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Design of a Novel Carbon-Fiber Ankle-Foot Prosthetic using Finite Element Modeling

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Abstract. Recently, researchers worldwide have made considerable efforts to enhance amputees' quality of life by designing improved prosthetic feet. The ideal prosthetic for this job is that one which seamlessly mimics the functions of the human foot. To achieve this objective, accurate design is thus required. In this paper, a novel design for a carbon-fibre ankle-foot prosthetic is considered. The geometry of the designed ankle-foot prosthetic was created to satisfy a wide range of anthropometric parameters, taking into consideration the available previous designs in the published literature. AutoCAD version 15 was used in this work for modeling and creating the geometry, and ANSYS Workbench software version 16.1 was used for the finite element modelling based on geometry retrieved from the AutoCAD software. The complexity of the suggested design was simplified by partitioning the design into parts according to function. The roll-over shape concept was considered in the current design, which acts as an important tool in the design, evaluation, and alignment of lower limb prostheses and orthoses. Carbon fibre-epoxy composite material was utilised to manufacture a light and high strength prosthetic foot. The current study revealed that the proposed design offered a smooth roll-over shape and good response to energy return requirements in ankle-foot prosthetics, with the keel and heel design behaving as a non-prismatic cantilever beam. The keel and heel thickness require optimisation based on the specific materials used. FE analysis showed successful heel and keel deflections, although inadequate deflection was demonstrated in the vertical loading test. The heel deflected by 29.18 mm under a load of 300 N, while the keel deflected more than 25 mm under 1,230 N, and the deflection under a vertical load of 1,230 N was about 8.1 mm. The strain and stress seen in the three tests were within safe limits, while most of the energy was absorbed in the ankle component of the prosthesis.

1. Introduction

Complex functions require complex geometrical models. In order to mimic human foot in all its functions, an extremely complex geometry is required for any prosthetic, which is why the modeling of prosthetics is an issue of great importance.

It is essential to understand normal foot biomechanics before any foot prosthetic modeling is applied, including information on the internal stresses and strains of the foot and ankle as part of their biomechanical behaviours. It is difficult to measure those variables directly, and thus a comprehensive computer model is generally used to obtain this essential information. CAD/CAM prosthetic software is widely available on the market, and can be used to access the data required to develop or modify many types of prosthesis; options include Infinity CAD systems: AutoScanner & AutoSculpt [1] Biosculptor: BioScanner, BioShape Software & DSS Digital Socket System [2], and Rodin4D: FastScan 3D & Software [3]. However, most of these CAD/CAM prosthetic software programs are used only by the companies which produce them to develop various prosthetic components.

In order to provide an extension to insufficient experimental results, many researchers have turned to computational methods to seek more clinical information. Many researchers have achieved a great success by using computational modeling, particularly finite element modeling, due to its potential for modeling structures with irregular geometries and complicated material properties, as well as its simple representation of complex boundary conditions and loads in both static and dynamic analysis. A multitude of parameters can be predicted using FE methods in terms of simulating the foot with different loads and supports, including load distribution, stress, strain, and the absorbed energy of the ankle-foot structure. Successful FE analysis begins with appropriate and successful geometric modeling which fits all design requirements.

The ankle-foot group is subject to complex movement and does not stay in the same configuration throughout use. In particular, the ankle and subtalar joints have ranges of motion which extend past the neutral position in both directions [4], [5].

Creating an innovative prosthetic ankle-foot design, modeling it, and analysing the suggested model were accomplished in this work.

2. Design Considerations

2.1 ISO Standards

There are two main standards that define the procedures used for testing prosthetic leg and foot systems. These ISO standards were created for prostheses to ensure that these are appropriate and safe for users.

The first is ISO 10328 (structural test for lower limb prostheses). In ISO 10328, the term "prosthetic limbs" refers to any externally applied device that replaces in whole or part a missing or incomplete part of a human limb. This standard designates test methods, load conditions, and several other parameters. ISO 10328 is applicable to transtibial, knee-disintegration, and knee transfemoral prostheses. There are three types of test structures referred to in ISO 10328: complete, partial, and other structure [6]. This paper deals primarily with the requirements of the full structure test in the creation of the relevant model.

