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# Optimal Material Selection for Manufacturing Prosthetic Foot

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## ABSTRACT

The foot is an essential part of the components of the prosthesis. Therefore, the selected materials' mechanical properties, cost, and weight must be considered when manufacturing the prosthetic foot. This study studied the mechanical properties of selected materials used for prosthetic feet. The material chosen is Carbon Fiber, Glass fiber, and hybrid composite material. This study aims to simulate chosen materials to find the optimal material selection for manufacturing prosthetic feet by assuming boundary conditions, reaction forces, design consideration, and application. The simulation was done by the finite element analysis ANSYS-14.5 program. The result of the force plate test shows the ground reaction force equal to 750N at heel strike,700N at mid-stance, and 650N at the toe-off stage. The finite element result shows the maximum Von-Misses stress equal to 119MPa at the toe-off stage, and the hybrid composite material has the maximum safety factor. Furthermore, the results showed that the mechanical properties of the hybrid composite materials are the best, as the yield stress is 560MPa, the ultimate stress is 678MPa, and the modulus of elasticity is 6.2GPa. The result shows that the Hybrid composite material has excellent improvement in mechanical properties such as lightweight, stiffness, high mechanical properties, and cost-efficiency. Hence by considering the body weight of the amputee, gait cycle, and analyzing the material properties, the hybrid composite material is the best suitable should be selected to manufacture foot prostheses.

*Keywords***:** Carbon fiber, composite material, foot, hybrid material, prosthetic

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## INTRODUCTION

A prosthesis is an artificial device used by people who suffer from amputations due to disease or accidents (Kadhim et al., 2020a; Herbert et al., 2005). The lower limb prosthetic parts are the pylon, the socket, and the foot, as shown in Figure 1 (Kadhim et al., 2020b). A prosthetic foot is a manufactured device that replaces a lost limb and restores some function to amputees (Awad & Kadhim, 2022).

In recent years, different prosthetic parts have been manufactured and developed, such as knee parts (Arteaga et al., 2020; Zhang et al., 2021; Kadhim et al., 2020c; Wang et al., 2020) and prosthetic sockets (Estillore et al., 2021; Vitali et al., 2017; Sakuri et al., 2020; Marable et al., 2020, Kadhim et al., 2019; Monette et al., 2020), and hip joint application (Annur et al., 2020; Abdullah et al., 2019; Delikanli & Kayacan, 2019; Gavali et al., 2016). Many researchers were interested in the design and manufacturing of prosthetic feet. Hadi and Oleiwi (2015) investigated the tensile strength of polymer blends as prosthetic foot material reinforcement by carbon fiber. Mohammed and Salman (2020) studied designing and modeling a prosthetic foot made of suitable composite materials (high-density polyethylene (HDPE) filled with 60% Date Palm Wood) (DPW). Tao et al. (2017) used 3D printing of polylactic acid to design and optimize the prosthetic foot. They printed a prosthetic foot using filament made of Polylactic Acid (PLA) and a hobby-level printer. Tryggvason et al. (2020) investigated the Dynamic FEA used to modify the design and analyze the energy of a variable stiffness prosthetic foot. Bence and Dávid (2017) created a 3D-printed Energy Storage and Return (ESAR) foot prosthesis with an intriguing novel shape suitable for people with trans-tibial amputations and employing ABS material as a filament.

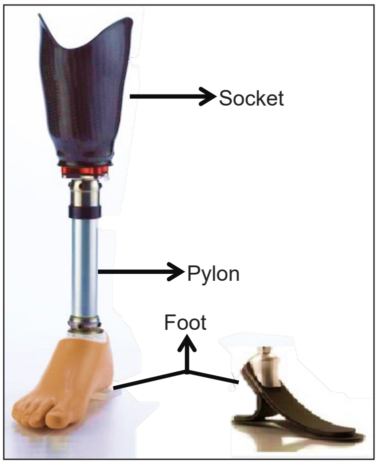


*Figure 1*. The parts of the lower limb prosthetic (Awad et al., 2022)

Oleiwi and Hadi (2021) Most prosthetic feet currently available are made from polyethylene and polyurethane materials. These feet always have mechanical failure due to fatigue problems in the metatarsal region due to the dorsiflexion and plantarflexion movements, as shown in Figure 2.


