Design and evaluation of a novel bioinspired prosthetic foot for running applications in lower limb amputees

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ABSTRACT

With the rise in transtibial and transfemoral amputations, the number of athletic amputees has steadily increased. This study aims to develop an alternative prosthetic foot for the lower limb to address the limitations of conventional prosthetic designs and better meet user requirements. The proposed prosthetic foot offers a promising solution by incorporating cost-effective materials and mechanisms. The primary objective is to create a prosthetic device suitable for sports activities – particularly running – allowing lower limb amputees to participate in endurance sports using mechanically enhanced limbs that closely mimic the function and characteristics of natural biological limbs. The mechanical and miscibility properties of the prosthetic foot were evaluated through experimental, theoretical, and numerical approaches. Polyester matrix laminates reinforced with both natural and synthetic fibers were fabricated using a vacuum-assisted system and subjected to tensile, hardness, bending, fatigue, and Fourier transform infrared (FTIR) spectroscopy tests. To assess loading behavior and user comfort, force plate measurements during the gait cycle provided insight into ground reaction forces, moments, and abutment interface pressures, supplemented by F-Socket testing. Finite element analysis was used to determine the distribution of safety factors, strain energy, total deformation, and equivalent von Mises stress and strain. Laminates reinforced with hybrid glass, carbon, and linen fibers demonstrated optimal tensile strength, bending resistance, fatigue performance, and hardness. FTIR spectroscopy analysis further indicated significant interaction between the fibers and the resin. Gait cycle analysis revealed that the prosthesis made from composites reinforced with carbon, glass, and linen fibers exhibited superior comfort, with a maximum applied force of 610 N and acceptable interface pressure values – making it suitable for prosthetic applications. In conclusion, the selected materials meet established safety standards, confirming their suitability for prosthetic foot design. This study underscores the orthopedic potential of biodegradable materials and highlights advancements in biomedical engineering through enhanced biocompatibility and durability.

Keywords:
Amputation; Biomaterials; Finite element methodology; Foot; Sport prosthetics

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1. Introduction

Running has become one of the most prominent events in the Paralympic Games. The use of artificial carbon blade prostheses in sprinting and long jump has reached remarkable performance levels, sparking debates about the fairness of these mechanical advantages compared to able-bodied athletes.[1] Nevertheless, increased participation in adaptive sports has not only heightened public interest but also fostered greater awareness and inclusivity for individuals with amputations. Advancements in prosthetic components for daily use have steadily expanded the functional capabilities available to athletic amputees. Over the past two decades, prosthetic components and designs have undergone continuous advancements for professional sports, particularly for transtibial and transfemoral amputees who require sprinting functionality.[2] Since the lifespan of a prosthetic foot reflects the overall durability of the device, developing reliable prosthetic feet is especially crucial in developing countries. Several designs have been introduced to meet the needs of amputees in less developed countries. For instance, the International Committee of the Red Cross foot, created in Geneva, and the Snelson foot are produced in developed countries and distributed to low-income countries for practical use.[3] The Flex-Foot was the first prosthetic foot with a distinctive shape, resembling the letter "J," and was specifically designed for running competitions.[4]

The prosthesis must fulfill its function during running or walking by undergoing appropriate tests and assessments, and by adapting to changing boundary conditions throughout use – even though it may not replicate the healthy human foot in all respects.[5] Composites have been employed across various industries, including the manufacture of artificial limbs, to help amputees lead normal lives and participate in diverse activities, particularly sports.[1,6] However, many amputees who wish to participate in sports are unable to do so due to the high cost of sport-specific prostheses, which are typically designed for a specific function and are not suitable for walking or daily tasks. Although Van Phillips introduced the first prosthetic racing blade in 1989, numerous prototypes have since been developed and utilized. In addition to synthetic fibers, such as ultra-high-molecular-weight polyethylene, carbon, and glass fibers, polylactic acid is commonly used in three-dimensional printed prosthetic feet due to its biodegradability, affordability, and ease of fabrication.[7] Comfort is significantly influenced by the form and function of the prosthetic device. Carbon fiber, while lightweight and highly durable, is expensive and relatively stiff, which limits its ability to conform to the natural shape of the foot compared to softer materials. Improper customization of the prosthesis may result in pressure points and discomfort. With meticulous design and careful material selection, three-dimensional printed prosthetic feet have emerged as modern commercial solutions capable of achieving mechanical strength comparable to traditionally manufactured components.[8] This technology enables rapid prototyping and design variation, allowing researchers and medical professionals to test multiple designs and material combinations at a relatively low cost.[9]

To meet the specific needs of athletic amputees, several factors must be considered when selecting materials for prosthetic feet. These include high tensile and compressive strength, corrosion and shear resistance, low density, adaptability, and overall stability. In addition to material properties, the prosthetic foot must also exhibit key mechanical features – such as 20° of flexion, 20° of rotation, and an energy return efficacy of 117%. Furthermore, prosthetic feet should be readily accessible and widely available. Ensuring affordability is essential to make them attainable for as many individuals as possible. In addition, the prosthetic foot should be easy to put on and remove, easily maintainable or replaceable, and flexible enough to accommodate a range of user needs.[10,11] Common materials used in prosthetic feet include titanium, rubber, carbon fiber, fiberglass, polyurethane, and hardwood. These materials offer dynamic performance, are lightweight, store energy efficiently, and can be customized to support a full range of motion throughout the gait cycle.[12]

In settings where expensive resources are unavailable – such as in earthquake-affected areas and conflict zones – plant-based biomaterials may serve as a viable alternative.[13] Natural fiber composites can be developed to replace traditional materials, such as metals and synthetic fibers. They are more environmentally friendly, reusable, relatively abundant, and less expensive than synthetic fibers.[14,15] Their excellent strength-to-weight ratio and notable biocompatibility make them highly suitable for prosthetic applications. Bio-composites are typically formed by combining natural fibers with polyester or epoxy resins. However, some natural fibers lack the strength or stiffness required to securely support the limb during use. To address this, hybrid composites combining natural fibers with synthetic materials, such as glass, carbon, or Perlon have been developed.[16,17]

The primary objective of prosthetic development is to enhance the quality of life for athletes who have lost a lower limb. Over the past few decades, the design and functionality of prosthetic feet have evolved significantly. These advancements stem from the need to produce prosthetic limbs that mimic the performance of human feet, allowing amputees to run, walk, and engage in various physical activities.[18,19] Rahman *et al.*[20] investigated the effects of incorporating nanopowder particles into unsaturated polyester. This technique aims to improve the mechanical properties of the matrix used in prosthetic sockets by introducing nanopowders at different mass fractions – specifically 3%, 6%, and 9%. The composite samples were fabricated using the hand lay-up method and subsequently tested for tensile strength, impact resistance, bending, and hardness. The results of the study demonstrated that the mechanical properties improved with increasing nanopowder content. Hayder *et al.*[21] investigated the manufacturing and design features of a sporting prosthetic foot composed of polymethyl methacrylate polymer composites reinforced with various fibers – including ultra-high-molecular-weight polyethylene, glass, Perlon, and carbon fibers. The study involved tensile and density testing. Results showed that the material performance improved with the addition of more fiber layers and the use of different types of fibers.

Using the vacuum bagging technique, Oleiwi *et al.*[22] investigated the application of natural materials in manufacturing below-knee prosthetic sockets through numerical, mathematical, and experimental approaches. Tensile tests were conducted on lamination groups with different stacking configurations,

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revealing that natural reinforcements can produce bio-composites with enhanced performance. Fahad *et al.*[23] developed a functional prosthetic foot model capable of supporting an amputee's body weight during walking. Numerical analysis using ANSYS assessed the stresses on the foot model under assumed human weight, demonstrating that the design was successful with no mechanical failures and that the chosen manufacturing materials were effective. Abdul Kareem *et al.*[24] combined mathematical, numerical, and experimental methods to develop and analyze a prosthetic foot. Using boundary conditions within ANSYS, they examined composites reinforced with various fibers – including carbon, Perlon, kevlar, and glass. Their results indicated that since the modulus is directly proportional to the fiber volume percentage, increasing the fiber content enhances the mechanical properties of the laminate.

