

MANUFACTURING AND ANALYSIS OF PROSTHETIC FOOT USING COMPOSITE MATERIAL

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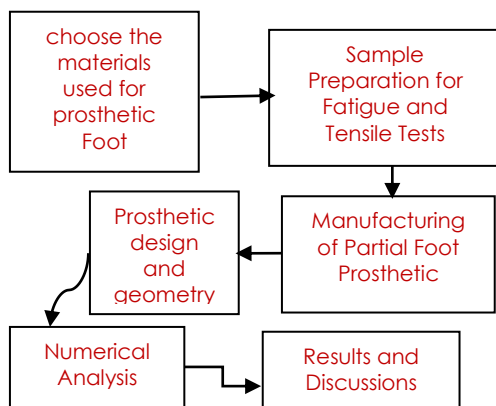
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Graphical abstract



Abstract

The design and development of prosthetic feet play a crucial role in enhancing mobility, comfort, and overall quality of life for amputees, as an effective prosthetic must support body weight, enable a natural gait, and absorb shock during walking. However, conventional designs such as the SACH foot often lack sufficient flexibility, durability, and responsiveness for dynamic activities, while high-performance alternatives like carbon fiber-based models remain costly, creating a need for a lightweight, cost-effective solution with improved performance. This study addresses this gap by designing, manufacturing, and evaluating a composite prosthetic foot using carbon fiber, fiberglass, and Kevlar to optimize strength, durability, and affordability. The prosthetic was divided into a Keel and Heel, fabricated using layered composites (11 carbon fiber layers with additional reinforcement, 2 fiberglass layers, and 2 Kevlar layers), with a 15° dorsiflexion angle to simulate natural gait, and analyzed using ANSYS 14.5 for deformation, stress distribution, and safety factor, alongside mechanical testing. The developed prosthetic foot weighed 412 g and demonstrated effective gait simulation for below-knee and through-knee amputees, with tensile properties reaching yield strengths of 138.057 MPa and 102.486 MPa, ultimate strengths of 174.2 MPa and 146.257 MPa, and elastic moduli of 2.384 GPa and 5.616 GPa for two sample groups. The design maintained structural safety under normal loading with safety factors above 0.86 but became unsafe beyond 96 kg body weight, with reduced lifespan above 86 kg.

Keywords: Mechanical properties, Foot, Prosthetic limb, Numerical analysis

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1.0 INTRODUCTION

According to a 2016 study that determined the average daily step count and preferred walking rate, people normally take about 6,500 steps per day [1]. The optimal walking speed may vary from person to person, although it is generally accepted to be around 1.3 m/s [2]. People, their families, and society at large may be significantly impacted by amputation, particularly when it affects the lower limbs. Amputations of lower limbs are often associated with the following concerns and challenges: Mobility loss, a reduction in quality of life, functional limitations, an impact on daily activities, psychological and emotional effects, and socioeconomic consequences are a few of the problems that could occur [3]. People who have suffered lower limb amputations usually have different physical capabilities than healthy individuals. include the following: Reduced sedentary conduct, reduced mobility, increased fatigue, and a slower walking pace [4].

Lower limb amputations have become more common in developed countries, and the two main causes of these amputations are diabetes and auto accidents [5]. A significant portion of lower limb amputees—more than half—are over 65. Vascular disorders, which are more prevalent as people age, are mostly to blame for this [2]. With the use of prosthetics, people who have lost a lower limb may be able to restore many of their regular activities, lifestyle, and stability [6-8]. It could be challenging to adapt mechanical limbs to the human body. Making sure the prosthetic limb and the residual limb are completely connected while offering optimal usability and comfort [9]. Making prosthetic limbs operate like the human body does naturally is quite challenging. Many factors need to be considered during the design phase in order to ensure functionality and user satisfaction [10–12].