*Figure 2*. Mechanical failure of the traditional prosthetic foot (Yousif et al., 2018)

This study proposed three common materials to manufacture the prosthetic foot. The materials are carbon fiber, glass fiber, and the hybrid composite material that consists of a mixture of carbon fiber and glass fiber in addition to resin. The purpose of suggesting these materials is because all of these materials have high mechanical properties and are suitable for this application. Also, to compare these materials to choose the best material for manufacturing the prosthetic foot. The proposed materials for use in the manufacture of the prosthetic foot were tested for mechanical properties. In addition, the foot prosthetic model has been tested by the Finite element method as a case study to understand better the stress distribution and safety factors and optimize the selection of materials.

## MATERIALS AND METHOD

### Materials

In this study, three groups of materials will be tested. Each material will be a case study for manufacturing the prosthetic foot. Each material group consists of several layers according to the study cases listed below:

1. Case (1) (twenty layers of carbon fiber with lamina)
2. Case (2) (twenty layers of fiberglass with lamina)
3. Case (3) (ten layers of carbon fiber + ten layers of fiberglass, the arrangement is periodically recurring a layer of carbon fiber, followed by a layer of fiberglass, and then a layer of carbon fiber).

The lamination process produces samples of tensile and fatigue tests to examine the materials to know their mechanical properties. The material needed in lamination is the following (two Polyvinylalcohol PVA bags, layers of each material group, epoxy with hardener with a ratio of 80:30, a vacuum device, and Jepson mold). Figure 3 shows the positioning of the Jepson mold at the stand of the vacuum pressure system.

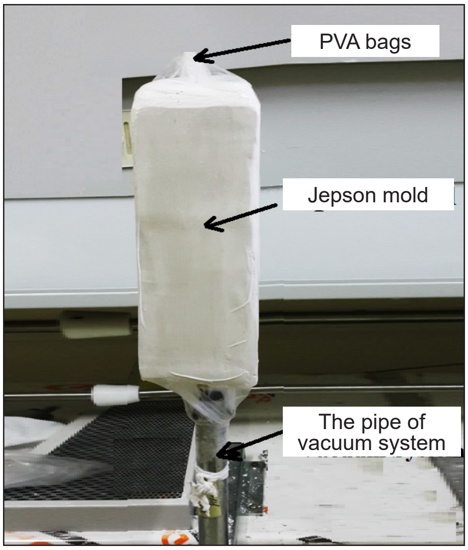


*Figure 3*. The Jepson mold at the stand of the vacuum pressure to lay up the layers of fibers

Put the first piece of the PVA on the gypsum molds and suction the air between the PVA and gypsum with the vacuum system, then put the materials' layers on the plaster mold, and then put the second piece of the PVA and suction the air between two bags with the vacuum system, then mix the overlying resin 80:20 polyurethane with the hardener and put this mixture on these layers. Thus, using a vacuum system, the air and the mixture of the lamina are suctioned from the space in which the casting process is made. Finally, maintain the vacuum at constant pressure at room temperature until the laminations are cool, then cut them according to the size of the samples for the mechanical test.

## Tensile Test

A CNC machine cuts each casting sample into three samples for tensile testing. The dimensions of the specimens are cut according to ASTM D638 (2014). The thickness of samples varies depending on the layers of each material case, as shown in Figure 4. The samples were tested at a 3 mm/min speed by a Testometric device type. The specimen was placed in the grip of the tensile testing machine, and the test was performed by applying tension until it underwent fracture, as shown in Figure 5. Figure 6 shows the carbon fibers and glass fibers group specimen. The figure of the hybrid sample is similar to the shape of the carbon fiber specimen because its outer surface consists of a layer of carbon fiber.