Due to the need for novel materials for prosthetic components – primarily focused on competitive sports – there has been a persistent lack of parts specifically designed for recreational sports. Furthermore, the growing interest of athlete amputees to participate in sports as part of their rehabilitation has not received sufficient attention. Since synthetic feet do not offer the same versatility as natural feet, enhancing the user's skill level is essential. The extent to which a prosthetic device replicates the characteristics of a natural foot plays a key role in selecting an appropriate artificial foot. Prosthetic feet made from fiber-reinforced composites are favored for their strong, lightweight design that supports energy storage, dispersion, and retention during walking, thereby improving gait efficacy. The effectiveness of the foot varies depending on the composite's adaptability, fiber selection, mixture type, and overall prosthesis design, as these factors influence the ratio of energy stored to energy lost. Although natural fibers sourced from conventional materials have advanced, prosthetic feet made from natural fiber laminates have yet to be widely utilized by amputees who frequently engage in physical activity. Therefore, this study aims to design and evaluate a novel prosthetic foot using biocompatible and environmentally friendly materials to reduce weight and cost while maintaining durability and strength, drawing on previous studies and advancements. It is essential to examine and design the sports prosthetic foot from both scientific and manufacturing perspectives, utilizing mathematical and numerical analyses. Using ANSYS software, boundary conditions are applied to analyze the properties of various laminations composed of a polyester matrix reinforced with different fibers, including jute, linen, carbon, glass fiber, and Perlon.

2. Methodology

2.1. Materials of prosthetic feet

The components used in the composite casting process for fabricating the sports prosthesis foot included carbon textiles, glass fiber, Perlon white stockinet, hardening powder (element 617P37), and a polyvinyl alcohol (PVA) bag. All materials, including those for the Jepson mold, were supplied by Ottobock SE & Co.KGaA (Germany). Detailed specifications and product information for these compounds can be found on the company's official website (https://www.ottobock.com/en-ex/home).

Myfabrics Textile Co., Ltd (Germany) processed both linen and jute fibers into mats. Before silane application, the fibers underwent a two-stage alkali pre-treatment. In the first stage, raw natural fibers were immersed in a 2% (w/w) sodium hydroxide solution for 12 h at room temperature, which initiated fiber swelling. In the second stage, the fibers were immersed in a 7.5% (w/w) sodium hydroxide solution at 100°C for 90 min. The treated fibers were then thoroughly rinsed with filtered water and air-dried at 100°C for 12 h. To enhance silane penetration into the cellulose hydroxyl groups, the fibers were sonicated following immersion in water for three hours. These chemical treatments were performed to modify the surface morphology, eliminate impurities, and improve the mechanical strength and interfacial bonding between the natural fibers and the polyester matrix.

2.2. Foot sample manufacturing

The vacuum molding process facilitates the fabrication of an optimal and polished laminated prosthetic foot. Given that the lamination involves different stacking sequences regardless of fiber orientation, the resulting specimens can be categorized as quasi-isotropic composites, where fiber alignment yields equivalent strength across the entire plane of each part. A sensitive weight scale was used to measure the fibers after they were precisely cut to fit the Jepson mold, which had a cubic design of $17 \times 16 \times 11\ cm^3$.

The hardener and polyester resin were combined in a 2:1 ratio (resin to hardener) at room temperature and mixed thoroughly for 20 min. The curing time required to obtain a homogeneous composition followed the method established by Ottobock SE and Co.KGaA. The mold was secured to the vacuum-forming equipment and positioned on its stand. To prevent the matrix-soaked fibers from adhering to the mold, the inner PVA bag was placed over it. The pressure valves were then released to approximately 0.06 MPa at room temperature. The first set of fibers was arranged according to the lamination configuration specified in **Table 1** and **Figure 1A**. Subsequently, the second PVA bag was positioned, and the matrix mixture was poured into the outer PVA bag, ensuring uniform distribution over the mold. As illustrated in **Figure 1B**, the PVA bag was secured using cotton thread. A cubic laminated composite was formed by maintaining a constant vacuum until the mold had cooled (**Figure 1C**).

All lamination groups were fabricated using the same manufacturing method. The volume fractions were calculated based on the measured weights of both the resin and the reinforcing materials. Detailed information regarding the manufacturing method was obtained from the Ottobock SE and Co.KGaA's website.

2.3. Mechanical and miscibility tests

2.3.1. Tensile test

This test utilized a universal testing machine (Instron, United States) at room temperature, applying a 5 kN load and a strain rate of 1 mm/min strain in accordance with the standard test method for tensile properties of plastics (ASTM D638). **Figure 2** presents a standard tensile test specimen. The test produced stress-strain curves for all 24 samples. The elastic modulus (E), ultimate tensile strength (UTS), specific strength, modulus at break, and other tensile parameters were calculated for these samples.[25]

2.3.2. Bending test

The three-point bending test was conducted using Instron's universal testing machine. To generate a curve illustrating the correlation between force (N) and displacement (mm) for the composite sample, a centralized vertical load was applied along the axis of the laminated composite flexural specimens. The test yielded the flexural strength and modulus of each laminated sample, following the guidelines of the Advancing Standards Transforming Markets (ASTM) standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials (ASTM D790).[26] **Figure 3** shows the standard and experimental specimens utilized in this study.

Table 1. Types of laminated composite material

Lamination name	Type of layers	Stacking sequence	Total number of layers
Laminate 1	Two Perlon layers–three J layers–two Perlon layers	3J	5
Laminate 2	Two Perlon layers–three J layers–two C layers–two Perlon layers	CJ	7
Laminate 3	Two Perlon layers–three J layers–two G layers–two Perlon layers	GJ	7
Laminate 4	Two Perlon layers–three J layers–one G layer–one C layer–two Perlon layers	CGJ	7
Laminate 5	Two Perlon layers–three L layers–two Perlon layers	3L	5
Laminate 6	Two Perlon layers–three L layers–two C layers–Two Perlon layers	CL	7
Laminate 7	Two Perlon layers–three L layers–two G layers–two Perlon layers	GL	7
Laminate 8	Two Perlon layers–three J layers–one G layer–one C layer–two Perlon layers	CGL	7

Abbreviations: C: Carbon; G: Glass; J: Jute; L: Linen.

2.3.3. Hardness test

The Shore-D hardness test was conducted on the laminated composite samples using a Shore-D durometer (DeFelsko Corporation, USA) to determine the average hardness values. The indenter of the device was pressed into seven distinct surface points of each specimen, and the mean value was recorded. The laminated composite groups were tested in accordance with the ASTM standard test method for rubber property – durometer hardness (ASTM D2240).[27]

2.3.4. Fatigue test

A fatigue test was conducted using a cyclic fatigue-testing instrument (HSM20, Instron, United States) that applied an alternating bending load at constant amplitude. Bending stresses were generated by fixing one end of the specimens and applying transverse flexion along its axis. Test failure was indicated by the formation of cracks under cyclic stress in flat specimens. The test was conducted at room temperature with a stress ratio of 1, using the same instrument, under the following conditions: 1400 rpm, 230 V, 20 Hz, and 0.4 kW power.

2.3.5. Fourier transform infrared (FTIR) spectroscopy analysis

FTIR spectroscopy analysis was employed to identify rotational, bending, and vibrational movements of chemical bonds as indicators of composite components. This method facilitates the identification of functional groups and the overall chemical structure of the materials.[28,29] Following the guidelines of the ASTM standard practice for general techniques for obtaining infrared spectra for qualitative analysis (ASTM E1252), the FTIR analysis was conducted by the Materials Engineering Department of the University of Technology, Baghdad, Iraq, using a TENSOR-27 FTIR instrument (Bruker Optics Corporation, United States). After placing the specimen within the device, FTIR analysis was performed on the spectra of polyester composites reinforced with both synthetic and natural fibers.[30]

