Design & Analysis of Ankle Foot Orthosis for Assisting Car Driver after Ankle Surgery

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ABSTRACT
Car accidents often occur and normally affected the car driver's foot and ankle. If it is involved surgery for the ankle treatment, the recovery process normally takes a long time. As a normal practice, ankle foot orthosis (AFO) will be worn by an ankle injury patient for shorten the recovery process and also to protect the foot from the pressure of the pedal car while driving especially during the event of such a sudden stop. However, the detail investigation of the suitability of AFO in absorbing or stand the pressure from pedal car during emergency stop is still lacking. Thus, the aim of this study is to investigate the suitability of the current AFO in absorbing or stand the pressure from pedal car during emergency stop and then propose the optimum one. The study was carried out by measuring the foot anthropometric of volunteer which it is to be used in designing the proposed AFO using SolidWorks software. There are three designs were constructed and analyzed to determine the optimum. Analytical process is done using ANSYS software and carbon fiber and polyprophelene (PP) were chosen for analyze the most suitability material for this special AFO (to use for protect immobilize foot during emergency braking). In respect to the material of AFO, results obtained can be concluded that PP is not suitable for this special AFO in absorbing impact during emergency brake. The FE results of the three designs were recorded and compared using the "screening" concept. Design with lowest stress factor is considered as the optimum design and suitable for drivers who have undergone ankle surgery. Based on the screening concept table, the second design is chosen as the optimum one. It gave the lowest maximum stress 4.5495 E + 08 and the safety factor was7.03. In respect of the geometry, based on FE simulation result and concept screening table, we can concluded that the design 2 was the optimum design. However, a better confidence of this optimum design to apply in AFO can be obtained by producing the real AFO model and then further testing needs to be conducted in order to evaluate whether or not, this device able to sustain the impact of emergency braking.

Keywords: *Ankle Foot Orthosis, finite element analysis, optimization, anthropometric, screening concept.*

I. INTRODUCTION

Nowadays, ankle foot orthosis (AFO) is one of a modern technology that had been developed. AFO function is to support the patient those who have the problem with the ankle, for example ankle fracture or weak sport at the ankle joint. AFO can be categorized into three groups, which are passive AFO, semi-active AFO and fully active AFO. The passive AFOs no need an electrical component or power sources, but needed a few of mechanical components (springs and dampers). The semi-active AFO are capable of varying flexibility of the ankle joint by using computer control and it is do not include any actuator to a power supply. It is used to modulate the damping at the joints. Fully-active AFO is more complex device among the AFO because it normally contain on board power source, control system, sensors, and actuators [1]. This fully active usually used to produce torque for propulsive assistance and motion control. Active AFO is a device that developed with robotic control system, which mean the AFO could interact with the unpredictable environment [2, 3]. It can help the person that wears it in plantarflexion and dorsiflexion [4]. The passive ankle foot orthosis is a type of AFO that generally used nowadays because of the characteristics such as simplicity, light weight, and compactness. The characteristics are very important in generating a good AFO because it gives the big impact to the ankle during the recovery process [5]. The fixed or articulated joints are normally developed at this time. The non-articulated AFOs with fixed ankle could affect the knee biomechanics. Those who are wear the AFO, their ankle joint movements are limited during mobility [6].

Yamamoto et al developed AFO to provide dorsiflexion assistance for hemiplegic patients [7]. While the passive articulated AFOs that have developed by Ottobock can provide a cosmetically appealing and functional option for dorsiflexion assist [5]. However, there are still lacking of research paper that emphasize on application of AFO in assisting patient that undergone ankle surgery to safely driving a car especially during emergency braking. During emergency brake the driver foot generates force by pressing on the brake pedal with plantarflexion. The driver will modulate the pressure on the pedal to stop the vehicle at between 20 to 120 pounds which is about 137.895 kPa to 827.37 kPa. Average brake reaction force in the emergency braking event was nearly 796 N. Humans are called on to use their senses to safely bring a vehicle to a stop condition [8].

In doing investigation on application of AFO during emergency braking, the Finite Element Method (FEM) is a suitable method since most of engineers use it to analyse their product design. There are also lot of previous researchers used FEM for biomechanics applications [9-13]. Thus, this study fully utilized FEM in checking either the proposed designs of AFO is suitable for the emergency braking application and also in obtaining the optimum design.