ISO 22675 (Testing of ankle-foot devices and foot units) was also carefully taken into consideration in this work, a this ISO standard discusses suitable procedures for the cyclic load testing of ankle/foot devices, and reviews the loading conditions that can be used to mimic the loading of natural gait. The most important consideration identified by ISO 22675 is the static loading test that can be used on prosthetic ankle-foot devices. It also explains the appropriate procedures for such static loading tests [7].

It is important to use ISO standards and follow the correct procedures for a wide range of applications to achieve accurate and useable results.

2.2 Anthropometry

Anthropometry refers to human measurement in terms of the systematic measurement of the physical characteristics of the human body, which generates a range of dimensional descriptors of body size and shape. Anthropometry plays an important role in industrial design, clothing design, ergonomics, and architecture as statistical data about the distribution of body dimensions in the general population are used to optimise products.

Measurements as seen in Figure (1) were used as reference data in the design and creation of the suggested ankle foot prosthetic model.

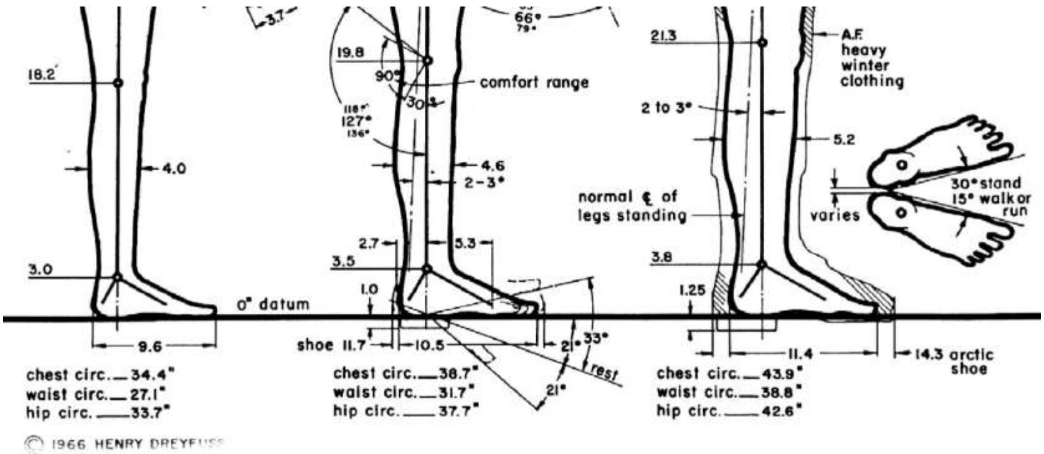

Figure (1) Human lower limb measurements [8]

2.3 Roll-over shape

The roll-over shape is a newly developed method for analysing the function of ankle-foot mechanisms. It references the effective rocker shape that the lower limb system conforms to when a person takes a step [9]. It can thus also be defined as the resulting path from the centre of pressure of the net force during heel contact to opposite heel contact, without considering the path of the centre of pressure from opposite heel contact to toe-off [10]. The roll-over shape concept is an important tool in the design, evaluation, and alignment of lower limb prostheses and orthoses in adults.

The sound human ankle-foot roll-over shape seen in Figure (2) was taken into consideration in the current design, giving the model a curvature in the fore foot and front foot that mimics the human ankle/foot configuration.

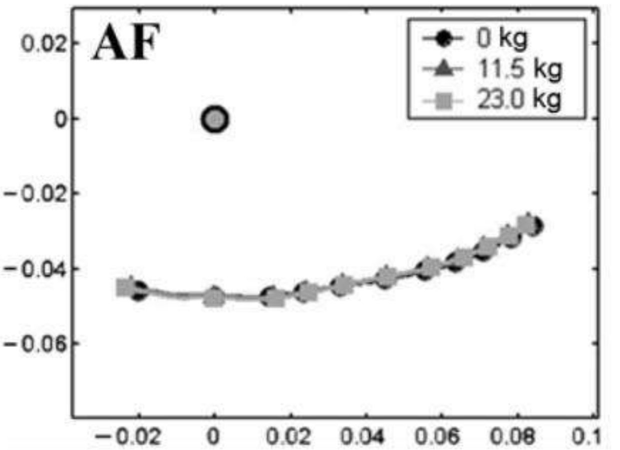

Figure (2) Roll-over shapes of an able-bodied person's foot. The able-bodied person's foot roll-over shape is shown at walking speeds with three Added-weight conditions throughout the entire stance time [11].