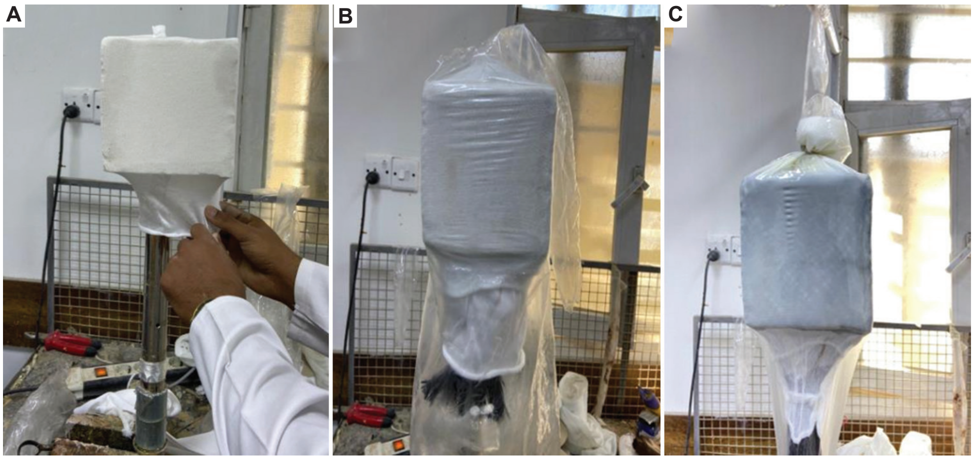

Figure 1. (A-C) The procedures for preparing the specimen for the test using the same manufacturing method for all lamination groups

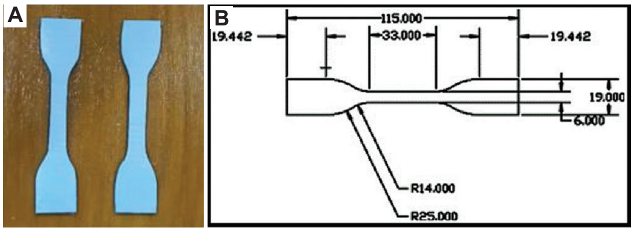

Figure 2. Standard tensile test specimen: (A) pre-test samples and (B) sample measurements in millimeters

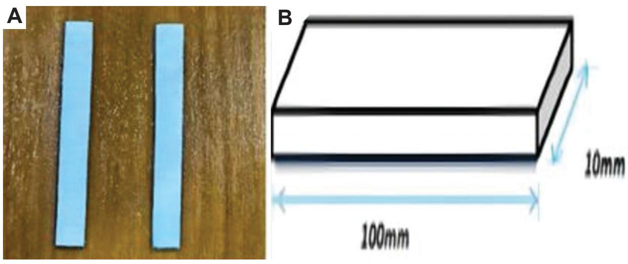

Figure 3. Standard and experimental specimens used in this study: (A) pre-test samples and (B) sample measurements in millimeters. The test provided the flexural strength and modulus of elasticity for each laminated sample.

2.3.6. Force plate testing

Gait analysis was conducted to evaluate the biomechanical performance and movement patterns of a patient using lower limb prosthesis. During this analysis, data were collected regarding the patient's comfort, postural stability, ease of mobility, and any gait abnormalities encountered while using the prosthesis. To assess athletic performance during walking, sprinting, or activities, such as jumping, force plate testing was employed to measure the load-time curve and peak ground reaction forces under different conditions. A 30-year-old male amputee with an osseointegrated prosthesis – measuring 1.60 m in height and weighing 67.7 kg, with a left limb amputation – participated in this study. Informed consent was obtained before participation, and the research was approved by the Ethics Committee of the College of Engineering, Nahrain University. The experimental setup included a force plate system integrated into a wooden deck to capture gait-related data.

2.3.7. F-socket test

The amputee's comfort, mobility, and overall satisfaction with the prosthesis are significantly influenced by interface pressure distribution. Following fabrication, the foot prosthesis was evaluated using the F-Socket. A 30-year-old male patient with a left foot amputation was assessed for interface pressure. A MatScan sensor system (Tekscan, Inc., USA) was employed for this dynamic load evaluation. The sensor was positioned on each side of the socket around the stump and connected to the F-Socket software to record pressure data during movement. This testing procedure was approved by the Ethics Committee of the College of Engineering, University of Misan.

3. Theoretical analysis

3.1. Safety factor

Engineers account for uncertainties, variations in material properties, fluctuating loads, and other factors that may exceed intended operating conditions by utilizing a safety factor.[31]

The maximum attainable safety factor is 15; however, this value decreases to zero when the stress in a specific region exceeds the material's strength. This condition significantly increases the likelihood that the applied stress will surpass the material's strength limit, potentially leading to failure before the intended design life.[32] The theoretical safety factor is determined using the following formula:

$$\text{Theoretical safety factor} = \frac{\text{Experimental failure stress}}{\text{Equivalent von Mises stress}} \tag{I}$$

3.2. Failure index

The probability of material failure under loading conditions is assessed using failure index values. A material is considered to have failed if its failure index is equal to one or above.[33] The failure index, defined as the ratio of von Mises stress to empirical fatigue strength, can be calculated using the following formula:[34]

$$\text{Failure index}\,(k) = \frac{\text{Equivalent von Mises stress}}{\text{Experimental failure stress}} \tag{II}$$

3.3. Fatigue limit

Goodman's empirical equation is commonly used to describe the relationship between mean stress and the fatigue limit:[33]

$$\frac{\sigma_a}{\sigma_e} + \frac{\sigma_m}{\sigma_{ts}} = 1 \tag{III}$$

where:

(i) σ_a is the equivalent of von Mises or amplitude stress
(ii) σ_e is the endurance limit
(iii) σ_m is the mean stress.

3.4. Fatigue ratio

Empirical relationships between fatigue and tensile properties have been established through extensive research over the years. Despite their generalized nature, engineers can still apply these relationships to estimate preliminary fatigue behavior. The fatigue ratio is defined as the ratio of a material's endurance limit to its UTS:[35]

$$\text{Fatigue ratio}\,(R_f) = \frac{\text{Endurance limit}\,(\sigma_e)}{\text{Tensile strength}\,(\sigma_{ts})} \tag{IV}$$

4. Numerical analysis

Finite element analysis is an effective method for validating mechanical results under realistic boundary conditions. This analysis evaluates strain, stress, deformation, and stored energy, often producing results closely matching experimental data.[36,37] Static analysis forms the primary basis for failure assessment. In addition, the expected durability of the prosthetic foot under applied forces can be estimated by calculating the safety load factor based on the maximum stress identified in the failure analysis.[38]

In this study, the ANSYS Workbench 19 software (Ansys, Inc., United States) was used to simulate the performance of the sports prosthetic foot. The composite materials intended for prosthetic manufacturing were characterized, followed by the creation of the foot's geometric model. The model was then meshed by subdividing it into smaller components, boundary conditions were applied, and results were analyzed and compared.[39]

A comprehensive understanding of the mechanical properties of the composite materials is crucial for accurate modeling. Key tensile properties – such as yield strength, Young's modulus, and UTS – were determined experimentally, while Poisson's ratio and density were estimated using the rule of mixtures, as shown in **Table 2**.[40] The foot geometry was developed based on a European patent prototype,[41] with the width adjusted to 90 mm to enhance stability, facilitate smooth running dynamics, and distribute the load more evenly across the foot surface.

The load-bearing capacity of the prosthetic depends on the amputee's weight and movement velocity. Given that the ground reaction force during locomotion is approximately 2.29 – 2.26 times body weight, a 67.7 kg amputee jogging at 3 m/s was selected for the analysis.[42] The prosthetic foot was secured at the top using a pair of holes and subjected to a downward force of 1,554.87 N at the base, as shown in **Figure 4**. Specifically, fixation was achieved through two bolt holes designed to attach component 221 to the socket, while the other end remained unconstrained, as illustrated in **Figure 5A**. For the finite element analysis, the prosthetic foot model was meshed by dividing it into 740 nodes and 662 elements, as shown in **Figure 5B**. Smaller mesh divisions typically result in more accurate and reliable simulation outcomes.

5. Results

5.1. Results of the experimental analyses

Table 3 presents the average thickness of the prosthetic foot in relation to the type of reinforcement used, highlighting comparisons across different volume fractions and the number of layers of support materials. It also includes the modulus-to-density and strength-to-density ratios for all laminated groups reinforced with linen and jute fibers. Among the tested groups, those reinforced with Perlon, glass, carbon, and linen exhibit the highest UTS/density and E/density values, reaching 343.9 MPa.cm^3/g and 9.2 GPa.cm^3/g, respectively.

Figure 6 illustrates the relationship between the modulus of elasticity and the types of reinforcement – carbon, glass, linen, and jute fibers – varying in the number of layers added to the polyester matrix, with Perlon fibers held constant across all lamination specimens. The results show a positive correlation between the number of reinforcing layers and the modulus of elasticity. For instance, Young's modulus increases from 1.3 GPa with three layers of jute fiber to 1.4 GPa with three layers of linen fiber.