The lower limb prosthesis's several components frequently cooperate to provide the user with support, functionality, and comfort. The foot, metal pylon, ankle and knee joints, screws, bolts, and nuts, as well as the cushioning and suspension components, are the necessary components [13–16]. Prosthetic foot is a critical element of transtibial prosthesis. Performs many functions in managing the lower limb prosthesis, including protection, loads bearing, stability, shock absorption, and leverage [17]. The variety available in the market in terms of design and material of the prosthesis, makes it difficult for the prosthetist to choose the most suitable one for amputation [18]. Prosthesis prescriptions for amputees of the lower limbs mainly depend on the subjective experiences and empirical knowledge of prosthetists, therapists, and physicians; nevertheless, the prescription should ideally be based on the amputees' functional needs [19–21]. The current work is mainly focused on designing and manufacturing of an artificial foot by using two model of carbon foot

(Vari-Flex & Vari-Flex Modular) from ossur company by composite and make changes to the foot design Compared to the other foot constructed completely of carbon fiber, this one will be more cost-effective, more comfortable, and appropriate for a range of amputations in order to provide the patient with ideal gait cycle aid. and compared to existing designs, these innovations offer potential benefits that improve the user's quality of life and address many of the limitations of traditional prosthetics, including weight, durability, cost, and biomechanical alignment. Unlike previous studies that primarily focused on prosthetic feet made entirely from carbon fiber or low-performance designs like the SACH foot, this research introduces a cost-effective composite structure that strategically combines carbon fiber, fiberglass, and Kevlar to achieve comparable strength and durability while significantly reducing material costs. Additionally, the integration of a 15-degree dorsiflexion angle in the Keel offers a biomechanically optimized gait, especially during the transition from stance to toe-off—an improvement rarely addressed in earlier designs. By validating the design through both numerical simulations (FEA) and mechanical testing, this work provides a more practically viable and performance-oriented prosthetic foot, particularly suited for BK and TK amputees within specific weight ranges.

2.0 EXPERIMENTAL PROCEDURES

The materials utilized to make this prosthetic foot include PVA, neoprene rubber sheet, carbon fiber, fiber glass, Kevlar glass, hardening powder, chem marmolite polyester resin, and orthocryl lamination resin.

2.1 Materials Selection for the Foot

The materials used for foot are:

1-carbon, Glass and Kevlar fiber: Hybrid carbon, glass and Kevlar fiber composites are renowned for their rigidity, strength, and low weight. They most likely serve to harden and strengthen the prosthetic foot, increasing its resistance to damage from walking and daily use. Both the Heel and the Keel make up the foot. 11 layers of carbon fibers (with an additional 5 layers in the adapter location), 2 layers of fiber glass, and 2 layers of Kevlar fiber with lamination glue were used to create the first portion (Keel). Eleven carbon fiber layers, two fiber glass layers, and two Kevlar glass layers were used to create the second component (the Heel) using polyester resin.

2-Resin combined with a hardener: The polymer resins used in this investigation include orthocryl lamination resin and chem marmolite polyester resin. Resin-hardener mixture is used to coat the carbon and glass fibers, creating a strong and rigid composite structure for the prosthetic foot.

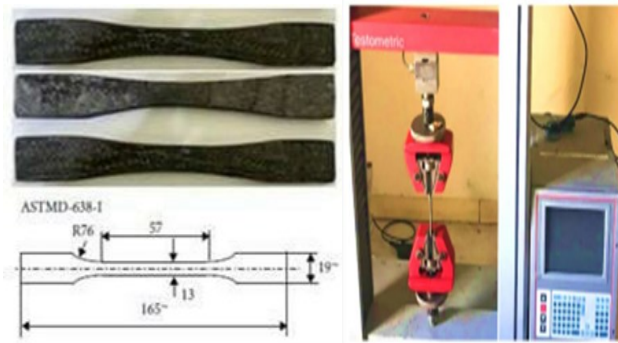


Figure 1 Tensile test device and tensile samples

2.2 Tensile Tests

The material's mechanical characteristics, which are determined by this test, are necessary for both theoretical and experimental computations. The universal testing tool (testometric) is used to test all tensile test samples. The cross-head speed is 5 mm/min and it is found in AL Nahrain University's mechanical department labs. The samples undergoing a tensile test are shown in Figure 1. As a result, the ASTM standard was considered for this test specifications. As illustrated in Figure 1, the test specimen dimension and shape for the D638 standard [22] were set for the material of the composite.

