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# Mechanical Properties and Numerical Modelling for Prosthetic Foot

Saif M. Abbas[1]*, Jumaa S. Chiad[2], Ayad M. Takhakh[3]

[1]Prosthetic and Orthotic Engineering Department, College of Engineering, Al-Nahrain University, Baghdad, Iraq
[2,3]Mechanical Engineering Department, College of Engineering, Al-Nahrain University, Baghdad, Iraq

*Email: saif.mohammed@nahrainuniv.edu.iq

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**Abstract**

This study uses laminated composite materials made of hybrid glass and carbon fibers to determine the mechanical characteristics of the foot. Tensile, bending, and fatigue of composite material were evaluated and applied to the ANSYS model. The volume fraction for carbon and glass fibers was 22.5% and 10.04%, respectively. The mechanical property results: σy = 40 MPa, σult = 150 MPa, and E = 1.2 GPa. The patient is a 30-year-old male with a left amputation side, 1.60 meters tall, and weighs 74 kg. The analysis was carried out for the two scenarios (toe-off and heel contact) as boundary conditions. The overall deformation, equivalent stresses, and foot safety factor have been calculated using ANSYS17.2 software. In the end, it appears that the foot is secure based on equivalent stress calculations and the Von-Mises hypothesis. The computed safety factor for the foot is constructed of a chosen composite material with the subsequent layers. When the heel (stance phase) is fixed at 1.3449, and the metatarsal (toe off) is fixed at 1.259, the safety factor for a force of 860 N is reached. The foot is secure, according to the Von-Mises hypothesis.

**Keywords:** Biomechanics; Fatigue; Gait cycle; Material characterization; Prosthetic limb; Simulation analysis

## 1. Introduction

People typically take around 6,500 steps per day in a normal setting, according to a 2016 study that documented the average daily step count and preferred walking pace. Although the ideal walking pace might differ from person to person, it is typically thought to be approximately 1.3 meters per second (m/s) [1]. Amputation may significantly affect people, their families, and society, especially involving the lower limbs. The following are some of the typical worries and difficulties connected with lower limb amputations: Loss of mobility, a decline in quality of life, functional restrictions, an influence on everyday activities, an emotional and psychological impact, and socioeconomic repercussions are some of the issues that might arise [2].

The physical abilities of those who have had lower limb amputations typically differ from those of healthy people. The following observations are typical: Lower sedentary behavior, slower walking speed, faster tiredness, and impaired mobility [3]. In industrialized nations, the frequency of lower limb amputations has been rising, and diabetes and traffic accidents are the two leading causes of these amputations [4]. More than half of lower limb amputees are older than 65, which is a large chunk. This is mainly caused by vascular diseases, which are more common as people age [1]. People who have lost a lower limb may regain a large amount of their usual functions, way of life, and stability with the help of prosthetics [5]-[7]. Adapting mechanical limbs to the human body may be quite difficult. Establishing a complete connection between the prosthetic and remaining limbs while providing maximum comfort and functionality [8]. Creating prosthetic limbs that naturally move as the human body does is extremely difficult. To guarantee functioning and user pleasure, several aspects must be considered throughout the design process [9], [10]. Many parts of the lower limb prosthesis often work together to support, function, and soothe the user. The essential parts are the socket, metal pylon, ankle and knee joints, screws, bolts, and nuts, as well as the cushioning and suspension materials and the foot [11]-[14]. Prosthetic limb manufacturing has advanced significantly, but for many people, particularly those with low financial means and those living in underdeveloped nations, the cost of these devices remains a substantial obstacle [15]. The idea of enhancing lower limb amputees' mobility is becoming more and more popular. Although prosthetic technology has



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advanced, many lower limb prostheses still on the market today are passively active, meaning they depend on the user's motions rather than offering powered aid [16]. Movements requiring a lot of force and control in the knee and ankle joints include ascending stairs and walking across uneven terrain. Research and development efforts are being made to address these issues and improve prosthetic limb functionality [17]. Energy storage and release are key components of many cutting-edge prosthetic designs that increase mobility and walking performance. The flexible springs or carbon-composite materials that can store and release energy during the various stages of standing and walking are frequently used in these prostheses [7].