Table 2. Properties of the composite materials used

Lamination	Density (g/cm^3)	Poisson's ratio	Yield strength (MPa)
3J	1.14	0.353	25
GL	1.25	0.356	42
CJ	1.125	0.335	52
CGJ	1.26	0.272	141
3L	1.138	0.33	30
CL	1.21	0.321	156
GL	1.2	0.277	94
CGL	1.23	0.3	380

Abbreviations: C: Carbon; G: Glass; J: Jute; L: Linen.

Figure 7 compares the tensile strength of the composite prosthetic foot, indicating that tensile strength also improves with an increasing number of jute and linen fiber layers, while Perlon fibers remain constant. Perlon fiber, which is odorless and considered non-hazardous, serves as a durable base layer for all laminated specimens.

Figure 8 presents the flexural test results for laminated groups reinforced with jute and linen fibers, as well as hybrid laminates incorporating carbon or glass fibers. A consistent correlation is observed between flexural strength and both the type of reinforcement and the number of layers—specifically jute, Perlon, glass, linen, and carbon fibers—across all lamination specimens.

Figure 9 illustrates the flexural modulus of hybrid laminates incorporating glass and carbon fiber layers, as well as laminates reinforced solely with linen and jute fibers. **Figure 10** presents the results of the hardness test, which was used to evaluate the surface hardness of laminates composed of glass, carbon, and natural fibers (**Figure 10**).

Figures 11 and **12** present the results of the fatigue stress tests, including the total number of cycles endured by each laminate until fracture. **Figure 13** illustrates the fatigue limits associated with different types of reinforcements. In addition, **Table 4** provides a detailed overview of the measurement locations and corresponding interface pressure settings. **Figure 14** illustrates the force curves over time for the left foot, represented by the red and green lines. The outcomes of the gait cycle analysis are detailed in **Table 5.**

Figure 15 displays the infrared spectrum of 100% unsaturated polyester. **Figure 16A** shows the FTIR spectrum of composite specimens reinforced with three layers of jute fibers, where the peaks corresponding to the C–O and C=O stretching vibrations appear at 1,433.9 cm^{-1} and 1,721.9 cm^{-1}, respectively. **Figure 16B** presents the FTIR spectrum of specimens reinforced with linen fibers.

In **Figure 16C,** an increase in the intensity of the C=O peak at 1,721.46 cm^{-1} is observed after incorporating hybrid laminates composed of jute and glass fibers. **Figure 16D** shows the FTIR spectrum following the addition of hybrid laminates with glass and linen fibers. Similarly, **Figure 16E** displays the C=O intensity at 1,720.7 cm^{-1} after the addition of hybrid laminates made from jute and carbon fibers.

A significant increase in C=O peak intensity is recorded at 1,722.9 cm^{-1}, as illustrated in **Figure 16F**, after the incorporation of hybrids composed of linen and carbon fibers. In **Figure 16G**, the C=O band is observed at 1,721 cm^{-1} when jute, carbon, and glass fibers are combined. Finally, **Figure 16H** shows a further increase in C=O band energy to 1,722.28 cm^{-1} in hybrids reinforced with linen, carbon, and glass fibers.

Table 3. Physical characteristics of the composites

Lamination	Thickness (mm)	Volume fraction (%)	Modulus-to-density ratio (GPa.cm³/g)	Strength-to-density ratio (MPa.cm³/g)
3J	3.5	22.07	1.14	24.4
CJ	4.4	23.25	2.66	57.7
GJ	5	29.29	1.92	52
CGJ	5.5	50.49	3.015	62.06
3L	2	26.3	1.2	30.7
CL	3.5	34	4.66	144.6
GL	3.8	47	4.95	97.5
CGL	4	60.4	9.2	343.9

Abbreviations: C: Carbon; G: Glass; J: Jute; L: Linen.

Table 4. Interface pressure in various regions

Area	Anterior	Lateral	Posterior	Medial
Interface pressure	140	280	240	170

Table 5. Gait cycle results

Parameter	Value
Total steps per 8 min	522
Cadence (steps/min)	88
Step period (s)	0.8
Length of right step (cm)	42.2
Length of left step (cm)	45.3
Step width (cm)	20.1
Stride length (cm)	86.2
Total stride per 8 min (cycles)	255
Total walking length per 8 min (m)	220
Total walking length per 1 min (m)	37
Walking speed (m/s)	0.8

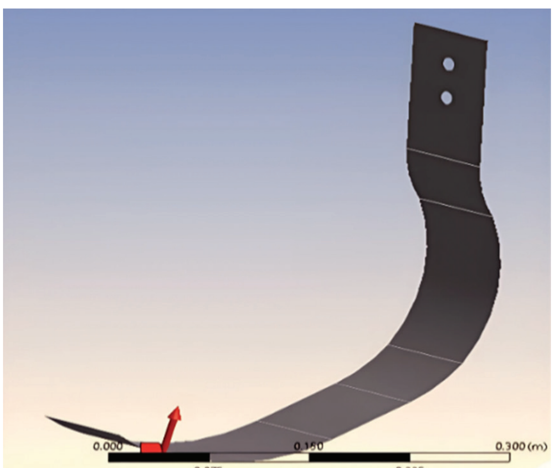

Figure 4. Position of the applied load. The prosthetic foot is secured at the top using a pair of holes and subjected to a downward force of 1,554.87 N at the base.

5.2. Numerical analysis results

Figure 17A shows the equivalent stress results from simulations of prosthetic feet reinforced with hybrid laminates containing Perlon, glass, or carbon fibers, as well as laminates reinforced

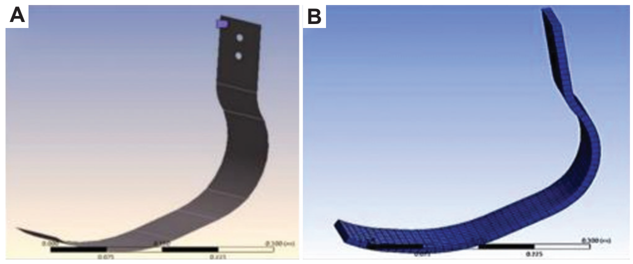

Figure 5. Position of boundary conditions and meshing process. (A) Application of boundary conditions and (B) meshing of the prosthetic foot. The foot is fastened at the top through two bolt holes designed to attach component 221 to the socket. For simulation, the prosthetic foot is divided into 740 nodes and 662 parts.

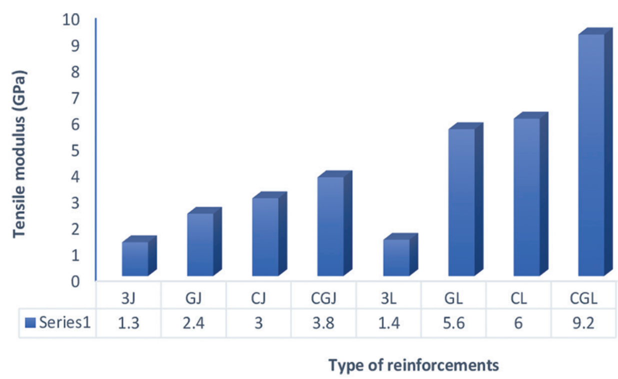

Figure 6. Number of fiber layers versus tensile modulus
Abbreviations: C: Carbon; G: Glass; J: Jute; L: Linen.

Figure 7. Number of fiber layers versus tensile strength
Abbreviations: C: Carbon; G: Glass; J: Jute; L: Linen.

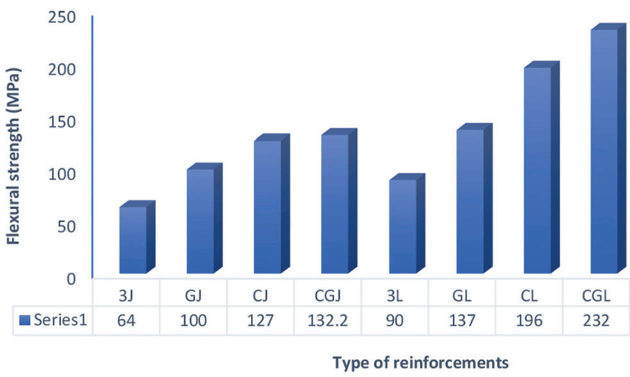

Figure 8. Flexural strength results for laminates reinforced with jute and linen fibers, along with hybrid laminates incorporating carbon or glass fibers

Abbreviations: C: Carbon; G: Glass; J: Jute; L: Linen.