2.4 Biomechanics of Ankle Joint

An understanding of the biomechanics of the human ankle joint under dynamic conditions allows insight into the design of ankle prostheses which could theoretically provide functionality similar to those of healthy limbs [12]. Ankle behavior can be approximated as a linear torsional spring in the progression stage of the stance phase of normal gait, as seen in Figure (3) [13]. The ankle acts differently in three main stages of the gait as follows:2.4.1 Controlled Plantarflexion (CP)

The CP starts at the heel strike and ends on the foot flat. In other words, the CP describes the process by which the heel and front foot initially makes contact with the ground. In [14] [15], the researchers indicated that the behavior of the ankle joint during the CP was compatible with the behavior of a linear spring where the joint torque corresponds to the joint position. As can be seen in Figure (4), segment 1-2 illustrates the linear spring behavior of the ankle.

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2.4.2 Controlled Dorsiflexion (CD)

This stage starts at foot-flat and persists until the ankle reaches the state of maximum dorsiflexion. The ankle torque, based on to its position during the CD stage, often behaves as a nonlinear spring, where stiffness increases with the increase in the ankle position. The human ankle's main function is to store elastic energy during the CD stages and to release it during the PP stage to propel the body upwards and forwards [14] [15]. Segments 2-3 in Figure (4) reveal the nonlinear spring behaviour of the human ankle joint during CD.

2.4.3 Powered Plantarflexion (PP)

PP starts at the end of the CD stage and continues until toe-off. For moderate to fast walking speeds, the work generated during the PP stage is greater than the work absorbed during the CP and CD stages [14][15][16]; thus, additional energy is supplied together with the spring energy stored during the CD stage to achieve high plantarflexion strength during the late stance. This means that the ankle during the PP stage in series with the CD spring can be modelled as a torque source. The area surrounded by points 2, 3, and 4 defines the amount of extra energy added to the ankle joint during the PP stage.

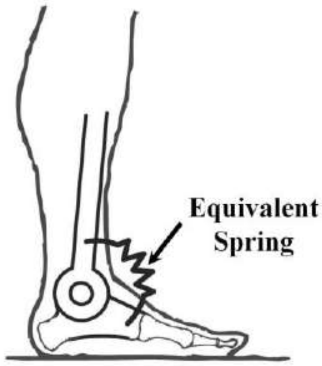

Figure (3).

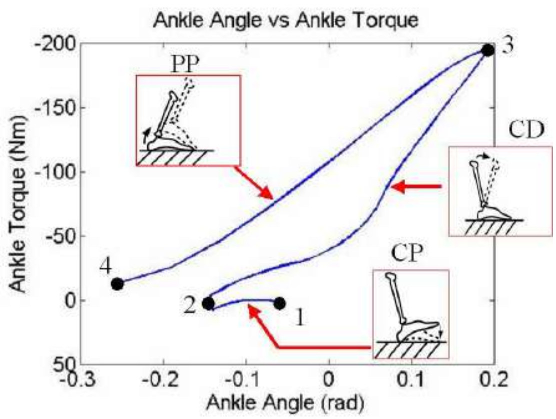

Figure (4) Ankle torque versus angle during level-ground walking.

Table 1 Human Ankle Specifications [17]

	Peak Power	Peak Torque	Peak Angular velocity
Normalized Human Ankle Response	4W/kg	2.3Nm/kg	0.25Nm/kg at 5 rad/sec
Approximate values for a 75kg person	300W	172.5Nm	18.75Nm/kg at 5 rad/sec

Based on the above considerations, the suggested design was given a helix shape capable of behaving as a three-stage spring. This involved the use of a quarter turn helix of uniform thickness and pitch.