II. METHODOLOGY

A. Anthropometric Measurement of the Foot

The anthropometric measurement of the foot was the first step that needs to conduct in this study as did by other researcher [2]. The measurements were conducted in order to have the sample of adult's foot before proceed into the AFO designing stage. There are in total 9 areas of the ankle foot that was selected to be measured, as shown in the Table 1 and Fig. 1.

Table 1. Anthropometric data

No.	Anthropometric Parameter	Measurement (cm)
1	Tibia Length	21.30
2	Calf Girth	35.00
3	Knee Girth	34.50
4	Ankle Girth	23.30
5	Foot Length	26.70
6	Ball of Foot Length	5.10
7	Outside Ball of Foot Length	10.20
8	Heel Breath	5.40
9	Ball Breath	8.40

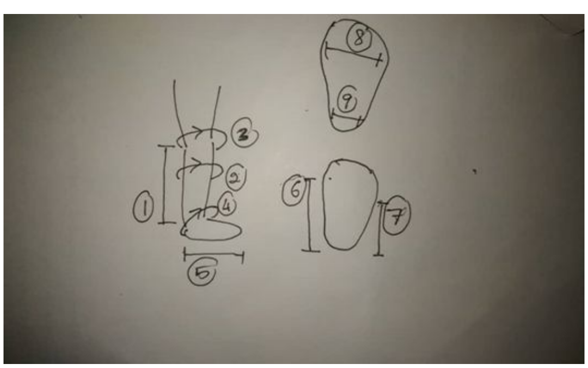
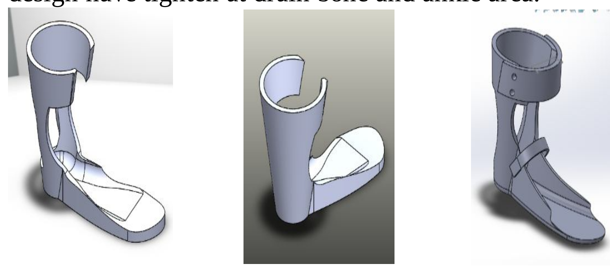


Fig. 1 Sketch view of foot anthropometric parameter

B. 3D Model of Proposed AFO Design

There are three difference designs of AFO were proposed (Fig. 2). They are different in term of;- (a) this design do not has calf support, design (b) has calf support and design (c) do not have calf support but this design have tighten at drain bone and ankle area.



(a) (b) (c)

Fig. 2 (a) Design 1, (b) Design 2, (c) Design 3

The concept of AFO for assisting car driver is designed based on passive AFO. The advantage of following passive AFO design is lighter than semi-active because semi-active and active AFO have extra parts to be assembled with the main AFO for example the motor, load cell, cylinder and etc. An active AFO also is not too complicated as others. If the design follows the others AFO concept, driver will face some problems when push the paddle. This is because in semi-active and active AFO contain the actuator to move the ankle position. The actuator movements will effects the time for driver to move the ankle and push the paddles. If the actuator suddenly moves slower when driving, the driver is risk to the accident anytime.

C. Finite Element Setup

The three proposed design were investigated and analyzed using Finite Element Method (FEM). Before FEM is done, the FE is needed to be setup in term of its boundary condition, so do the meshing of the models. Fig. 3 shows how the boundary condition is set up. Also, since flexibility is an important factor, two materials were studied in this FEM, which are carbon fiber and polyprophelene (PP). These two materials are very familiar in making of Ankle Foot Orthosis (AFO) and its mechanical properties are as shown in Table 2. The finite element analysis is done to obtain their total deformation, equivalent stress (Von-Misses) and safety factor after given load condition of car emergency brake. The Von Mises stress analysis was conducted in order to understand whether the designed material will yield when subjected to a complex loading condition. The pressure value for pressing the pedal brake (during emergency brake) have been choose based on previous research which is between 137895 Pa and 827370 Pa while reaction force is 796 N [8].