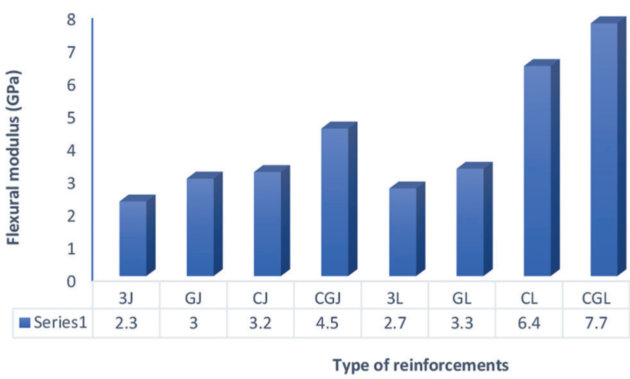

Figure 9. Flexural modulus results for hybrid laminates reinforced with glass and carbon fiber layers, along with laminates composed solely of linen and jute fibers

Abbreviations: C: Carbon; G: Glass; J: Jute; L: Linen.

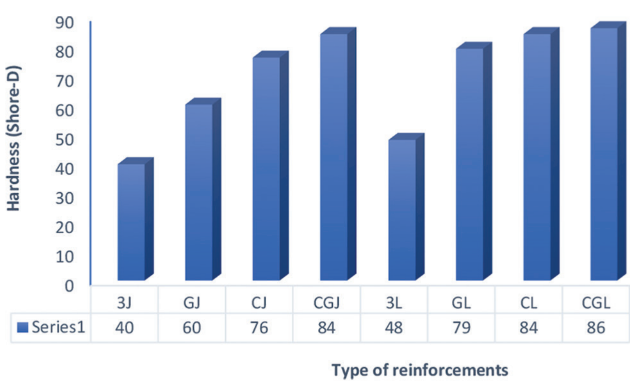

Figure 10. Number of fiber layers versus hardness

Abbreviations: C: Carbon; G: Glass; J: Jute; L: Linen.

solely with jute and linen fibers. **Figure 17B** presents contour maps illustrating the distribution of von Mises stresses, including the expected locations and magnitudes of stress concentrations.

Figure 18A displays the equivalent elastic strain for both natural fiber composites and hybrid laminates reinforced with carbon or glass fibers, modeled under running boundary conditions for athletic prosthetic feet. **Figure 18B** provides contoured visualizations of the equivalent elastic strain distribution for each group evaluated in the study.

Figure 19A illustrates the overall deformation of a prosthetic foot made from polyester reinforced with natural and hybrid fibers, including carbon and glass. The results show the distribution of deformation within the polyester matrix composite and highlight how both the type of reinforcement and the load location affect the expected position and magnitude of deformation. **Figure 19B** presents the deformation patterns in natural fiber laminates incorporating glass and carbon fibers.

Figure 20A presents the total strain energy of the prosthetic foot, influenced by the type and number of reinforcement layers, as well as the mechanical strength of the materials used. **Figure 20B** provides a contoured visualization of the strain energy distribution for each group included in this study.

Figure 21 provides a contour plot showing the general layout of safe and high-risk zones across the simulated composite foot structure.

5.3. Theoretical analysis results

The theoretical safety factor was calculated to comprehensively assess the performance of the newly proposed composite materials. The results, obtained using Equation I, are shown in **Figure 22. Figure 23** illustrates the relationship between the failure index and the type of reinforcement used in this study. In addition, **Figure 24** illustrates the relationship between the type of reinforcement and the fatigue ratio.

6. Discussion

6.1. Experimental work

Based on **Table 3,** the specimens' weight and thickness were measured using digital Vernier calipers (Verniershop, USA) and precision weighing instruments (Verniershop, USA). Volume fractions were calculated using the rule of mixtures. Specimen weights were further confirmed using the Archimedes method, and densities were determined according to the ASTM D792 standard test method for the density and specific gravity (relative density) of plastics by displacement.[43] Among the tested groups, the hybrid laminate reinforced with carbon, glass, and jute fibers is the heaviest, while the multi-layered laminate composed of Perlon and linen fibers exhibits the lowest thickness.[44]

Table 3 shows that absorption ability increases with the number of fiber layers. The results for fiber volume fraction support this observation, with the highest volume percentage found in the specimens reinforced with glass, carbon, and linen fibers, which is consistent with the findings of Jweeg *et al.*[45]

In addition, **Table 3** shows that the strength-to-density and modulus-to-density ratios increase with the number of linen or jute fiber layers. When glass and carbon fibers are incorporated into the laminates, these ratios are further enhanced, performing better than laminates composed solely of natural fibers.[46] This improvement is attributed to the higher tensile strength of glass fibers, while laminates reinforced with carbon fibers are lighter

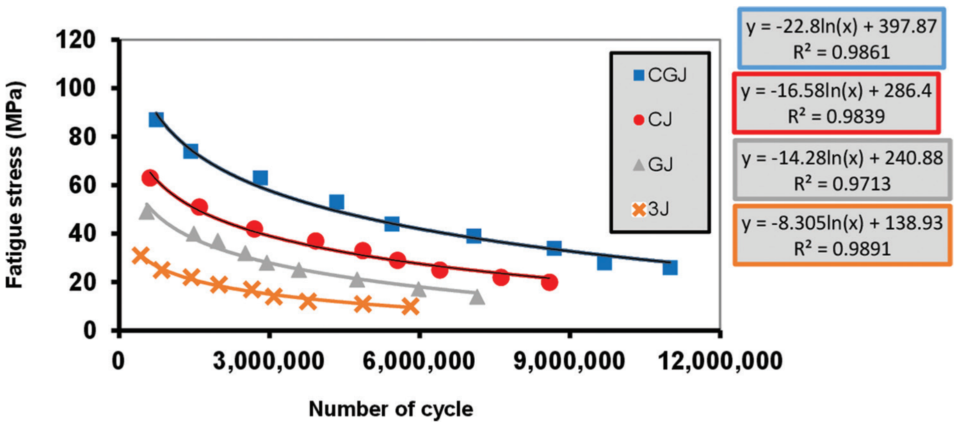

Figure 11. Fatigue stress of polyester matrix reinforced with jute fibers.
Abbreviations: C: Carbon; G: Glass; J: Jute.

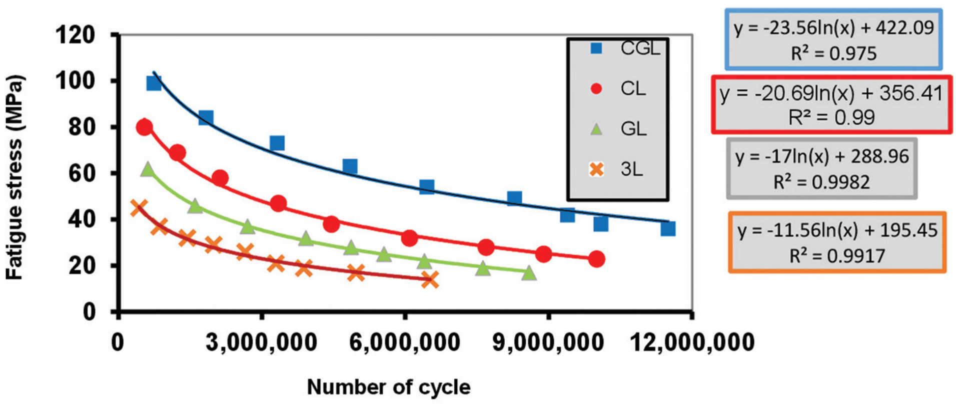

Figure 12: Fatigue stress of polyester matrix reinforced with linen fibers.
Abbreviations: C: Carbon; G: Glass; L: Linen.