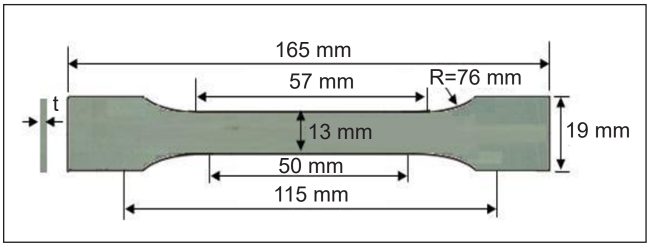
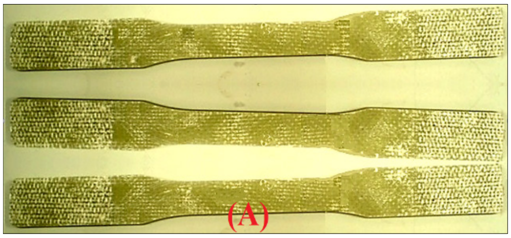
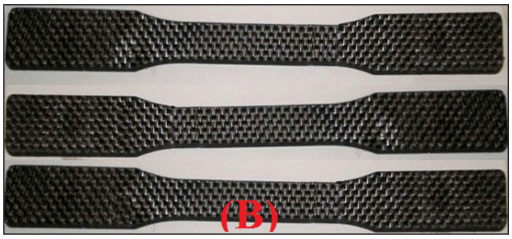



*Figure 4*. The ASTM D638 dimensions of tensile specimen

*Figure 5*. The clamped samples with the jig and tensile device




(a)




(b)

*Figure 6*. (a) The tensile specimen of fiberglass; (b) The tensile specimen of carbon fiber

## Fatigue Test

The CNC machine cut eight samples of each casting case to test the fatigue machine (Roberts & Hart, 2001). The dimension of the spearman's cutting is according to the spearman's standard of fatigue device test. The length of the fatigue specimen is 100 mm and the width 10 mm, while thickness varies with each group of a composite material layup, as shown in Figure 7. Figure 8 shows the fatigue specimen of carbon fibers and glass fibers group without the figure of the hybrid sample due to its similarity to the shape of the carbon fiber specimen.

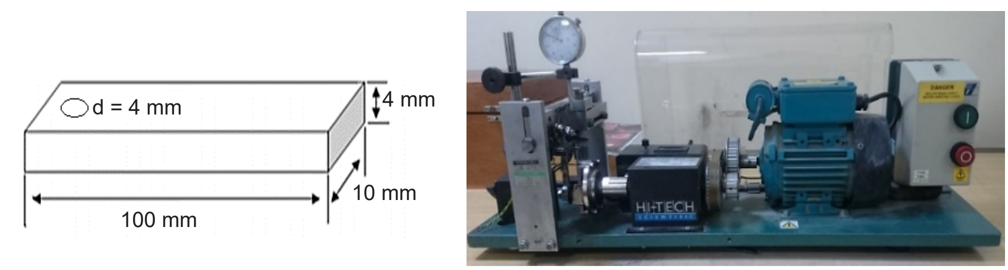



*Figure 7*. The fatigue test specimen's dimensions with a fatigue machine (HI-TEICH)

*Figure 8*. The fatigue specimens of carbon fibers and fiberglass

## Test of Ground Reaction Force

The ground exerts the ground reaction force on a body in contact with it (Müller & Schiffer, 2020). When the normal or amputee person walks on the ground, the reaction force affecting on the body through the foot, the reaction force consists of three components of forces, two in a horizontal direction and one in a vertical direction of the foot, as shown in Figure 9. In this test, the patient walks normally on the device, and the device records the values of the reaction forces on the body for the steps taken by the patient while passing on the device. This test aims to measure the ground reaction values on the body that will apply as a boundary condition during the simulation for the material's suggested feet. The patient has a transtibial amputee who walked on the force plate device to measure the reaction force that must be applied on foot during finite element analysis, as shown in Figure 10.