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3. Methods

CAD systems accompanied by CAM systems are used as integrated tools in many clinics and prosthetic workshops. The CAD system's capabilities in terms of digital storage and its compatibility with FE tools, creates a powerful faculty for assessment and analysis of prosthetic and orthotic devices.

3.1 Determination of Axes for Prosthetic Components

In order to ensure consistent and comparable measurements and results, it is important to determine the alignment for all testing components. The coordinates that used to describe the alignment were given in the Cartesian coordinate system with positive Y in the upwards vertical direction, positive X in the right horizontal direction, and Z outwards.

The alignment for the prosthetic feet was determined using ISO 22675. The ISO standard indicates that the longitudinal axis of the foot should pass through two identified points, one located at the centre of the widest part of the foot, and the other located at the centre of the ankle region, one quarter of the distance from the posterior of the foot. The centreline is then considered to be the zero/neutral axis for the alignment of the test setup. Figure (5) shows an ISO 22675 diagram for determining the central axis for the feet and the main geometrical considerations [7].

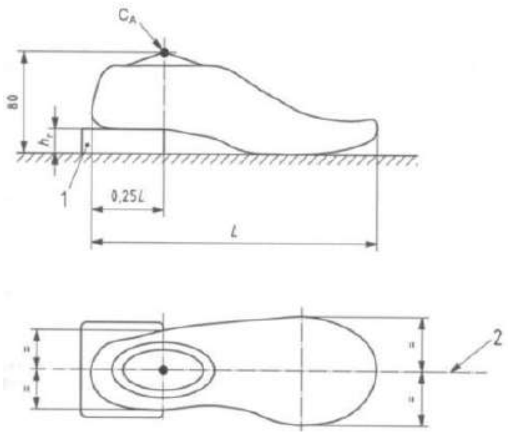

Figure (5): ISO 22675 main foot geometrical considerations.

3.2 CAD Modeling

The first job was to create the prosthetic sole shape profile, as seen in Figure (6), with central axis and geometrical dimensions coincident with ISO 22675.

By taking previously mentioned considerations, including prosthetic standards, anthropometry, and roll-over shape into account, and using approximated calculations to apply bending in curved beam methods, a side profile shape of the suggested prosthetic foot was created, as seen in Figure (7).

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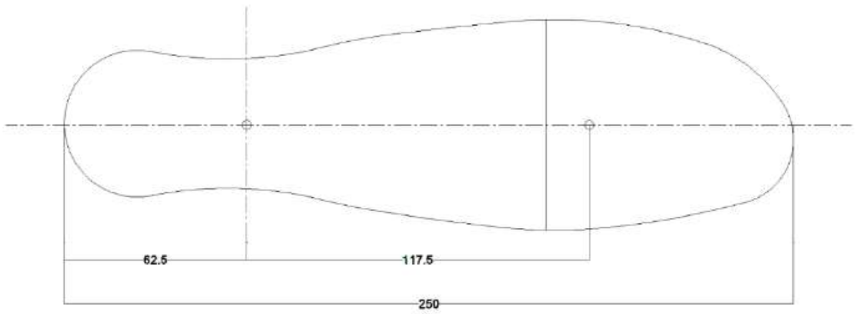


Figure (6) Sole shape profile.

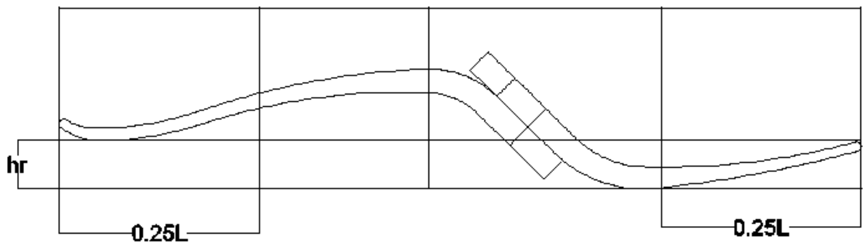


Figure (7): Prosthesis heel and keel components - side profile.