2.3 Bending Test

Bending test is also called Flexural Bend Testing (The standard commonly used for bending tests on materials like resins and composites is ASTM D790), flexural tests of composite materials are useful as an alternative or supplementary method to determine tensile and compressive properties [23]. Flexural strengths can be used to numerically determine other composite material strength values by visual inspection of failure behavior and basic bending stress analysis [24]. Bending test is performed using a testometric instrument apparatus, as seen in Figure 2. The use of a milling machine necessitates a specific shape for the specimen. As seen in Figure 2, face and root end tests were a crucial tool for determining the ductility and toughness of friction stir weld samples that passed the 90° bend test.

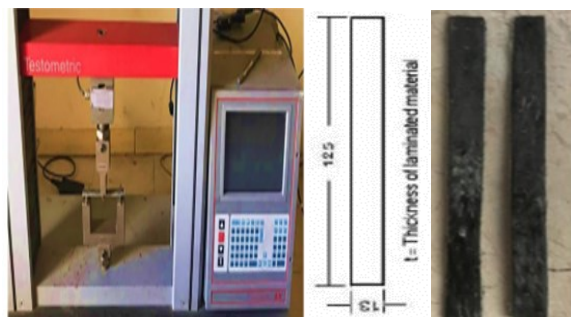


Figure 2 Bending test device and bending samples

2.4 Manufacturing Procedure of Prosthetic Foot

Manufacturing Procedure for the two parts of foot (Heel, Keel) include taking pattern (negative mold) for the two parts then applying the negative cast by using pop for the upper part (Keel) and for the lower part (Heel), preparing for rectification, cast rectification, rectification process for the Heel includes just adjusting the edges, for the Keel part slight change was made in the design of the part by increasing the angle dorsiflexion approximately 15 degree which can assist the foot to have easily and comfortable as shown in Figure 3.



Figure 3 Rectification stage

Lamination of the prosthetic foot for both Heel and Keel was performed under vacuum with procedures that included mounting the positive mold at the laminating stand, completing the connection with the vacuum forming system through the pressure tubes, pulling the inner PVA bag in the positive mold, and opening the pressure valves to a value of approximately 30 mm Hg at room temperature, and putting the layers of materials (carbon fiber, fiberglass, and Kevlar fiber) according to Table 1 for Heel and Table 2 for Keel. Pulling the outer PVA and maintaining the smaller end above the valve region by fastening the PVA bag with a cotton string. For the Keel, the mixing of the hardening powder about 300-310 ml with orthocryl lamination resin (the selected resin-hardener ratio ensures controlled curing, desired physical properties, and compatibility with the application process, ensuring the final product meets its intended functional and aesthetic standards) was mixed with 1-1.5 parts of the hardening powder. This combination was evenly distributed throughout the lamination stockinet and placed in the outer of PVA bag.

For the Heel, using B-chem marmolite polyester resin 4 because this part is in contact with the ground therefore will have to use material that's kind of flexible and use for shock absorption, using about 210 ml then it putted in the outer PVA bag, and it evenly distributed throughout the lamination stockinet, finally the constant vacuum is maintained until the material became cold and dry then the result lamination was left. The two parts were cut by oscillator to the desired design. as shown in Figure 4, 5.

Table 1 Layers of materials of Keel

Types of Material	Number of Layers	Place of Layers
Carbon Fiber	3	All (adapter place and Keel)
Carbon Fiber	3	adapter place
Carbon Fiber	2	All (adapter place and Keel)
Fiber Glass	2	All (adapter place and Keel)
Carbon Fiber	2	adapter place
Carbon Fiber	2	All (adapter place and Keel)
Kevlar Fiber	2	All (adapter place and Keel)
Carbon Fiber	4	All (adapter place and Keel)

Table 2 Layers of materials of Heel

Types of Material	Number of Layers
Carbon Fiber	3
Carbon Fiber	2
Fiber Glass	2
Carbon Fiber	2
Kevlar Fiber	2
Carbon Fiber	4