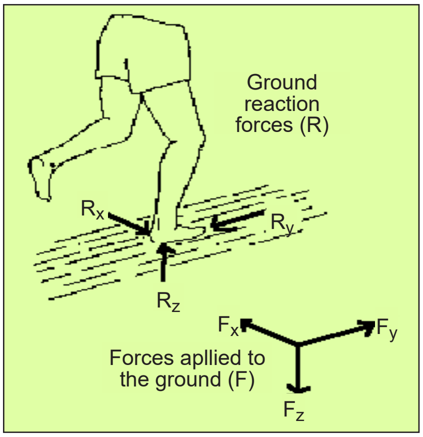



*Figure 9*. The components of ground reaction force

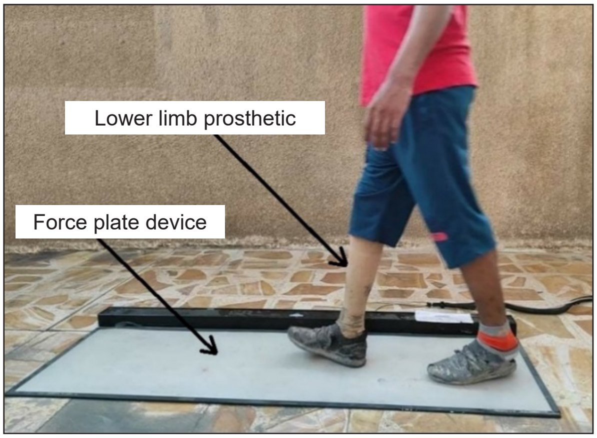



*Figure 10*. The patient with a transtibial amputee walked on the force plate device

## Finite Element Analysis

It was a useful tool for understanding load transfer through prosthetic applications. The finite element technique is a full-field analysis for calculating the state of stresses, safety factors, and other mechanical parameters in a specific field:

1. The Solid-works 2020 software designed the three-dimensional model of the prosthetic foot.
2. The designed model was transferred to ANSYS 14.5 software to analyze a static load test and find the Von-Misses stress and the safety factor when applying the boundary conditions.
3. Meshing was done with tetrahedrons, as shown in Figure 11.

Mesh convergence tests were done previously to determine the best mesh size. A mesh size of 2 mm was chosen for this model based on the convergence analysis.

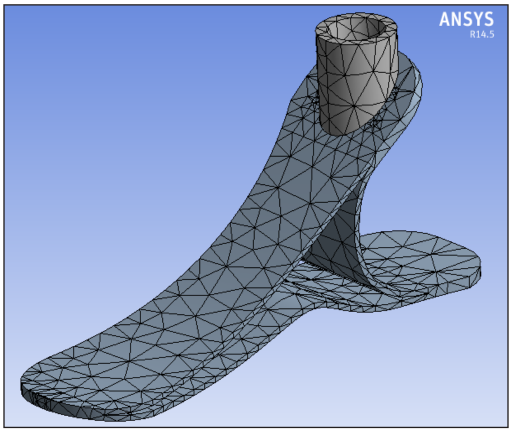



*Figure 11*. The mesh of the foot prosthetic model

## RESULTS AND DISCUSSION

The tensile tests showed the mechanical properties of the three study cases of the materials used to manufacture the prosthetic foot. Figure 12 shows the stress-strain curve of the three tested materials, whose mechanical properties can be summarized in Table 1. The results showed that the hybrid composite material has better mechanical properties than carbon fiber and fiberglass due to the anisotropic properties in all the hybrids. Failure is generally noncatastrophic when hybrid composites are stressed under tension (i.e., It does not happen suddenly). The carbon fibers fail first when the load is applied to the hybrid composites, and the load is then transmitted to the glass fibers. The matrix phase must maintain the applied load when the glass fibers fail. Therefore, the failure of the composite event coincides with the failure of the matrix phase (Callister, 2007).

The modulus of elasticity for hybrid material equals 6.2 GPa, ultimate stress is 678 MPa, and yield stress is 560 MPa. The fatigue test results showed the stress endurance equal to (425, 300,90) MPa for the hybrid composite material, carbon fiber, and glass fiber, respectively. Glass fiber has low stress compared to others due to the higher strength of carbon fiber. Therefore, it behaves like elastic material with good bearing capacity during tensile loading (Naito & Oguma, 2017; Dong, 2016). Anisotropic properties may be seen in all the hybrids. Failure is generally noncatastrophic when hybrid composites are stressed under tension (i.e., It does not happen suddenly). The carbon fibers fail first when the load is applied to the hybrid composites, and the load is then transmitted to the glass fibers. The matrix phase must maintain the applied load when the glass fibers fail. The composite event's failure coincides with the matrix phase's failure.