Figures (6) and (7) were thus the basic profiles used to create the heel and keel components of the prosthesis.

The ankle component was considered as a twisted beam shape to create the desired human ankle-analogous torque, ankle joint stiffness, and moment-angle relationships. A helix shape was adopted to work as spring, as this can behave as a linear or non-linear spring, according to the material used. A beam shape was thus constructed of uniform thickness and pitch with a quarter turn twist.

Finally, the created components were assembled into an ankle-foot prosthetic model for analysis with the FE tool to ascertain function and reliability.

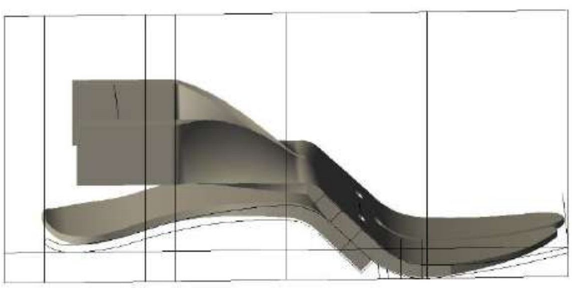


Figure (8) The assembled model.

Figure (9) The prosthetic model with pylon adapter.

3.3 FEM Analysis

FEM modeling and analysis are essential in any project or research of this type, as they give important pre-evaluation data about the whole design and its individual parts. Thus, designers and researchers can save time and money on development, making the right decisions going forward, and reviewing their considerations for future work.

In this work, this step was thus taken before any progressing to the experimental work. ANSYS Workbench 16.1 was used in these analysis procedures because of its wide range of engineering applications, and the was scheduled based on the following procedures (see Figures 10 and 11):

- Design modeling using Mechanical AutoCAD.
- Importing and meshing ACAD geometry in ANSYS Workbench ACP (pre) system.
- Choosing a suitable material based on the engineering data components; here, the chosen material was epoxy carbon fibre woven (230 GPa) wet.
- Creating cut off geometry in a down-stream geometry system.
- Identifying laminates and plies required to build a solid model using ACP (pre) system setup components.
- Upstreaming the ACP (pre) system data to a Static Structural system.
- Obtaining results and transforming these into an ACP (pro) system.

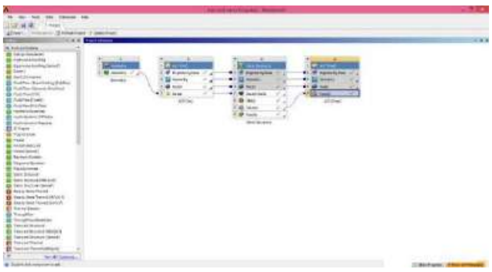


Figure (10) Main schematic of this work ANSYS workbench projects.

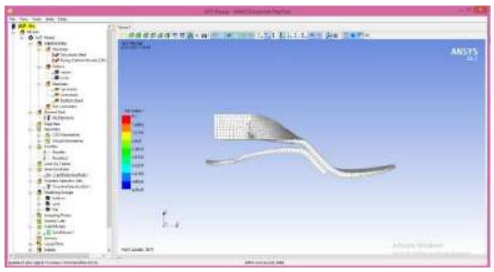


Figure (11) ACP (pre) setup component

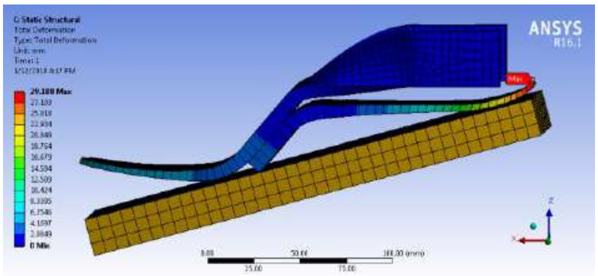
4. Results and Discussion

Three FEM analysis tests were performed in this work; heel test, keel test, and vertical loading test. All tests boundary conditions were presumed as stated in the AOPA'S PROSTHETIC FOOT PROJECT [18].