Figure 4 Lamination of the Keel



Figure 5 Lamination of the Heel

Assembly of the prosthetic foot include grinding the two parts and make holes to connect the Keel and the Heel together, and using an adhesive material (MASTERBRACE ADH 2200) which is a mixture of two parts, putting it between Heel and Keel to make the foot stronger and to not slip off easily during the gait cycle then Make holes connect the adapter to the Keel together, put the alignment wedges between the pylon and foot module and put it in dorsiflexion position, adding the neoprene rubber to work as shock absorber because neoprene's shock-absorbing qualities come from its ability to deform under pressure and return to its original shape, which helps reduce the effects of sudden forces and vibrations , and adding it in the vacancy between the adapter to the Keel to obtain a distinct and acceptable shape. Finally, clean the foot and grinding the edge of it and put it in the socks used to cover the composite foot module to protect the foot and eliminate noise between foot module and foot shell, then put it in foot cover, as shown in Figure 6.



Figure 6 The final view of the foot

3.0 RESULTS AND DISCUSSION

The artificial foot tested on three cases, each differs from the other in terms of level of amputation, length and weight shown in Figure 7. It is important to note that the patients who were selected amputated form a long time, the least one who was selected was an amputated from 10 years and this to ensure that the patients have the experience to give right impression of the foot, their information.



Figure 7 Cases study with the prosthetic foot.

3.1 Force Plate Results

The estimation of ground response forces and moments on a foot throughout a patient's gait cycle using a force plate can provide valuable information about the loading patterns that the foot experiences. The peak pressures at toe-off and Heel contact are important considerations. Noting any notable differences between the traits of the left and right legs is also crucial. Peak values of forces and moments during Heel contact and toe-off can be used by clinicians and researchers to evaluate the loading conditions on the foot as well as the foot's functionality and stability during gait. For first case Figure 8 show foot pressure patterns (pressure distribution map). The colors indicate varying levels of intensity, with red representing the highest values and blue the lowest) and Figure 9, (a) show the force with time curve and the maximum force is 520 N (b) show the area with time curve and the maximum area is 85 cm² (b) show the pressure with time curve and the maximum pressure is 80 kpa.

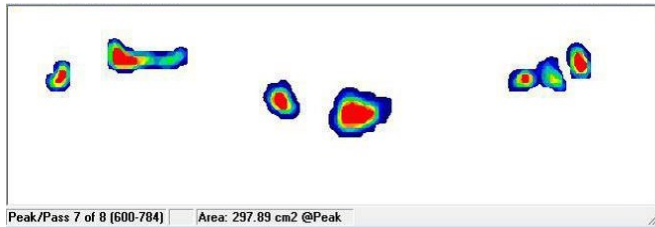


Figure 8 pressure patterns

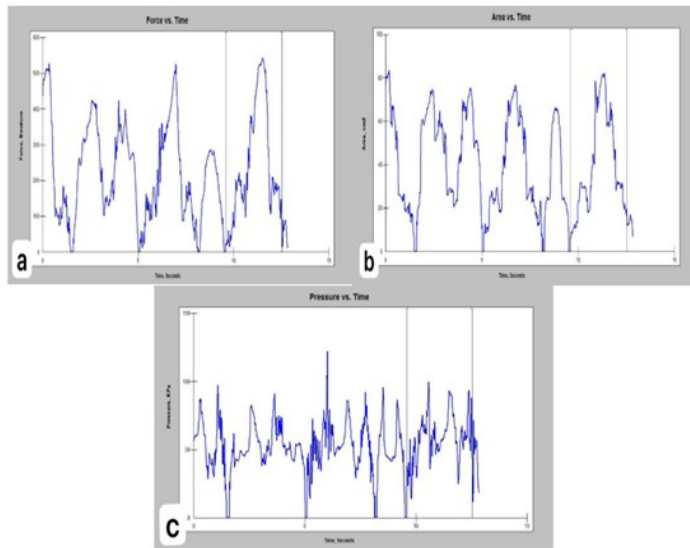


Figure 9 (a) Force vs. Time. (b) Area vs. Time. (c) Pressure vs. Time

For second case Figure 10 show foot pressure patterns and Figure 11 (a) show the force with time curve and the maximum force is 330 N (b) show the area with time curve and the maximum area is 40 cm² (b) show the pressure with time curve and the maximum pressure is 240 kpa.