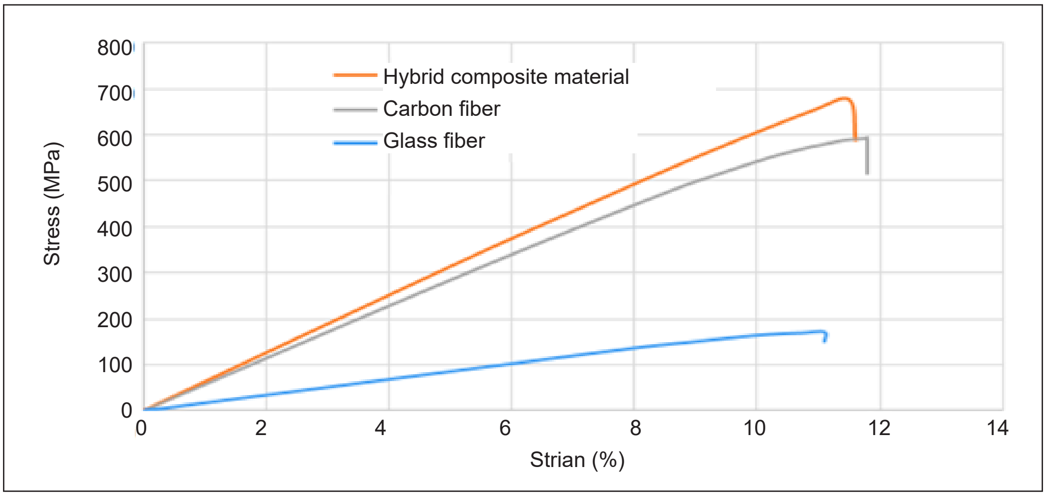



*Figure 12*. The stress-strain curve of the three tested materials

Table 1
*Overview of the tested materials' mechanical properties*

| Number of cases | Number of layers | E (GPa) | $\sigma_{ult}$ (MPa) | $\sigma_y$ (MPa) | Thickness (mm) |
|---|---|---|---|---|---|
| Case (1) | 20 | 5.7 | 580 | 448 | 4.1 |
| Case (2) | 20 | 1.7 | 170 | 160 | 4.48 |
| Case (3) | 20 | 6.2 | 678 | 560 | 4.22 |

Figure 13 shows the relationship between repeated stresses and the number of cycles of fatigue testing for the three tested materials.

Figure 14 shows the values of ground reaction force resulting from the gait cycle test. The ground reaction force curve is divided into three regions (heel strike, mid stance, and toe-off). The reaction force value equals 750 N at heel strike, 700 at midstance, and 650 at toe-off). The values of ground reaction force are used as a boundary condition in the FEM analysis of the foot.

