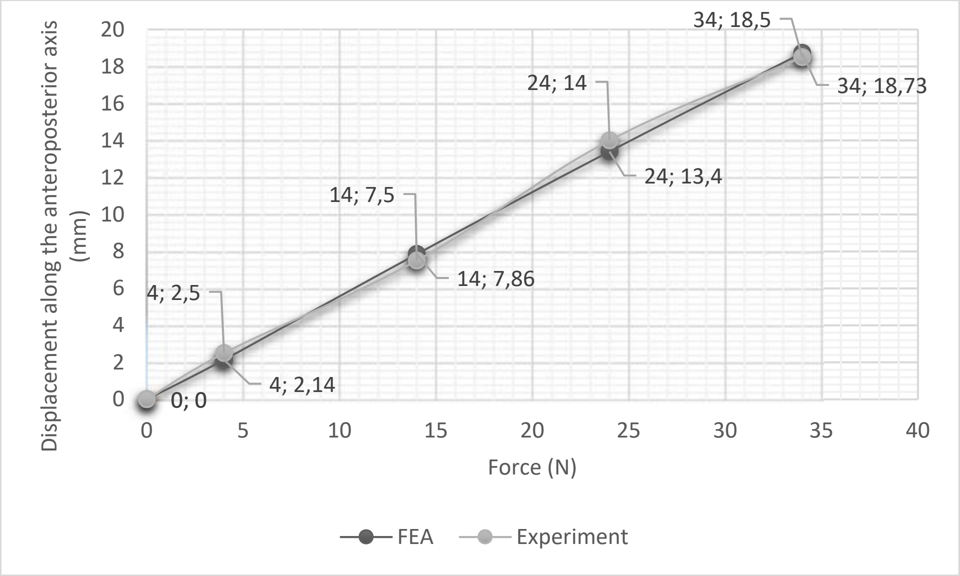


Figure 5. The Comparison of Experiment and Finite Element Analysis

To observe the locations in which the maximum stress values occur over the AFO model, a representation of the stress distribution is given in Figure 6. It can be seen from the figure that maximum stress values occurred around the medial and lateral sides of the AFO, as expected.

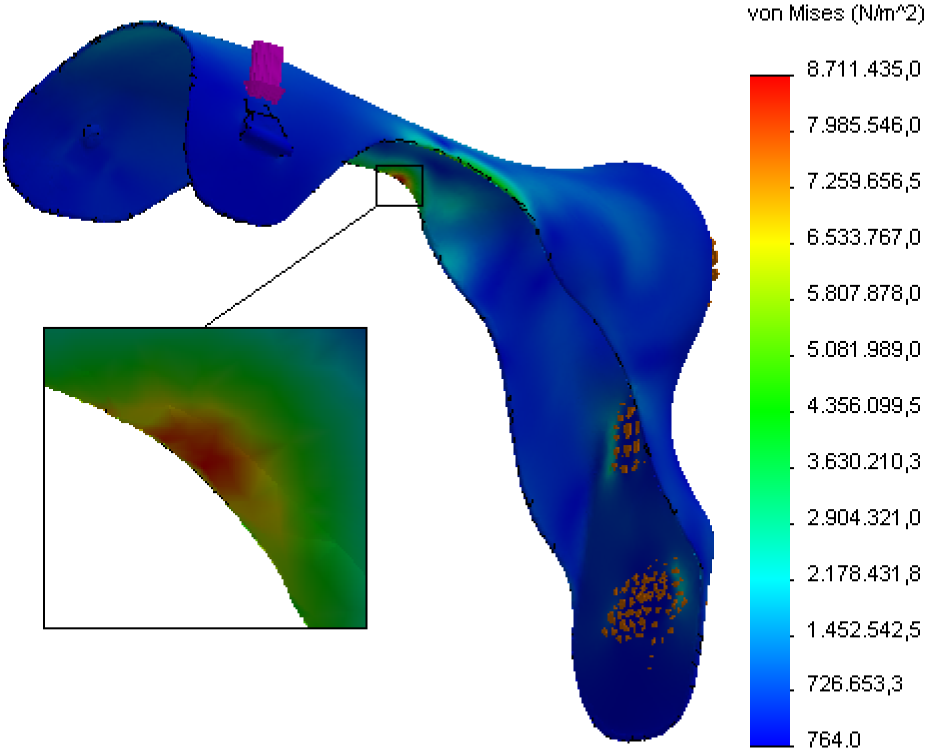


Figure 6. Stress Distribution of the AFO Model

CONCLUSION

In the study, displacement results obtained from finite element analysis of an AFO model was compared with the experimental measurements. It was sent that the experimental and theoretical results are in good agreement. It was deduced that the finite element modeling approach could be used for the future studies regarding mechanical characterization of the new AFO models. Therefore mechanically optimal orthosis designs can be accurately modeled and analyzed with a time and cost saving approach. Moreover, it is considered that the results derived from this study can be employed to model different AFO concept designs for different biomechanical requirements. AFO was converted into high quality point cloud data by a 3D optical scan system and then a 3D solid object by some commercial software packages. The high-resolution 3D AFO model also played a crucial role in the success of finite element analysis of the AFO.

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