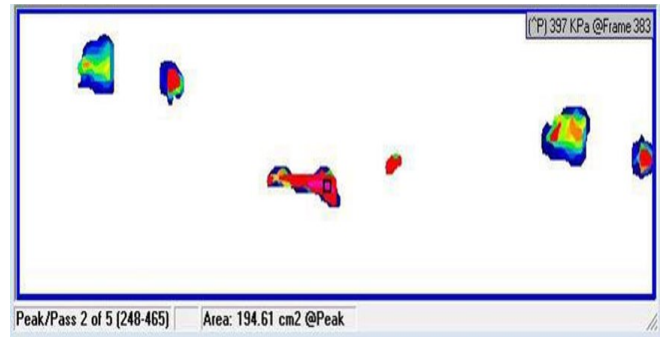


Figure 10 pressure patterns

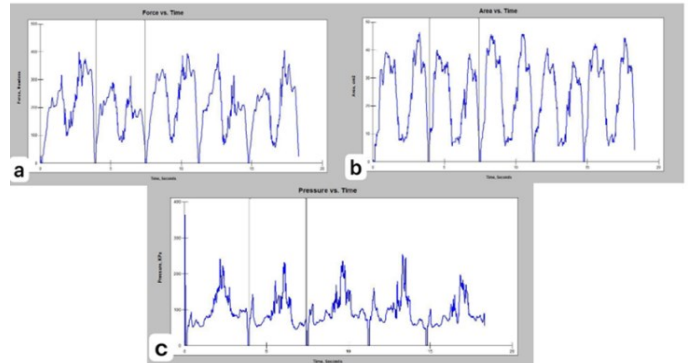


Figure 11 (a) Force vs. Time. (b) Area vs. Time. (c) Pressure vs. Time

For third case Figure 12 show foot pressure patterns and Figure 13, (a) show the force with time curve and the maximum force is 650 N (b) show the area with time curve and the maximum area is 54 cm² (b) show the pressure with time curve and the maximum pressure is 190 kpa.

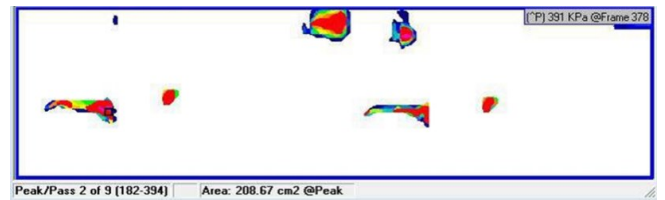


Figure 12 pressure patterns.

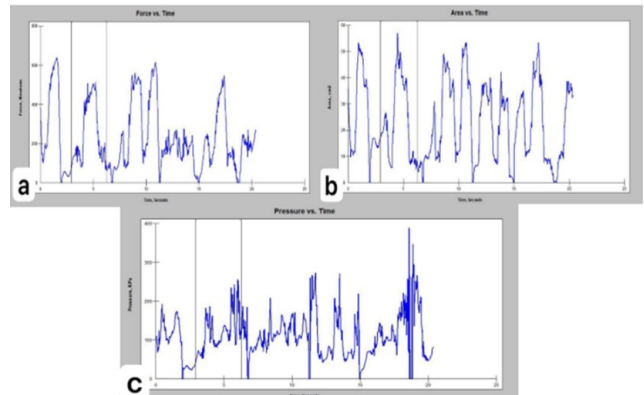


Figure 13 (a) Force vs. Time. (b) Area vs. Time. (c) Pressure vs. Time

The patients are walking well on the force plate, as seen by the minor differences shown in Tables 3, 4, 5, 6, 7 and 8 which show the patient's Step-Stride and gait cycle, respectively.

Table 3 Step-Stride Table.

Step-stride	01		
	Left	Right	Difference
Step time (sec)	0.85	0.96	0.11
Step length (cm)	47.5	46.0	-1.6
Step velocity (cm/sec)	55.8	47.9	-7.9
Step length/leg length (ratio)	n/a	n/a	n/a
Step width (cm)	6.8	7.4	0.6
Stride time (sec)	1.87	2.11	0.24
Stride length (cm)	93.9	95.8	1.9
Stride velocity (cm/sec)	50.2	45.4	-4.8
Maximum force (%BW)	n/a	n/a	n/a
Maximum force (N)	211.48	476.92	265.90
Impulse (%BW *SEC)	n/a	n/a	n/a
Impulse (N *SEC)	122.48	371.52	249.03
Maximum peak pressure (KPa)	245	270	25
Foot angle (degree)	6	12	6

Table 4 Gait Cycle Table (sec).