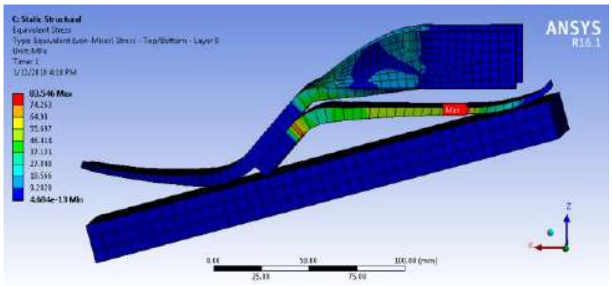
The tests results were as follows:

4.1 Heel test

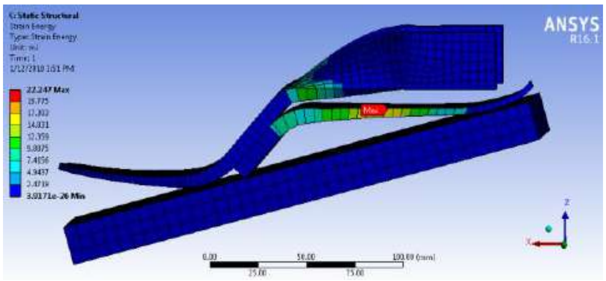
The heel test was represented as a simulation of the heel strike on the ground during the human gait cycle. The results of this analytical test were encouraging, as it classified the prosthesis as offering a dynamic response. Both the stress and strain resulting in the structure were under the material properties limits, with a good safety factors. The deformation under testing load was sufficient throughout the range of prosthetic foot deformation, and the absorbed strain energy showed dominance in the heel part of the device. These tests were simulated under loads of 300 N.



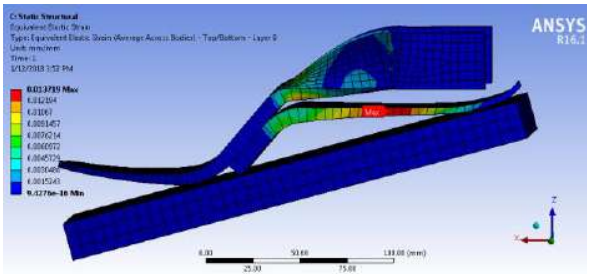
(a)



(b)



(c)



(d)

Figure (12) Heel test results; (a) deformation, (b) stress, (c) strain energy, and (d) strain.

The heel component behaved non-linearly by serving as non- prismatic cantilever beam as shown in figure (13).

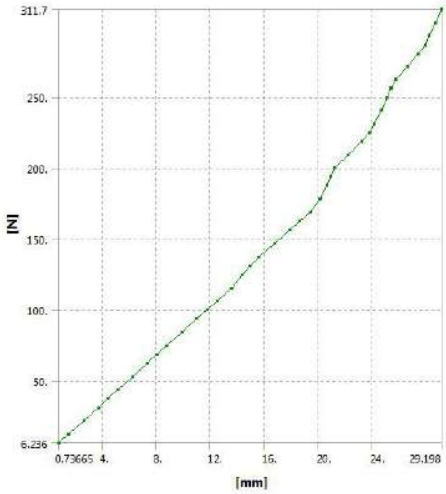
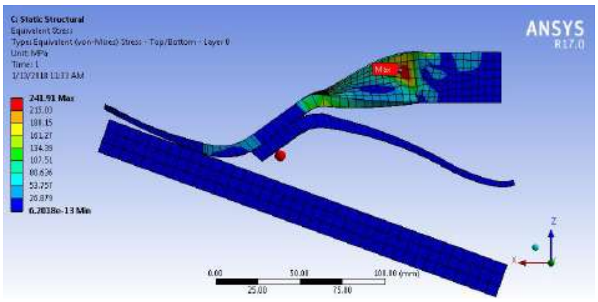


Figure (13) Heel test load-deflection curve.