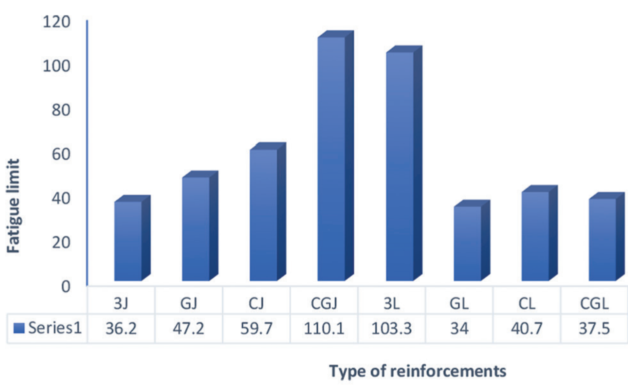

Figure 13. Fatigue limit of polyester matrix composites with different types of reinforcement.
Abbreviations: C: Carbon; G: Glass; J: Jute; L: Linen.

than those with glass, resulting in even higher modulus-to-density and strength-to-density ratios for carbon fiber laminates. These results are consistent with the findings of Callister and Rethwisch.[47] In contrast, laminates reinforced with three layers of jute fibers exhibit the lowest ratios among all laminate categories.

As shown in **Figure 6,** the tensile properties are significantly influenced by the type of reinforcement and the matrix material used. The slope of the curves in the elastic region is used to determine the modulus of elasticity for each group.[48] The values of Young's modulus increase when two layers of glass fibers are added to composites laminated with natural fibers. In laminates reinforced solely with jute and linen fiber layers, the improvements are 72.4% and 70%, respectively. These differences are attributed to the higher elastic modulus of glass fibers compared to Perlon, jute, and linen fibers.

In addition, the modulus of elasticity of glass fiber composites increases with a higher fiber volume fraction.[49] This increase in modulus is primarily due to the remarkable strength and rigidity of carbon fibers. As the number of reinforcing layers increases, the fibers further stiffen the composite, thereby enhancing the modulus of elasticity.[50] **Figure 6** demonstrates a clear increase in Young's modulus with the incorporation of carbon and glass fibers, identifying this configuration as the best-performing laminate. This enhancement is attributed to the inherently higher Young's modulus of carbon and glass fibers compared to natural fibers. Notably, reinforcing linen fiber with woven carbon and glass fibers improves mechanical performance using fewer layers, resulting in a lightweight and thin composite material suitable for prosthetic foot applications.[51]

Figure 7 illustrates that tensile strength increases with the fiber volume percentage, confirming that the strength of the composite improves as the number of fiber layers increases. The tensile

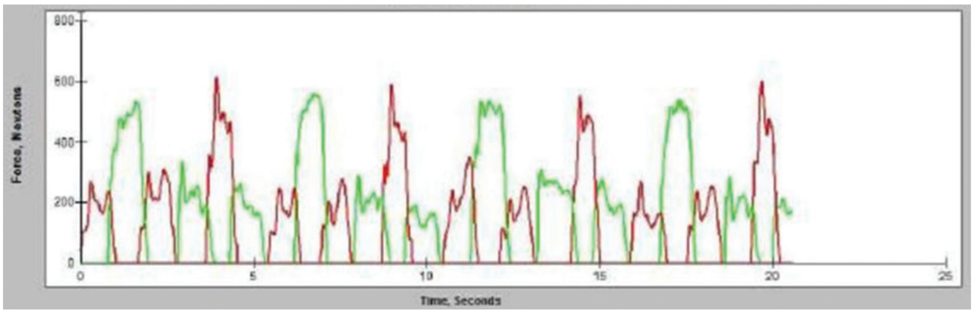

Figure 14. Force curves over time

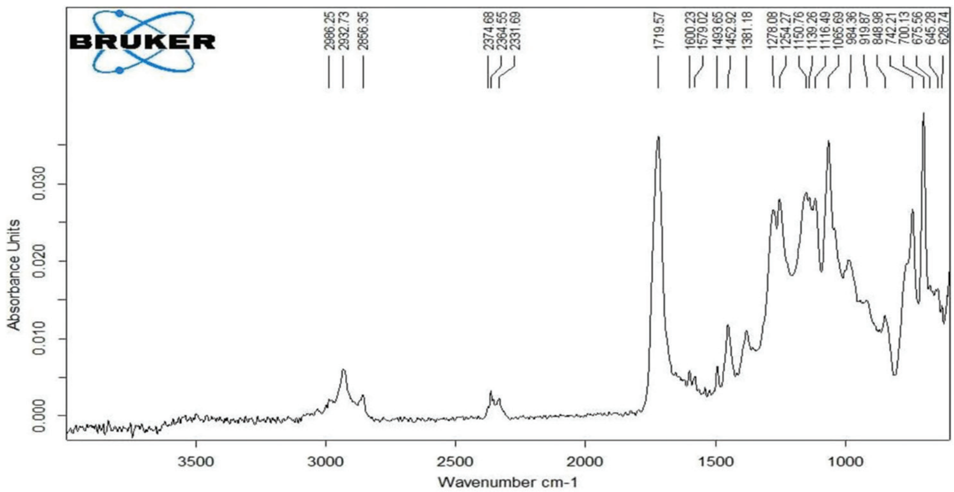

Figure 15. Infrared spectrum of 100% unsaturated polyester

strength of composite specimens reinforced with three layers of jute fibers and a consistent Perlon layer is 29 MPa. In contrast, specimens reinforced with three layers of linen fibers and a fixed Perlon layer exhibit a higher tensile strength of 35 MPa. In terms of mechanical performance, laminates composed of linen fibers demonstrate superior tensile strength compared to those with jute fibers, due to the inherently better tensile properties of linen. This trend remains consistent even when evaluating hybrid laminates containing carbon or glass fiber layers.[52]

In hybrid laminates, tensile strength reaches 50 MPa for specimens reinforced with three layers of jute and two layers of glass fibers, and up to 117 MPa for laminates with three layers of linen and two layers of glass fibers, when combined with natural and Perlon fibers. These findings highlight that modifying the type and quantity of reinforcements has a significant impact on tensile properties.

Several factors influence the strength and performance of composite materials, including the degree of fiber-matrix adhesion, the fiber-to-resin ratio, the mechanical properties of both fiber and matrix, and the manufacturing process.[53]

In hybrid laminates, tensile strength increases to 65 MPa for specimens reinforced with jute and carbon fiber layers, and reaches 175 MPa for laminates reinforced with linen and carbon fiber layers, when combined with natural and carbon fibers.[54] A comparison of the laminates reveals that the lamination reinforced with three layers of jute fibers, along with one layer of each carbon and glass fibers, and bonded with polyester resin, exhibits exceptional mechanical strength of 78.2 MPa. This improvement is attributed to the incorporation of carbon and glass fibers, which enhance load transfer from the polyester matrix to the reinforcement fibers, thereby improving the overall structural integrity of the composite.[55]

In addition, hybrid laminates incorporating glass, linen, and carbon fiber layers demonstrate the highest tensile strength of 423 MPa among all tested groups. Compared to laminates reinforced solely with linen fibers, those incorporating linen and carbon fiber layers show a 58.6% increase in tensile strength, while specimens reinforced with linen and glass fiber layers exhibit an even greater increase of 72.3%. These findings highlight that modifying the type of reinforcement and increasing the number of layers significantly enhances the fiber volume percentage within the cross-sectional area of the composite, which in turn boosts its tensile strength. This improvement is primarily due to the superior mechanical properties of the fibers compared to the polymer matrix.[49]

Figure 8 shows that, while the number of Perlon layers remains constant, the flexural strength increases with the number of fiber layers. Laminates reinforced with three layers of jute fibers and constant Perlon exhibit a flexural strength of 64 MPa, whereas those with three layers of linen fibers reach 90 MPa. The flexural strength of the linen-reinforced laminate is 28.8% higher than that of the jute-reinforced laminate. This improvement is attributed to the higher fiber volume fraction