The springs or carbon-composite materials compress and store potential energy during the stance phase of walking. Then, this energy is released at the push-off phase, giving the user forward momentum while requiring less effort. This process helps to reestablish a more organic walking pattern by imitating the way muscles and tendons naturally operate in the human body [18]. Prosthetic limbs are frequently put together by combining pre-made parts with a specially built socket that connects to the remaining limb [19].

In the area of biological rehabilitation, there has been an increase in interest in the creation of smart prostheses in recent years. Advanced technologies, including sensors, microprocessors, and actuators, are used in smart prostheses to improve functionality, increase control, and offer a more natural and intuitive user experience [20]. A vital first step in enhancing the rehabilitation and quality of life for amputees in underdeveloped nations is the creation of affordable prostheses. [21]. The project aims to create, manufacture, and analyze a foot prosthesis that is lightweight, strong, pleasant, aesthetically appealing, mechanically functioning, and simple to wear and maintain. The project seeks to greatly enhance the quality of life for people with below-knee amputations who require osseointegration prostheses by utilizing appropriate composite materials and a multidisciplinary approach.

## 2. Experimental Procedures

The study focuses on creating and testing prosthetic feet with certain materials and equipment.

### 2.1. Materials Selection for the Foot

*2.1.1. Carbon and Glass Fibers*

Composite materials made of hybrid carbon and glass fibers are noted for their strength, lightweight, and stiffness. They are probably used to strengthen and fortify the prosthetic foot, making it more resistant to wear and tear from regular use and walking, as shown in Fig. 1.

**Figure 1.** Carbon and Glass Fibers

*2.1.2 Resin combined with a hardener at a ratio of 80:20*

The resin employed in this study is a polymer resin (lamination 80:20 PMMA resin). The carbon and glass fibers are impregnated with this resin-hardener combination, resulting in a sturdy and stiff composite framework for the prosthetic foot, as shown in Fig. 2. The volume fraction for carbon and glass fibers was approximately 22.5% and 10.04%, respectively.


**Figure 2.** Resin (80:20) with a hardener

### 2.2. Tools and devices used for research

*2.2.1 A 3 * 6 * 28 cm mould from Jepson*

Fig. 3 shows the specific-sized mold from Jepson used to shape and form the specimen tests.

**Figure 3.** Jepson mould.

*2.2.2 Pressure vacuum*

Fig. 4 shows that a pressure vacuum system (vacuum pump Vac M1.5) is employed during manufacture to avoid gaps between the resin and fiber layers.

**Figure 4.** Pressure vacuum.

*2.2.3 Tensile Test Device*

The tensile test device, shown in Fig. 5, evaluates the mechanical qualities and tensile strength of materials created for prosthetic feet.

**Figure 5.** Tensile Test Machine.

Three samples were tested according to ASTM D638 type I. However, since the samples were prepared with different lay-up configurations, their thicknesses were equal to 6.7mm, as shown in Fig. 6.

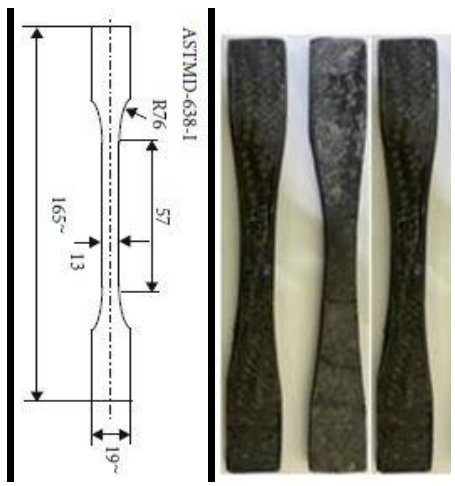


**Figure 6.** Tensile test specimen and dimension.

*2.2.4 Fatigue test for a flat specimen*

The fatigue test evaluates the fatigue life and durability of the composite material used in the prosthetic foot, as shown in Fig. 7.