4.2 Keel test

The keel test simulates the toe stage of the gait stance phase, which is an important part of providing forward movement to the human body. The results obtained by this analytical test show good deformation of the designed keel, which can be classified as a dynamic response, as it is required to deform more than 25 mm, according to the AOPA project. The stress and strain results again produced safe figures. The absorbed strain energy showed dominance in the ankle part of the device. The tests



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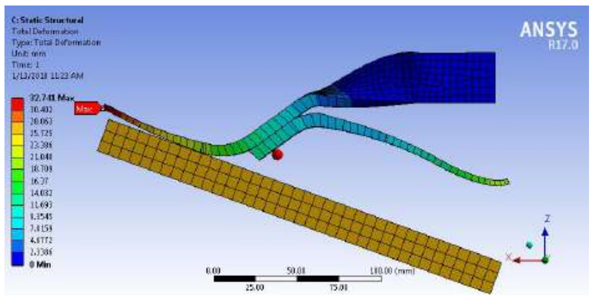

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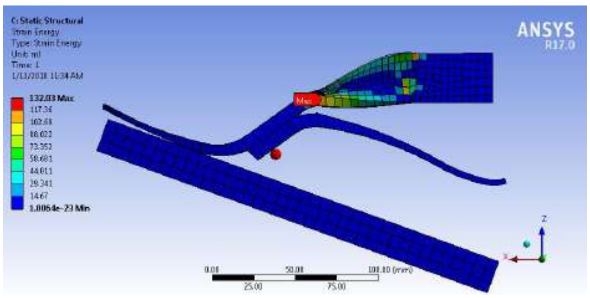

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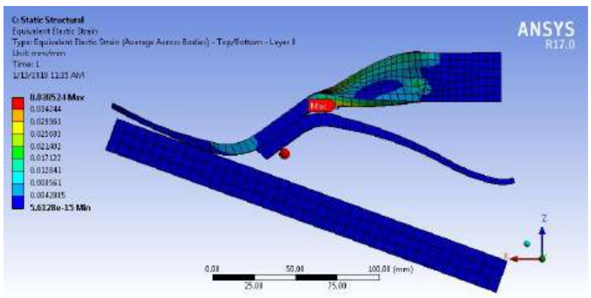


(d)

Figure (14) Keel test results; (a) deformation, (b) stress, (c) strain energy, and (d) strain.

The keel component behaves non-linearly when serving as non- prismatic cantilever beam as shown in figure (15).

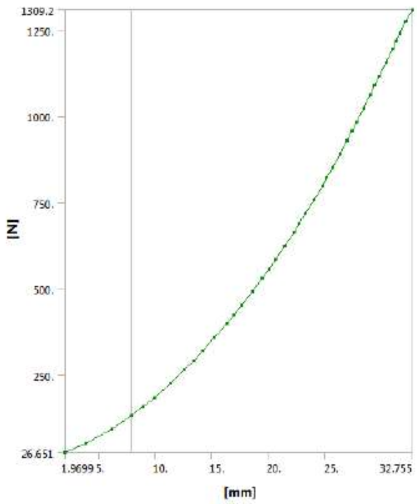
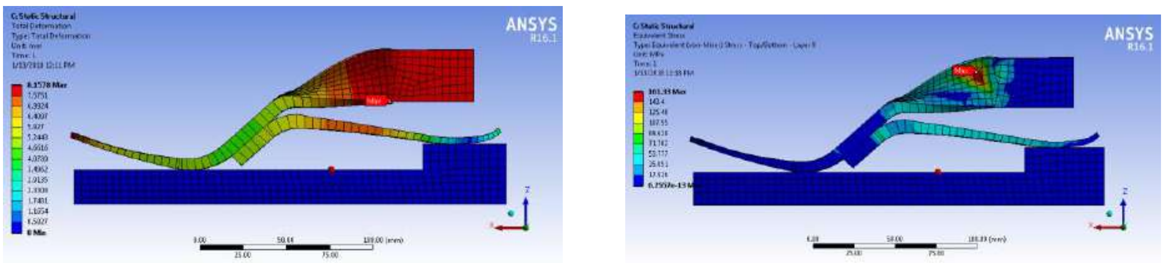


Figure (15) Keel test load-deflection curve.