Gait cycle (sec)	01		
	Left	Right	Difference
Gait cycle time	1.87	2.11	0.24
Stance time	1.26	1.23	-0.03
Swing time	0.61	0.88	0.27
Single support time	0.56	0.54	-0.02
Initial double support time	0.36	0.42	0.06
Terminal double support time	0.42	0.36	-0.06
Total double support time	0.78	0.78	0.00
Heel contact time	0.70	0.76	0.06
Foot flat time	0.20	0.50	0.30
Midstance time	0.33	0.44	0.11
Propulsion time	0.49	0.47	-0.02
Active Propulsion time	0.13	0.04	-0.09
Passive Propulsion time	0.36	0.42	0.06

Table 5 Step-Stride Table.

Step-stride	02		
	Left	Right	Difference
Step time (sec)	1.45	0.93	-0.52
Step length (cm)	55.9	45.2	-10.6
Step velocity (cm/sec)	38.4	48.5	10.1
Step length/leg length (ratio)	n/a	n/a	n/a
Step width (cm)	6.2	5.4	-0.8
Stride time (sec)	n/a	2.34	n/a
Stride length (cm)	n/a	97.3	n/a
Stride velocity (cm/sec)	n/a	41.7	n/a
Maximum force (%BW)	n/a	n/a	n/a
Maximum force (N)	248.36	335.61	87.26
Impulse (%BW *SEC)	n/a	n/a	n/a
Impulse (N *SEC)	188.86	336.58	147.72
Maximum peak pressure (KPa)	369	360	-9
Foot angle (degree)	6	5	-1

Table 6 Gait Cycle Table (sec).

Gait cycle (sec)	02		
	Left	Right	Difference
Gait cycle time	n/a	2.34	n/a
Stance time	1.31	1.51	0.20
Swing time	n/a	0.03	n/a
Single support time	0.66	n/a	n/a
Initial double support time	0.19	0.38	0.20
Terminal double support time	0.38	0.19	-0.20
Total double support time	0.57	0.57	0.00
Heel contact time	0.79	0.96	0.17
Foot flat time	0.09	0.38	0.30
Midstance time	0.51	0.52	0.02
Propulsion time	0.48	0.55	0.07
Active Propulsion time	0.29	0.23	-0.06
Passive Propulsion time	0.19	0.32	0.13

Table 7 Step-Stride Table.

Step-stride	03		
	Left	Right	Difference
Step time (sec)	0.89	0.49	0.39
Step length (cm)	34.0	6.4	27.5
Step velocity (cm/sec)	38.3	13.1	25.3
Step length/leg length (ratio)	n/a	n/a	n/a
Step width (cm)	13.5	15.9	2.3
Stride time (sec)	1.60	n/a	n/a
Stride length (cm)	52.7	n/a	n/a
Stride velocity (cm/sec)	32.8	n/a	n/a
Maximum force (%BW)	n/a	n/a	n/a
Maximum force (N)	273.11	337.99	64.88
Impulse (%BW *SEC)	n/a	n/a	n/a
Impulse (N *SEC)	184.99	271.50	86.51
Maximum peak pressure	360	346	-14
Foot angle (degree)	2	13	11

Table 8 Gait Cycle Table (sec)

Gait cycle (sec)	03		
	Left	Right	Difference
Gait cycle time	1.60	n/a	n/a
Stance time	1.08	1.13	0.05
Swing time	0.52	n/a	n/a
Single support time	n/a	0.64	n/a
Initial double support time	0.28	0.40	0.13
Terminal double support time	0.40	0.28	-0.13
Total double support time	0.68	0.68	0.00
Heel contact time	0.74	0.52	-0.22
Foot flat time	0.15	0.62	0.47
Midstance time	0.50	0.44	-0.07
Propulsion time	0.25	0.44	0.19
Active Propulsion time	0.01	0.05	0.04
Passive Propulsion time	0.24	0.39	0.15