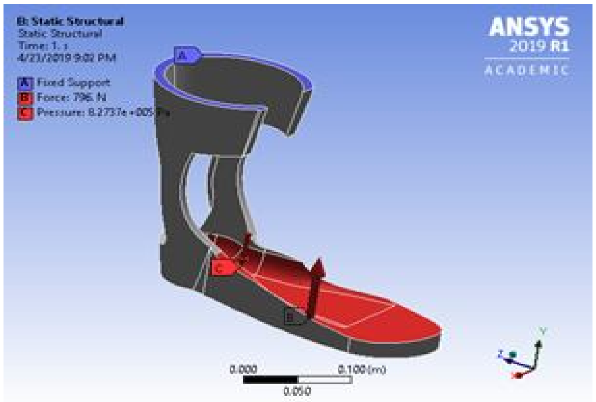


Fig. 3 Boundary condition and load applied on the 3D model

Table 2 Mechanical properties [14]

Properties	Carbon Fiber	Polyphylene (PP)
Density (kg/m³)	1800	902
Tensile Yield Strength (MPa)	3200	20.7

D. Concept Screening

Concept screening is the step to decide the optimum design which is better than the reference design (commercially available design). There must be more criteria listed in the table based on the target and the highest net score will be selected

III. RESULTS AND DISCUSSION

Base on the FE simulation result obtained (Fig.4), it is observed that failure areas (higher stresses) were in the lateral side of the orthosis. This is an agreement with the fracture position observed and reported by previous researcher [15].

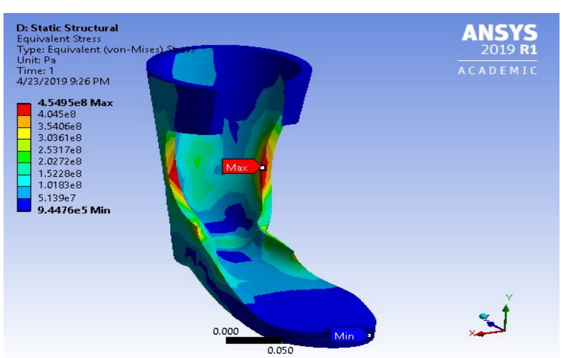


Fig. 4 Location of the Failure area (highest stress)

A. Influence of different materials

Since loading and boundary conditions were maintained, maximum stresses values in each simulated 3 proposed design resulting in equivalent stresses distributions, leading to the conclusion that material characteristics do not alter failure areas. On the other hand and since the selected materials (Table 2) present different mechanical flexibilities, results show that resulting deformation (Table 3) are quite different with a maximum value for PP of design 1, 2623 mm and 106 mm for carbon fiber during gait of emergency car braking. This was expected since PP is more flexible than carbon fiber. Besides, PP presents yield strength of 20.7 MPa (Table 2) which is far below to the maximum stress value of 1585 MPa as shown in Fig. 5. Therefore, this material could not be an option for this special AFO in absorbing the emergency brake impact. However carbon fiber seems a good option since its yield strength 3200 MPa is far above the maximum stress of 1585 MPa.

Table 3 FE simulation results for deformation and stress for all tested materials during gait of emergency car braking

Parameters	Proposed Design of AFO					
	Design 1		Design 2		Design 3	
	C.Fiber	PP	C.Fiber	PP	C.Fiber	PP
Stress (MPa)	1585	1563	454.95	515.79	585.34	593.38
Deformation (mm)	106	2623	29.655	782	35.75	944.75