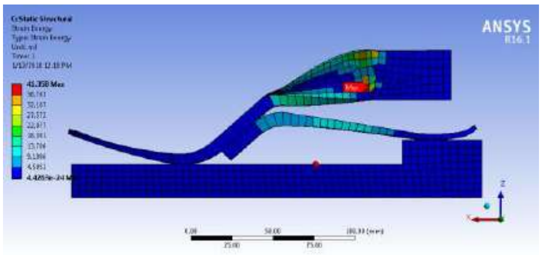
4.3 Vertical load test

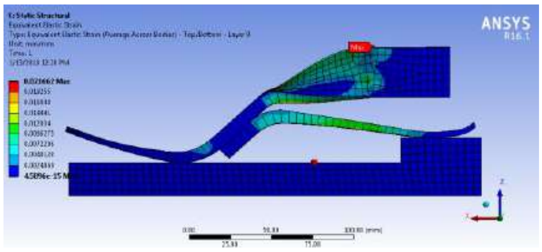
The test mimics of the stance phase of the gait cycle. This test showed a lack in deformation in the design's response to the test load applied (1,230 N), as based on the AOPA project. The stresses induced in the prosthetic were in safe ranges for the properties of the material used, and the strain energy was mostly absorbed in the ankle part of the prosthetic during the test; the strain was under the material strain limit.

The test results gave an indication that the design deflected insufficiently to meet vertical loading test. The ankle component behaves linearly, as its cross section is uniform, and it serves as twisted cantilever beam, as seen in figure (17).



(a) (b)





(c)

(d)

Figure (16) Vertical loading test results; (a) deformation, (b) stress, (c) strain energy, and (d) strain.

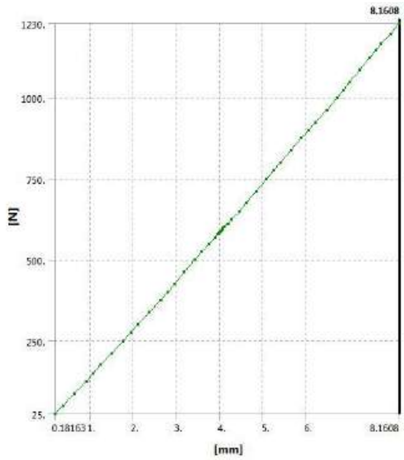


Figure (17) Vertical loading test, load-deflection curve.

The results obtained from the FE analysis are summarised in table (2).

Table (2) FE analysis results.

Test type	Load (N)	Max. Deflection (mm)	Stress (Mpa)	Strain	Energy absorbed (mJ)
Heel test	300	29.188	83.546	0.01372	22.247
Keel test	1230	32.741	241.9	0.03852	132.03
Vertical loading	1230	8.1578	161.33	0.021662	41.358

5. Conclusions and future work

The following points arose from this work:

1- Dealing with the design and modeling of prosthetic and orthotic devices requires adequate experience and an extensive knowledge of mechanical engineering, biomechanics, and anthropometry.

2- The ankle of a prosthetic foot is the most complicated part in terms of both design and function. This is one of the most important obstacles to the success of the prosthetic foot in terms of mimicking the human foot:

- The ankle behaves as linear spring in the controlled plantarflexion period, and a nonlinear spring in the dorsiflexion period of the gait cycle.
- It generates work during powered plantarflexion, absorbing less negative work during controlled plantarflexion and dorsiflexion phases.
- Ankle torque, work, and stiffness vary constantly with subject walking speed, load weight, and ground slope.

3- Keel and heel designs behave as non-prismatic cantilever beams; thus, a wider study is required to optimise keel and heel thickness according to the specific materials used, in spite of the semi-successful results achieved with the suggested design.

A wide range of further work is possible. The most important focuses are likely to be

1- Manufacturing and testing the suggested prosthesis.

2- Comparing the FE results with experimental results.

3- Modifying the ankle section of the model based on a more serious mechanical and biomechanical study.

4- Introducing a neuro-controlled system to achieve more effective performance.

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