3.2 Structural Performance

The model of prosthetic foot was analyzed by using Workbench software 14.5 to calculate the total deformation, equivalent stress (Von-Mises) and safety factor of the foot when the force was applied in three cases (stance phase, mid stance and toe off) when the force applied vertically on the foot and the foot fixed in different situation each time as shown in Figures 14-16. In image (a), the force applied is 142.6 N, representing a typical load condition. Image(b) shows the total deformation, with red regions indicating maximum displacement. If the deformation is too high, it may affect user comfort and walking efficiency. Ideally, deformation should be within an acceptable range to maintain natural gait biomechanics. The stress analysis in image (c) shows how forces are distributed across the prosthetic foot. High-stress regions (red/yellow) indicate potential weak points that could lead to material fatigue or failure. Green and yellow regions in the SF image indicate areas where the structure is approaching its material limits, suggesting potential design improvements.

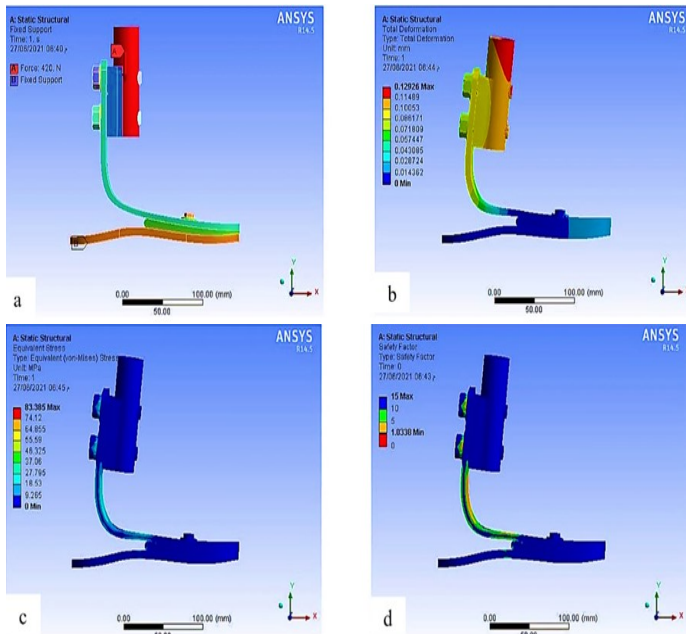


Figure 14 Case 1 when Heel fixed (a)-fixed support, (b)- total deformation, (c)-von-mises and (d)-safety factor

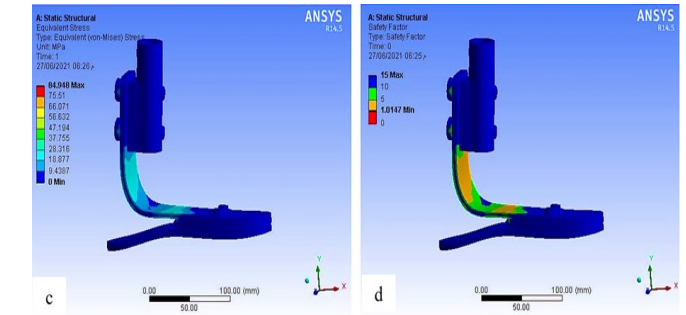
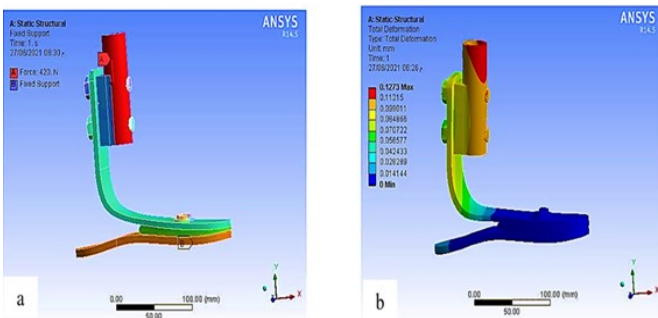


Figure 15 Case 2 when metatarsal fixed (a)- fixed support, (b)- total deformation, c. von-mises and (d)- safety factor