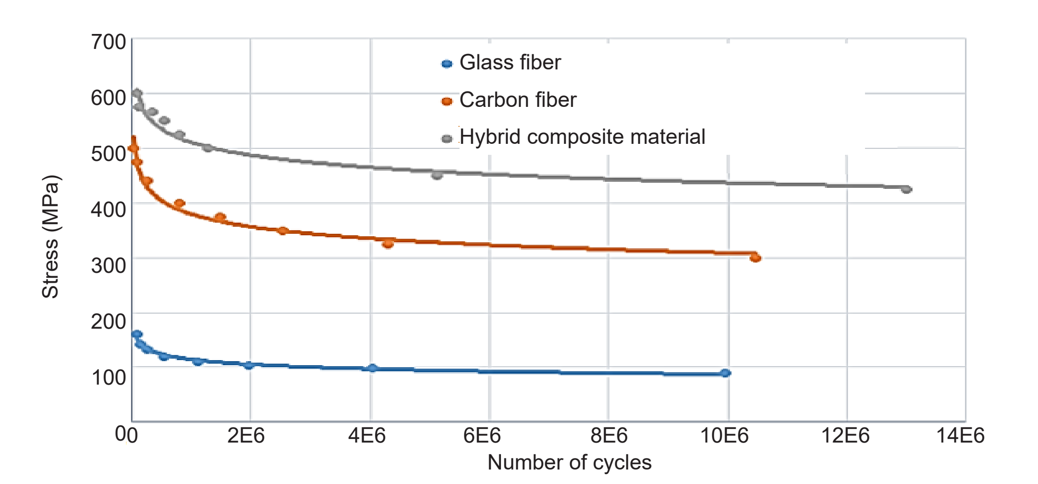



*Figure 13*. The S-N curve of the three tested materials

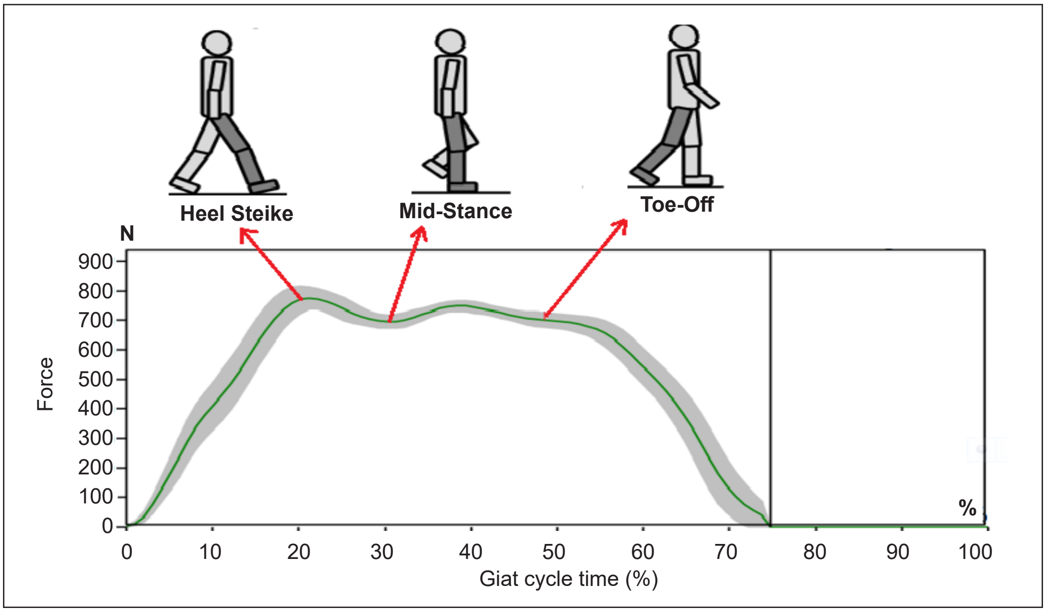



*Figure 14*. The curve of the ground reaction force of an amputee person

**The Boundary Condition for Analysis of the Prosthetic Foot.** For the analysis of the prosthetic foot, the boundary conditions must be applied to evaluate the generated stresses and the values of the safety factor for each study case of the materials group for the manufacture of the prosthetic foot. The boundary condition includes applying the value of ground reaction force at shank with fixed the foot at the heel at the initial contact stage of the gait cycle, as shown in Figure 15(a), the region (A) is fixed support and applied load at region (B). Next, for the stage of midstance, the reaction force is applied at the shank and fixed at the forefoot and rearfoot as shown in Figure 15(b), the regions (B) are fixed support and applied load at region (A). Finally, the boundary condition at the toe-off stage, the reaction force applied at the shank and fixed at the forefoot as shown in Figure 15(c), the region (B) is fixed support and applied load at region (A). The applied boundary conditions for simulating a prosthetic foot derived from the applied forces resulting from bodyweight on foot during gait cycle analyses (Baker, 2013; Levine et al., 2012).

The result of numerical analysis of prosthetic foot shows the stress generated due to applying the boundary condition. For example, Figure 16(a) shows the maximum stress value generated equal to 103.64 MPa when the patient walks at the heel strike. At the same time, Figure 16(b) shows the maximum stress equal to 65 MPa when applying the

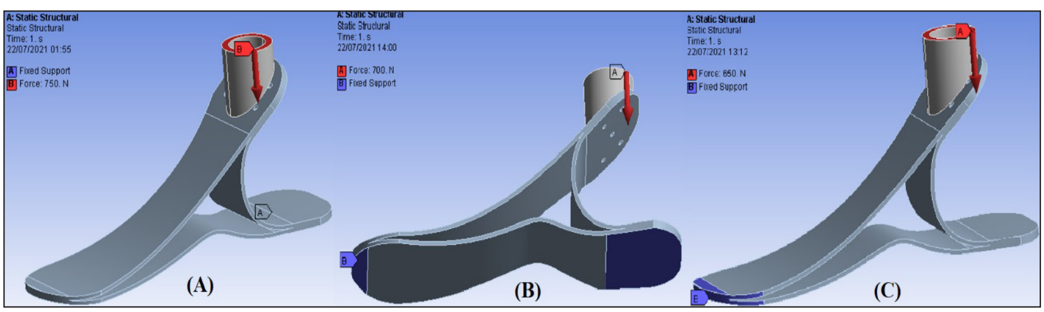



*Figure 15*. (a) The prosthetic foot model's boundary condition at heel strike position; (b) The prosthetic foot model's boundary condition at midstance position; (c) The prosthetic foot model's boundary condition at the toe-off position