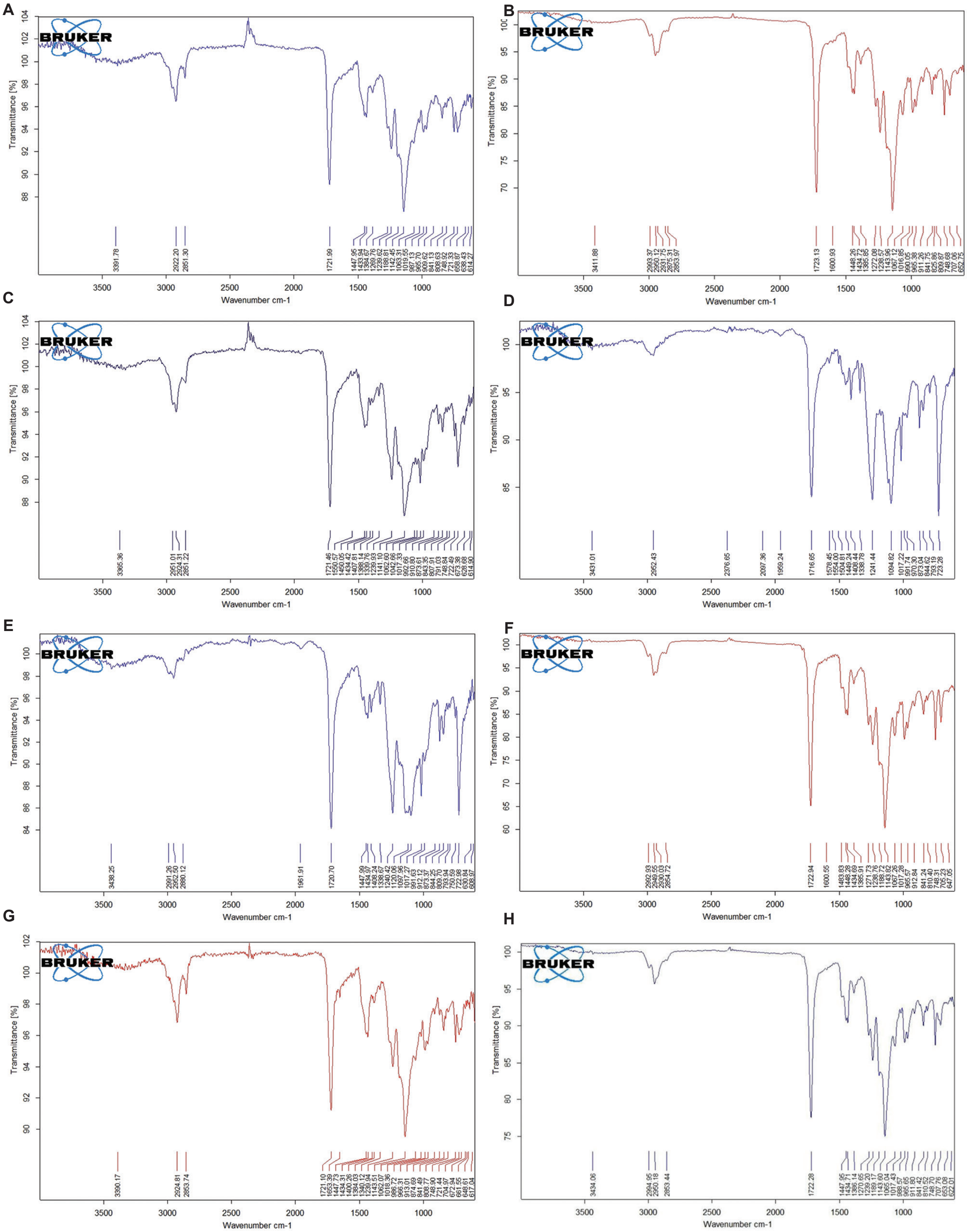

Figure 16. Fourier transform infrared spectra for laminates reinforced with: (A) three jute fiber layers; (B) three linen fiber layers; (C) glass and jute fibers; (D) linen and glass fibers; (E) carbon and jute fibers; (F) linen and carbon fibers; (G) carbon, glass, and jute fibers; and (H) carbon, glass, and linen fibers. Polyester composite bands are shown in detail both before and after the addition of natural fibers at different layer numbers, with the number of Perlon layers kept constant.

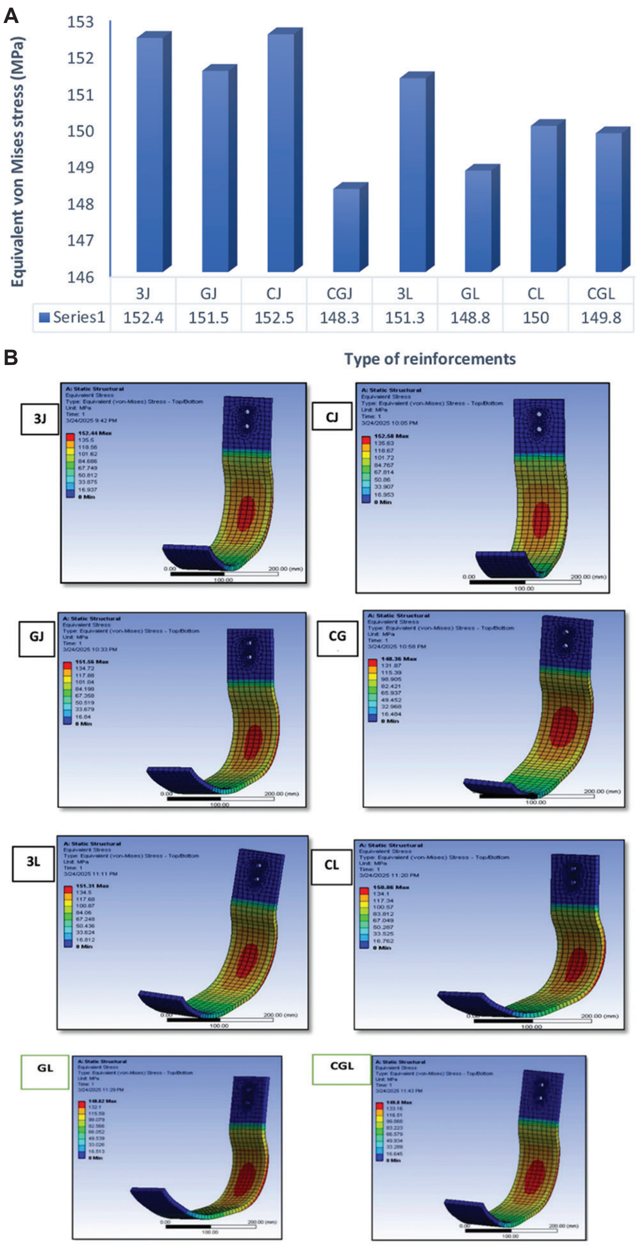

Figure 17. Equivalent stress analysis: (A) Equivalent von Mises stress results and (B) contour maps illustrating the distribution of von Mises stresses, including the expected locations and magnitudes of stress concentrations Abbreviations: C: Carbon; G: Glass; J: Jute; L: Linen.

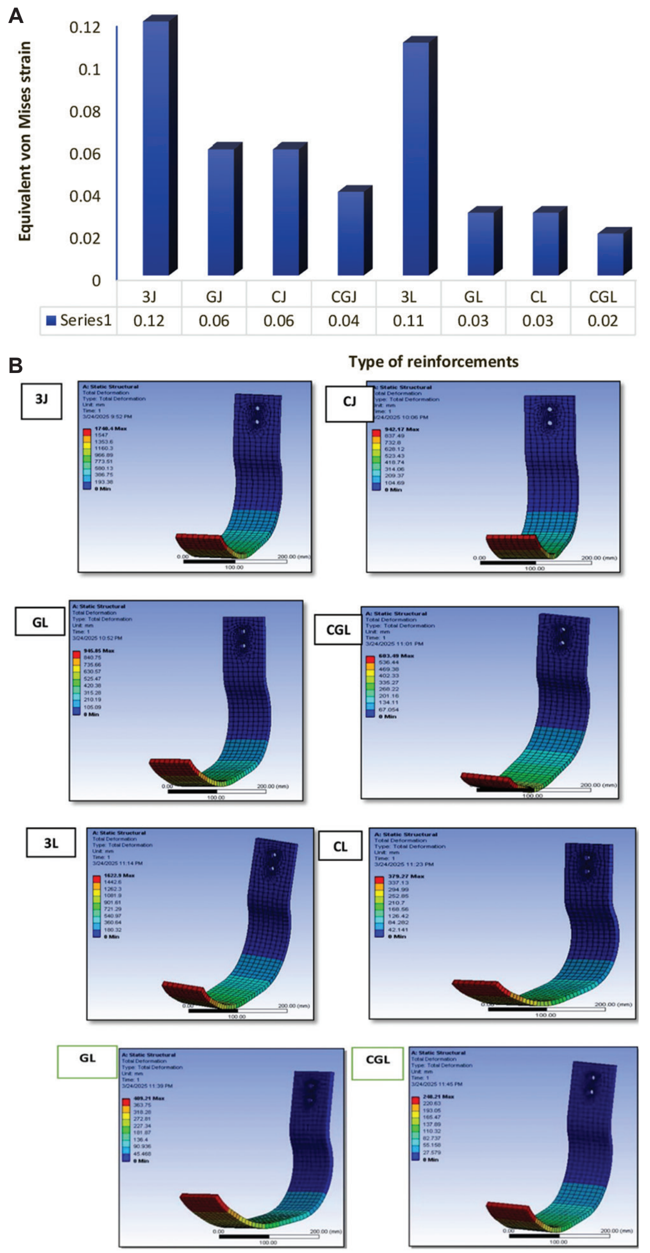

Figure 18. Equivalent strain analysis: (A) Equivalent von Mises strain and (B) contoured visualization of the equivalent elastic strain distribution for each laminated group evaluated in the study Abbreviations: C: Carbon; G: Glass; J: Jute; L: Linen.