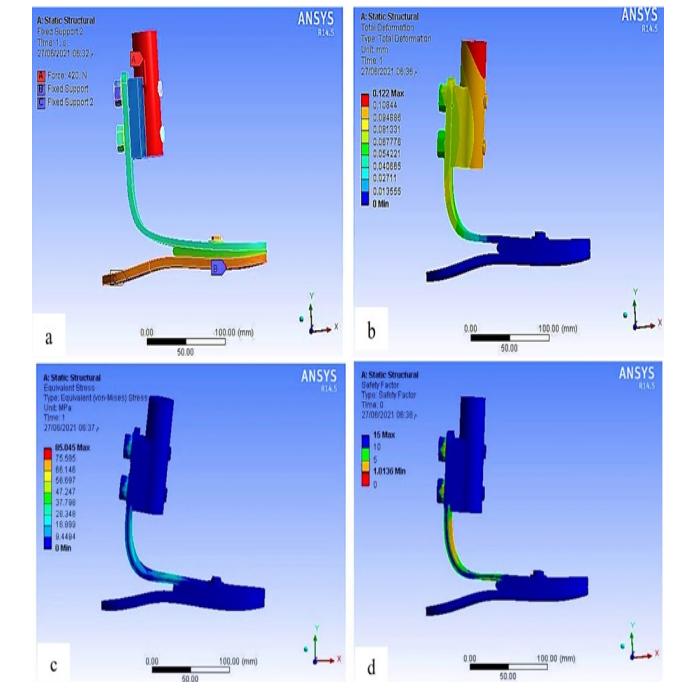


Figure 16 Case 3 when Heel and metatarsal fixed (a)-fixed support, (b)-total deformation, (c)-von-mises and (d)-safety factor

Our prosthetic foot weighing 412g and with a height of 19.5cm aligns with current trends in prosthetic design, where lightweight components are crucial for enhancing comfort and mobility. Similar studies, such as those by Zhao *et al.* (2020), have also focused on lightweight materials in the production of prosthetic devices. Zhao's work explored the use of carbon fiber-reinforced plastics, which are known for their high strength-to-weight ratio, a characteristic that you have similarly utilized with your composite materials. While our study does not specify the exact materials, the lightweight aspect of our design is consistent with broader trends in prosthetics for lower-limb amputees.

The 15-degree dorsiflexion Keel angle you applied is an interesting and important aspect of our study. Research from Kuo and McGowan (2017) supports this finding, where the dorsiflexion angle in prosthetic

feet is shown to significantly improve push-off and propulsion during gait. Similar studies have used angles ranging from 10 to 20 degrees for optimal gait mechanics. The findings in our study highlight how a carefully optimized Keel angle can improve walking efficiency and enhance the overall user experience. The expected lifespan of the prosthetic foot depends on factors such as material properties, loading conditions, fatigue behavior, and environmental influences. Based on the ANSYS simulation results, we can analyze its longevity under typical and extreme loading conditions. The prosthetic foot is expected to last around 3-5 years under typical conditions but may degrade faster (1-2 years) under extreme loading. Design improvements can enhance its longevity and performance.

4.0 CONCLUSIONS

Lightweight 412g foot with 19.5cm height, provides a good appearance under clothing. Glass fiber and Kevlar fiber can be used with carbon fibers to reduce the amount of carbon fiber used in manufacturing due to its high cost compared to glass fibers and Kevlar and then will get a product that is not less efficient than the product that only carbon is used in its manufacturing. Put the Keel angle at 15 degrees of dorsiflexion make the gait (from stance phase to toe off) more easily and help the patient to have more amount of push off to move the body forward.

Easily walking and good shock absorption for BK, TK patient, but excessive dorsiflexion degree for AK patient. For force (470), the safety factor when the Heel (stance phase) fixed 0.901, when the metatarsal (toe off) fixed 0.885, when the Heel and metatarsal (mid stance) fixed 0.862, therefore when Heel and metatarsal (mid stance) fixed is the most dangerous. According to the Von-Mises theory the foot is safe. When the weight equal and up to 96kg the failure occurs, when the weight equal to or less than 86kg the foot safe but not for a big time and when the weight equal to or less than 60 the foot is safe for a long time.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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