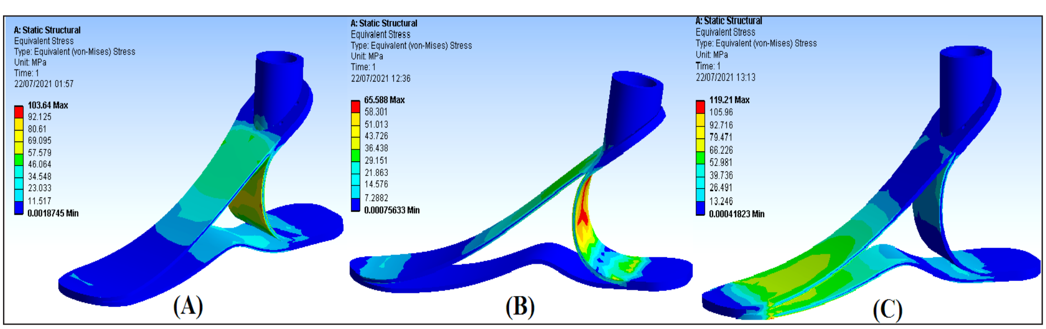



*Figure 16*. (a) The foot model's Von Mises stress at the heel strike stage; (b) The foot model's Von Mises stress at the midstance stage; (c) The foot model's Von Mises stress at the toe-off stage

boundary condition at the midstance phase. Therefore, maximum stress equals 119.2 MPa for toe-off boundary conditions, as shown in Figure 16(c). It was noted from the stress analysis results that there is a large difference between the maximum stress generated and the yield stress for each material, which explains the possibility of the success of the three groups of materials in manufacturing the prosthetic foot.

Also, the analysis shows that the safety factor for the prosthetic foot's material groups has been passed in design. The safety factor's value varies by region, based on the distribution of stresses generated and the endurance stress for each material group. Figures 17 to 19 show the foot model's safety factor when using carbon fiber, fiberglass, and hybrid composite material in three gait cycle phases (heel strike, midstance, toe-off). The results showed that the safety factor values were equal to more than 1.25 for all groups of materials and at all stages of the gait cycle. Therefore, the design will be safe if the fatigue safety factor is greater than or equal to 1.25 (Miller, 2002). The values of safety factors of three materials at three stages of the gait cycle can be summarized in Table 2.

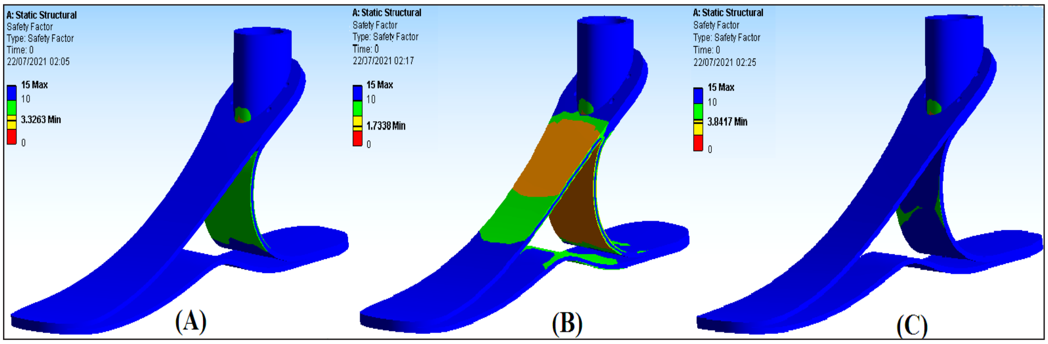



*Figure 17*. (a) The safety factor value for carbon fiber reinforced foot model at the heel strike stage; (b) The safety factor value for fiberglass reinforced foot model at the heel strike stage; (c) The safety factor value for hybrid material reinforced foot model at the heel strike stage