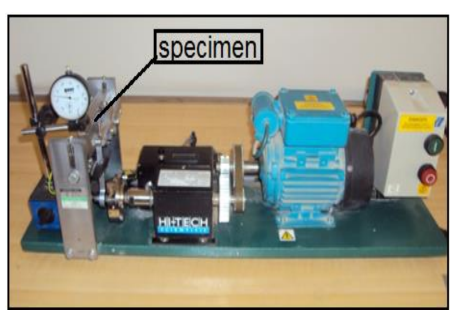


**Figure 7.** Fatigue test.

A flat specimen of the same composite material with dimensions (length=100mm and width=10 mm) is loaded repeatedly according to the standard ASTM D3479. Eight samples were used for the test. These samples were carefully created in accordance with the fatigue device's standard to guarantee that they adhere to the necessary measurements and technical requirements for the testing apparatus, as shown in Fig. 8.

**Figure 8.** Fatigue specimen.

*2.2.5 Bending test (Flexural Bend Testing)*

The bending test is performed on composite materials to determine their flexural strength. It involves applying a load to the material in a bending configuration and visually examining the failure behavior, as shown in Fig. 9.

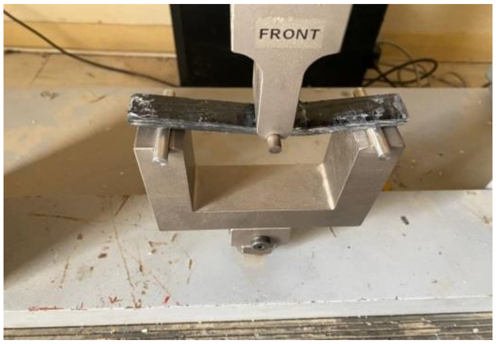


**Figure 9.** Bending test (Flexural Bend Testing)

The samples with dimensions (length=125 mm and width=10 mm) were specifically manufactured and tested according to the standard ASTM D790, the standard flexural test method, as shown in Fig. 10.

**Figure 10.** Bending specimen.

**2.3 Manufacturing Procedure of prosthetic foot**

*2.3.1 Foot Preparation*

The first step is to prepare the foot for wearing the prosthesis. Cleaning the foot could be necessary to remove any dirt or debris that might interfere with the molding procedure.

*2.3.2 Use of Plaster of Paris*

PoP is a form of plaster that may be combined with water to make a paste that can be molded. The areas of the foot that need to be captured in the negative mold are then covered with the PoP mixture shown in Fig. 11.

**Figure 11.** Application of PoP.

*2.3.3 Taking the Negative Mold*

After applying the PoP to the foot must be set and hardened before being removed. This procedure usually takes a while. To create a precise mold, the person's foot should not move throughout this period, as shown in Fig. 12.

**Figure 12.** Negative Mold with Jebson.

2.3.4 Removing the Negative Mold: Once the PoP has fully formed and hardened, the negative mold is gently removed from the foot. The upper and lower portions of the foot's form and curves should be preserved, as shown in Fig. 13.

**Figure 13.** Positive Mold.

*2.3.5 Cutting and Finishing*

The negative mold may require further cutting and finishing, as shown in Fig. 14, to ensure clean edges and precise measurements.

**Figure 14.** Trimming and Finishing.

*2.3.6 Creation of the prosthetic foot*

Using the successful model, the prosthetic foot is created using the right materials, such as carbon fiber and glass fiber. The individual's particular wants and requirements are considered when creating the personalized prosthesis shown in Fig. 15.

**Figure 15.** Prosthetic foot Fabrication.

*2.3.7 Fitting and Modifications*

When the prosthetic foot is finished, it is fitted to the user's foot, and any required modifications are made to provide a secure and functional fit, as shown in Fig. 16.

**Figure 16.** Fitting and Adjustments of Foot.

### 2.4 Cases Study

The artificial foot test on patients with below-knee osseointegration evaluated the prosthetic limb's loads in various walking situations. The subject had the following qualities: Weight: 74 kg (body force 860N); male; gender: 1.60 m tall: 30 years of age. Left is the amputation side, as shown in Fig. 17.

**Figure 17.** Cases Study

## 3. ANSYS Design of the Foot

ANSYS 17.2 software is used in a current task or project to develop and simulate a prosthetic foot. ANSYS is a potent engineering simulation tool for structural analysis, mechanical design, and other engineering applications.