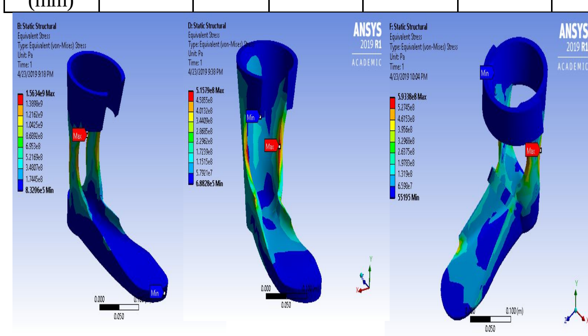


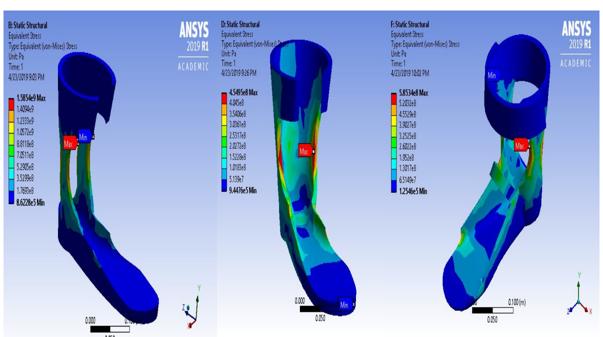
Fig. 5 FE simulation results for stress distributions in PP for 3 different design of AFO

Based on the summarize of the FE simulation result as shown in Table 3, design 1 has maximum of 1.585 GPa Von Mises stress for carbon fiber, while 1.5634 GPa for PP. The maximum deformation is 106.17 mm (maximum) for carbon fiber while 2623.8 mm (maximum) for PP. While Design 2, its maximum Von Mises stress is 454.95 MPa for carbon fiber and 515.79 MPa for PP. The maximum deformation is 29.655 mm (maximum) for carbon fiber while 782.67mm for PP. Design 3, maximum stress is 585.34 MPa Von Mises stress for carbon fiber, while 593.38 MPa for PP. The deformation is 35.75 mm (maximum) for carbon fiber while 944.75 mm (maximum) for PP.

B. Influence of geometry

When comparing the three models constructed with minor differences related mainly to commercially available AFO model (Fig. 6), the results are quite different as shown in Table 3. The curious fact is that in the design 2 (Fig.2) it seems that during emergency brake, there is not an increase in the resulting stress, as observed for design 1 and 3, which was of 200% increase in design 1 and 29% for design 2. This change could be related to the calf support, which only design 2 has it but this possibility has to be validated with other studies and geometries. Since overall results for the three models are quite different, one can state that the differences in these geometries are big enough to take any net conclusion for the geometry influence on stress distributions. Fig. 7 shows FE simulation results for stress distribution in carbon fiber for three proposes designs.

Fig. 6 Commercially available AFO model



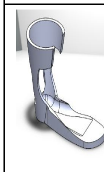
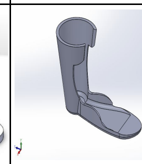
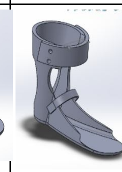
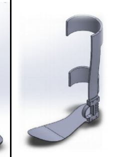
Selection Criteria	Proposed Design			Reference
	Design 1	Design 2	Design 3	
				
Von Mises stress	+	+	+	0
Total deformation	0	+	0	0
∑+	2	3	2	
∑0	1	0	1	
∑-	0	0	0	
Net score	1	3	1	
Rank	2	1	2	

Fig. 7 FE simulation results for stress distribution in carbon fiber, for 3 proposed design

a) Concept Screening

Table 4 below shows the selection of carbon fiber ankle orthosis based on three designs. Commercially available AFO design is chosen as a reference.

Table 4 Concept screening table of ankle foot orthosis (carbon fiber)

Notes:
+ = Better than reference
- = Worse than reference
0 = Same as reference

Based on the screening concept Table 4, the design 2 is chosen as the optimum design since it gained highest score. However, the selection criteria will be increased in the future in order to increase the confidence level of the chosen optimum design.

IV. CONCLUSION

In this study, three designs of passive ankle foot orthosis were proposed for use to assist patient that undergone ankle surgery in car driving especially during emergency brake. These three designs geometry is only have small different between each other. The same value of pressure and reaction force that act on the foot driver which are 137.895 kPa to 827.37 kPa for the pressure and nearly 796 N for the reaction force were applied on the FE models of the proposed designs. In respect to the material of AFO, based on the results obtained, it can be concluded that PP is not suitable for this special AFO in absorbing impact during emergency brake since it will fracture due to maximum stress is far above its yield strength but oppositely for the carbon fiber. In respect of the geometry, based on FE simulation result and concept screening table, we can concluded that the design 2 was the optimum design. However, fabrication and further testing needs to be conducted in order to evaluate this optimum design of AFO..

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