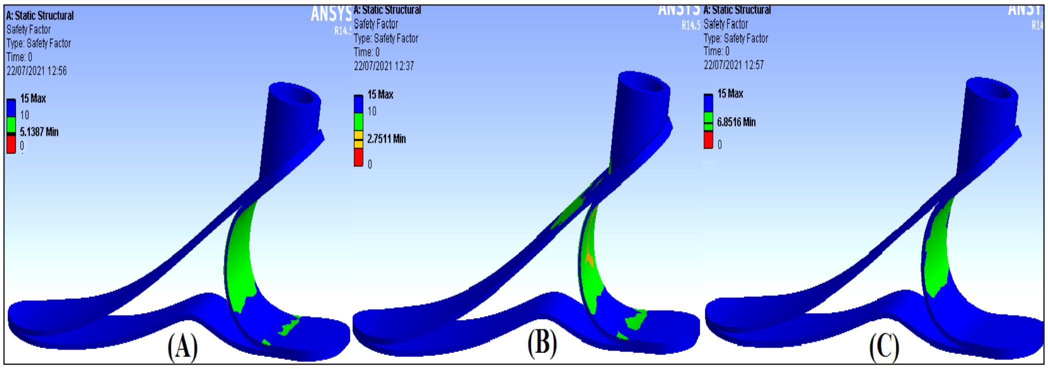



*Figure 18*. (a) The safety factor value for carbon fiber reinforced foot model at the heel strike stage; (b) The safety factor value for fiberglass reinforced foot model at the heel strike stage; (c) The safety factor value for hybrid material reinforced foot model at the midstance stage

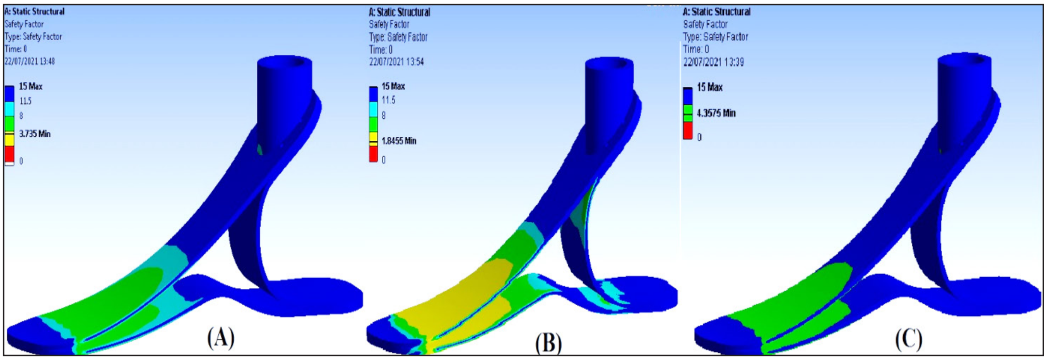



*Figure 19*. (a) The safety factor value for carbon fiber reinforced foot model at the heel strike stage; (b) The safety factor value for fiberglass reinforced foot model at the heel strike stage; (c) The safety factor value for hybrid material reinforced foot model at the toe-off stage

Table 2
*The safety factors summarized the values of three materials at different stages of the gait cycle*

| Material | Heel strick | Mid-stance | Toe-off |
|---|---|---|---|
| Carbon fiber | 5.7 | 580 | 448 |
| Glass fiber | 1.7 | 170 | 160 |
| Hybrid composite material | 6.2 | 678 | 560 |

## CONCLUSION

The previous results concluded that all the materials groups passed in design, but the best material to manufacture the prosthetic foot is the material in case (3), which is hybrids composite material (carbon and glass fibers). For manufacturing the prosthetic foot, it was decided to use a hybrid composite material because it has a better overall combination of properties than composites with only one fiber type. Various fiber combinations and matrix materials are used, but combining carbon and glass fibers in polymeric resin is the most common method. Carbon fibers are strong and stiff in comparison to other materials. They provide low-density reinforcement but are expensive. Glass fibers are less expensive than carbon fibers but lack their stiffness. The glass fiber–carbon fiber hybrid is stronger and harder, has greater impact resistance, and can be manufactured cheaper than similar all-carbon or all-glass reinforced polymers. Therefore, it was concluded that the hybrid material is the most suitable choice for manufacturing the prosthetic foot because of its high mechanical properties and lightweight compared to the prosthetic foot was made of carbon fiber or fiberglass.

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