ANSYS 17.2 would have been used in this project to simulate the prosthetic foot while considering its mechanical construction and material characteristics. The program enables the application of varied weights and boundary conditions to model how the prosthetic foot might behave in various situations, like walking, running, or other activities. Multiple processes involve using ANSYS Workbench to analyze a prosthetic foot model first created in SOLIDWORKS. This is how the process is outlined:

### 3.1 Bringing the SOLIDWORKS Model

Start by bringing the prosthetic foot's 3D model from SOLIDWORKS into ANSYS Workbench, shown in Fig. 18.

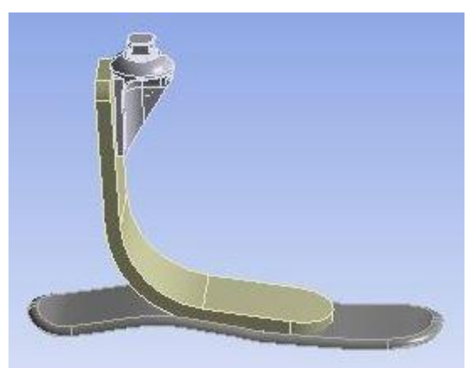

**Figure 18.** Solid Works Model of Foot

### 3.2 Apply Material Characteristics

Define the material characteristics of the different parts of the prosthetic foot, including density, Poisson's ratio, Young's modulus, and others, to appropriately depict the behavior of the materials under loading situations.

### 3.3 Mesh Generation

The model will now be discretized into small elements by creating a mesh across its surfaces. This meshing process divides the model into finite elements, which ANSYS may then employ for analysis. Accurate results require a mesh of superior quality. To achieve the appropriate mesh density and element type, ANSYS Workbench with 40118 nodes and 23121 elements offers a variety of meshing options and controls, as shown in Fig. 19.

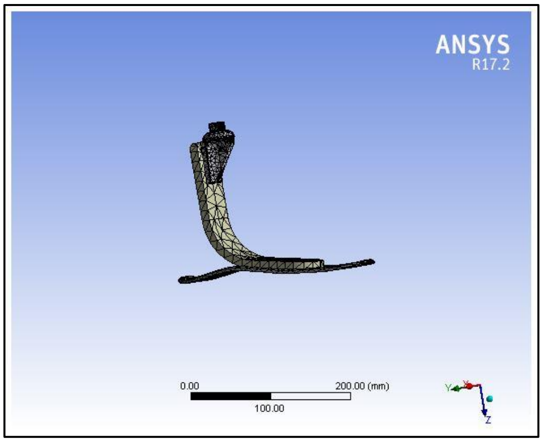


**Figure 19.** Mesh Generation of foot

### 3.4 Boundary Conditions

Establish the boundary conditions that replicate the real-world situations in which the prosthetic foot will function in step four. For instance, forces or displacements may be applied at particular locations to simulate the contact between the foot and the ground during running or walking. One case two has a fixed heel and metatarsal support, as shown in Fig. 20.

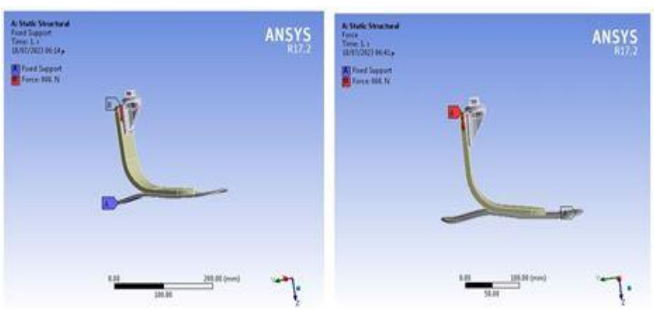


**Figure 20.** Boundary Conditions.

### 3.5 Determine the sort of Analysis

Select the sort of analysis that best meets your unique objectives. Depending on the prosthesis's intended function, common assessments for prosthetic foot models include static structural analysis and fatigue analysis.

### 3.6 Run the Simulation

When everything is ready, start the ANSYS Workbench simulation. To determine the overall deformation, safety factor, and stresses in the model of the prosthetic foot, the program will solve the equations based on the applied loads, boundary conditions, and material parameters.

## 4. Results and Discussion

### 4.1 Tensile Properties Results

In this experiment, the prosthetic foot's composite materials underwent a tensile test, and stress-strain curves Fig. 21. were generated. Mechanical characteristics, including Young's modulus (E), yield stress (***$\sigma_y$***), and ultimate tensile strength (***$\sigma_{ult}$***), were identified from these curves and listed in Table 1. Including glass fiber and carbon fiber in the composite material gives it its high yield stress, ultimate tensile strength, and elastic modulus. Their exceptional tensile qualities allow them to sustain high tensile loads without breaking or considerably deforming glass and carbon fibers, which are well recognized. This property helps explain why the composite material has a high yield stress and elastic modulus.

The prosthetic foot is sturdy and able to endure the mechanical stresses encountered during usage because of the balanced qualities provided by combining these strong fibers with other components in the composite.

**Table 1.** The tensile test results were evaluated from stress-strain curves.

| Sample | σy (MPa) | σult (MPa) | E (GPa) |
|---|---|---|---|
| 1 | 40 | 142 | 1.23 |
| 2 | 42 | 151 | 1.2 |
| 3 | 38 | 154 | 1.008 |

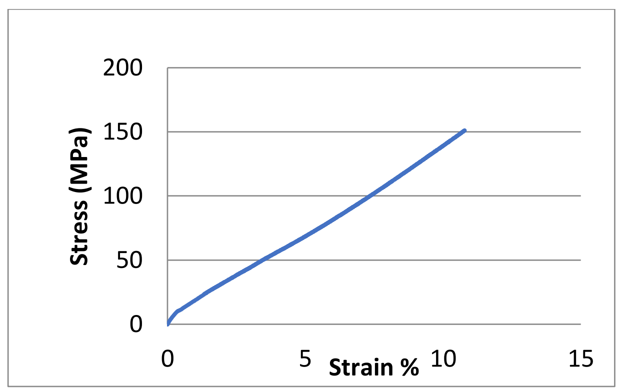


**Figure 21.** Average stress-strain curve.

### 4.2 Bending Properties Results

Fig. 22 shows the composite prosthetic foot's bending test curves. The force-deflection measurements for each sample are required to examine their mechanical characteristics. As shown in Table 2, the bending modulus (E) and stress peak (b) can be calculated from the force-deflection curves.

The bending test is very important for prosthetic feet and is used to develop and assess these devices. For those who have had a lower leg amputated, prosthetic feet are crucial because they enable amputees to regain their balance, mobility, and quality of life. The bending test, especially the bending modulus and stress peak assessment, offers important insights into the mechanical characteristics of the materials used to construct prosthetic feet. Engineers, manufacturers, and prostitutes benefit from this information.

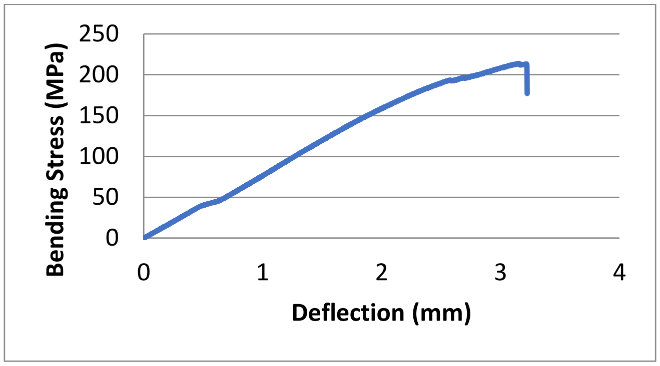


**Figure 22.** Average bending stress- deflection curve.

**Table 2.** Mechanical Properties That Determined from Stress-Deflection Curves

| No of sample | $\sigma_b$ max MPa | E flexural GPa |
|---|---|---|
| 1 | 193.588 | 2.164 |
| 2 | 213.795 | 3.0692 |
| 3 | 212.837 | 3.135 |

### 4.3 Fatigue Property Results

The carbon-glass fiber laminations subjected to the fatigue tests carried out in this study at room temperature are useful for evaluating the material's performance under repeated cycle loading. For many engineering applications, including prosthetic feet, fatigue failure is a major worry because it affects a material's capacity to sustain repeated stress cycles over time. Results allow for establishing a link between fatigue failure stress and cycle count. The number of cycles to failure and the fatigue failure stress have an inverse relationship, as shown in Fig. 23. This indicates that the material can withstand more cycles before failing as the fatigue failure stress drops for the equation with C= -0.172 and N= 815.16. On the other hand, more significant fatigue failure stresses suggest that the material will break after fewer loading cycles. The outcomes of fatigue testing help to guarantee that prosthetic feet are appropriate for long-term usage and can resist the demands of daily activities for people who have had their lower limbs amputated.

In engineering and material science, validating and comparing findings with an ANSYS finite element model using data gathered from tensile and fatigue testing is routine practice.

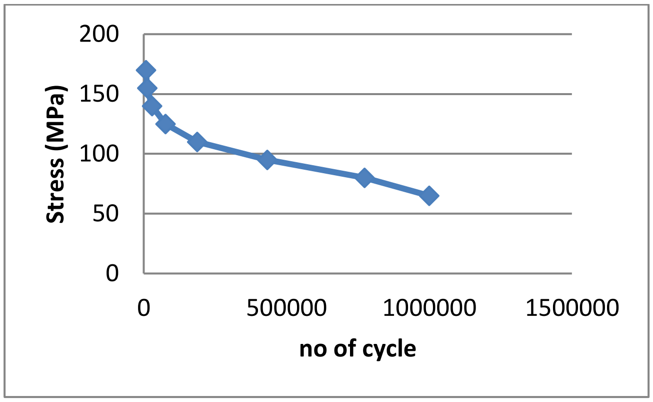


**Figure 23.** S-N curve for carbon-glass fiber.

### 4. Force Plate Results

Using a force plate during a patient's gait cycle, ground response forces and moments on an implant's abutment have been estimated; the results can offer important insights into the loading patterns that the implant encounters. The peak pressures at heel contact and toe-off are significant factors to take into account. Recognizing any significant variations in the right and left legs' characteristics is also important. Clinicians and researchers can assess the loading conditions on the implant's abutment and the functionality and stability of the implant during gait by examining the peak values of forces and moments during heel contact and toe-off. Fig. 24 shows the force with a time curve; the maximum force is 600N.

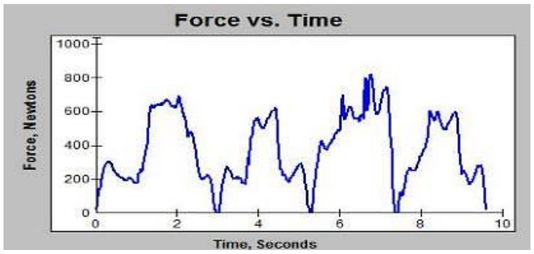


**Figure 24.** Force vs. Time.

Tables 3 and 4, which illustrate the patient's gait cycle and step-step, reveal slight variations that indicate the patient is walking well on the force plate.

**Table 3.** Gait Cycle Table (sec)

| Gait Cycle Table (sec) | Left | Right |
|---|---|---|
| Time of Gait Cycle | 1.99 | 1.98 |
| Time of Stance | 0.94 | 0.92 |
| Time of Swing | 1.06 | 1.04 |
| Time of Single Support | 0.63 | 0.65 |
| Time of Initial Double Support | 0.19 | 0.17 |
| Time of Terminal Double Support | 0.17 | 0.19 |
| Time of Total Double Support | 0.37 | 0.37 |
| Time of Heel Contact | 0.51 | 0.52 |
| Time of Foot Flat | 0.21 | 0.25 |
| Time of Mid stance | 0.19 | 0.22 |

**Table 4.** Step-Stride Table.

| Step-Stride Table | Left | Right |
|---|---|---|
| Time of Step (sec) | 0.66 | 0.61 |
| Length of Step (m) | 47.5 | 46.9 |
| Velocity of Step (m/sec) | 76.5 | 77.2 |
| Step Width (cm) | 14.2 | 14 |
| Stride Time (sec) | 1.29 | 1.27 |
| Stride Length (m) | 94.2 | 93.6 |
| Stride Velocity (m/sec) | 73 | 73.6 |
| Foot Angle (degree) | 7 | 10 |

### 4.4 ANSYS Results

In biomechanical engineering, analyzing a prosthetic foot using ANSYS Workbench software (version 17.2) to determine total deformation, equivalent stress (Von-Mises), and safety factors are normal practice. The analysis might be done for the two scenarios (toe-off and heel contact) using various boundary conditions:

*4.4.1Heel contact*

Use a force that simulates the weight the foot would receive during the stance phase. To replicate the stance phase, where the foot bears the body's weight, the foot should be locked at the locations where it makes contact with the ground.

*4.4.2 Toe Off*

To replicate the loading during this phase, apply the vertical force acting on the foot during the toe-off phase while maintaining the foot locked at the proper positions.

The results of the two cases are shown in Table 5. and in Fig. 25 to Fig. 30.

**Table 5.** ANSYS result when the heel is fixed:

| Fixed position | Total deformation (mm) | Equivalent stress (Vonmises) (Mpa) | Safety factor |
|---|---|---|---|
| When the heel is fixed | 29.235 | 64.094 | 1.3449 |
| When the metatarsal is fixed | 24.479 | 117.72 | 1.259 |

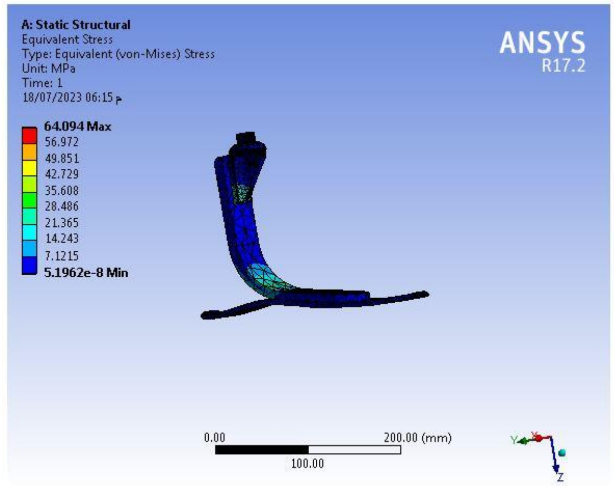


**Figure 25.** Equivalent stress (von Mises)

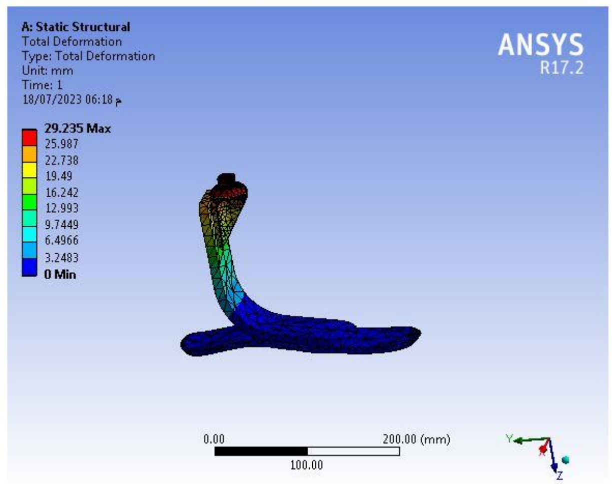


**Figure 26.** Total deformation

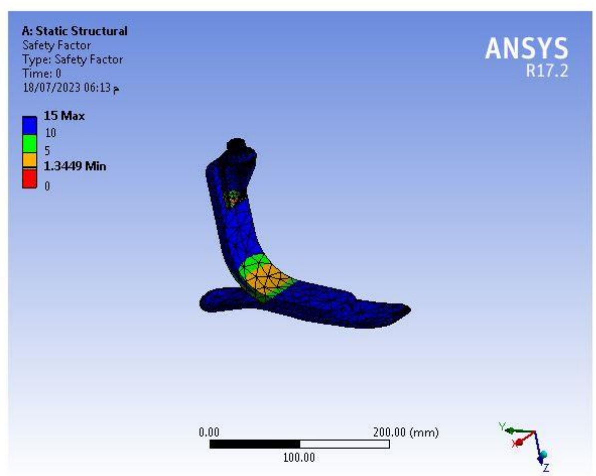


**Figure 27.** Fatigue factor of safety.

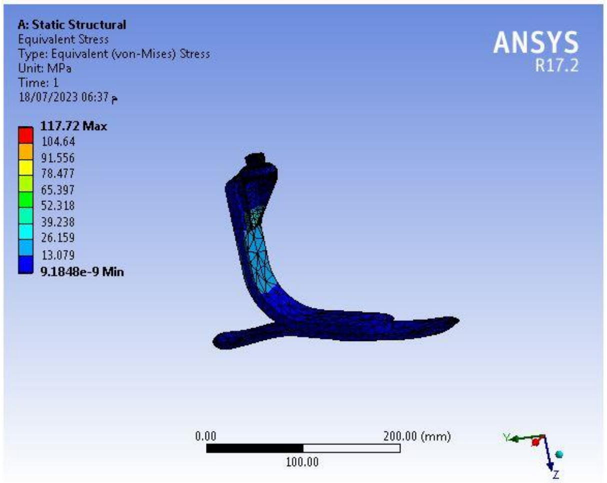


**Figure 28.** Equivalent stress (von Mises)

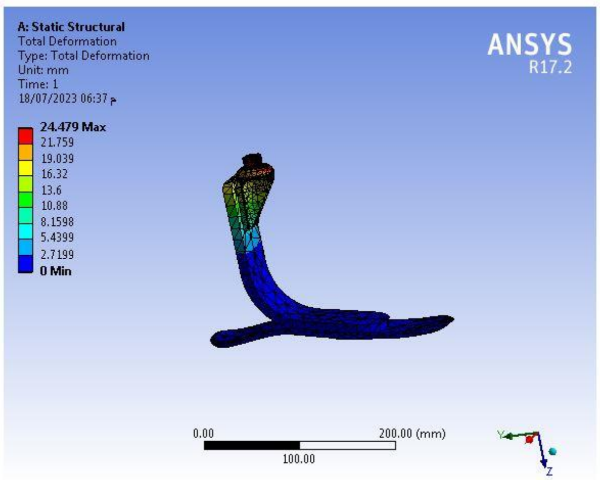


**Figure 29.** Total deformation

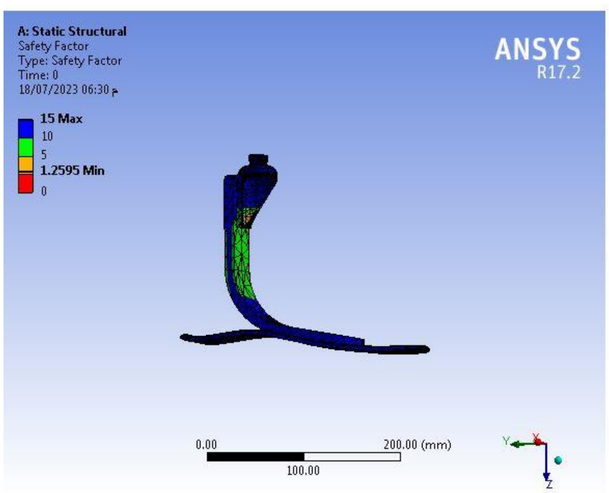


**Figure 30.** Fatigue factor of safety.

The safety of composite material for the prosthetic feet for heel contact and toe-off is acceptable.

## 5. Conclusions

The design and fabrication of the prosthetic foot are comfortable, lightweight, durable, and flexible and provide good cosmetics. A useful method that may be used for various prostheses and orthotics is the material selection technique for a prosthetic foot, which entails examining the suggested prosthesis to choose the optimum material based on the total deflection. Due to the complete deviation in the element of safety from the model findings, custom-made prostheses and orthotics are built to match the specific demands of each patient, taking into account parameters like amputation level, body proportions, weight, activity level, and other personal concerns. The impression of the patient when using the foot is good because the results of the force plate are almost equal, which means the time for each leg is equal. For force=860N, the safety factor when the heel (stance phase) is fixed =1.3449, and when the metatarsal (toe off) is fixed=1.259, therefore when heel and metatarsal cases are acceptable. According to the Von-Mises theory, the foot is safe. The cost of the manufactured foot is low compared to commercial feet, about 80%.

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## Conflict of Interest

No conflicts of interest exist, according to the authors, with the publishing of this work.

## Author Contribution Statement

Author Saif M. Abbas suggested the research problem, developed the foot prosthetic, conducted the experimental work, and analyzed the foot design using ANSYS 17.2.

Authors Jumaa S. Chiad and Ayad M. Takhakh verified the analytical methods, conducted the manuscript's structure, and organized the outcomes of this study.

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