of linen, which offers greater resistance to bending and twisting stresses than the polymer matrix.[45]

The flexural strength of laminates reinforced with three layers of jute fibers increases by 36%, while those reinforced with three layers of linen fibers combined with glass fiber show a 34.3% increase. These findings underscore the significant role of fiber properties in influencing flexural strength. The addition of glass fibers significantly enhances the flexural performance of hybrid laminates. Overall, changing the type of reinforcement has a significant impact on the flexural properties of composite materials.[56]

The flexural strengths of laminates reinforced with carbon and linen fiber layers and those with carbon and jute fiber layers are 196 MPa and 127 MPa, respectively. This demonstrates that the introduction of carbon fiber layers, while maintaining layers of jute, linen, and Perlon fibers, significantly increases the flexural strength. Carbon fibers possess superior mechanical properties compared to jute, linen, and even hybrid laminates reinforced with natural and glass fibers.[57]

Flexural strength is crucial for prosthetic foot, as it enables the composite to support body weight and extreme mobility. Thus, incorporating carbon and glass fiber layers enhances the resistance to bending loads in laminated materials. Among the tested groups, the laminate reinforced with Perlon, carbon, glass, and linen fibers exhibited the highest flexural strength under constant Perlon fiber content. When hybrid linen fibers

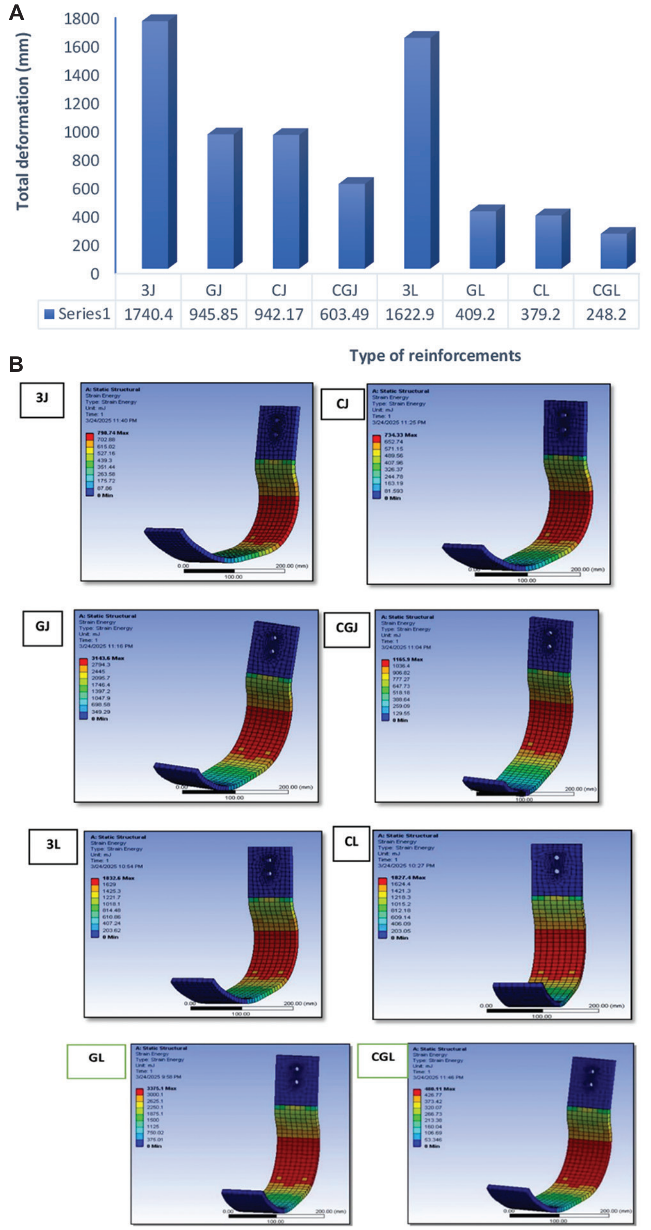

Figure 19. Total deformation analysis: (A) Total deformation results and (B) simulation of the effect of strengthening fibers on total deformation, with a contoured visualization of deformation for each laminate group evaluated in the study Abbreviations: C: Carbon; G: Glass; J: Jute; L: Linen.

were used instead of jute, the flexural strength reached 232 MPa for laminates reinforced with carbon, glass, and linen fiber layers, compared to 132.2 MPa for those reinforced with carbon, glass, and jute fiber layers. Consequently, the addition of carbon and glass fibers significantly improves the flexural strength of the group.[47]

Figure 9 shows that the flexural modulus increases with the number of fiber layers. In addition, it reveals that the flexural modulus of laminates reinforced with glass and carbon fiber layers increases compared to those reinforced solely with natural fibers and a comparable number of Perlon layers.[45] This finding indicates that modifying the type of reinforcement while keeping the Perlon fiber constant increases the flexural modulus.

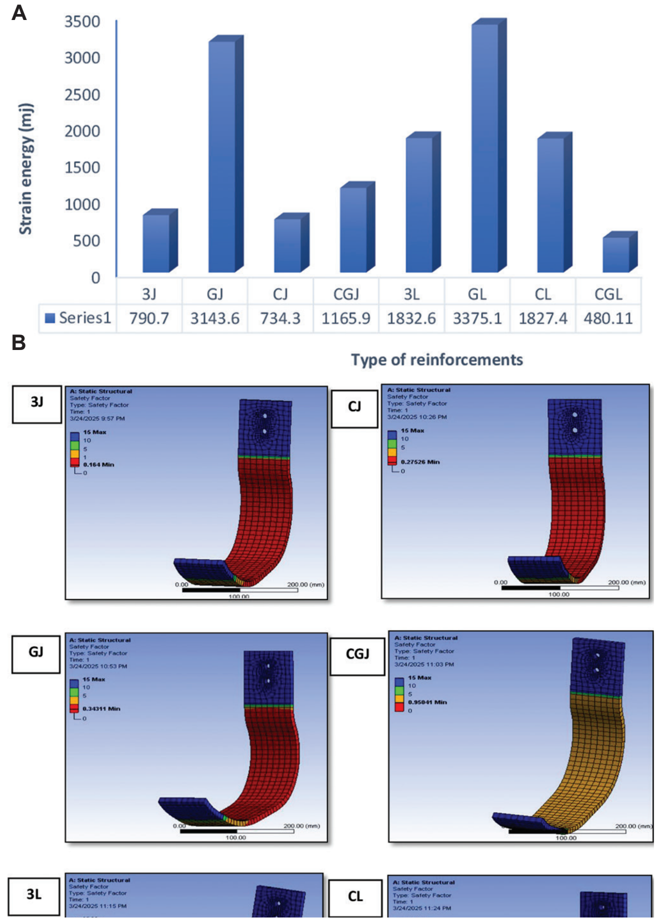

Figure 20. Strain energy analysis: (A) Strain energy results and (B) simulation of the effect of strengthening fibers on strain energy, with a contoured visualization of strain energy distribution for each laminate group evaluated in the study Abbreviations: C: Carbon; G: Glass; J: Jute; L: Linen.

Specimens with three layers of jute fibers and consistent Perlon fibers show a flexural modulus of 2.3 GPa, whereas those with three layers of liner fibers show 2.7 GPa. The modulus further improves in laminates reinforced with glass and linen fibers, as well as in those reinforced with glass and jute fibers, suggesting that glass fibers contribute more significantly to flexural modulus than the resin matrix. Consequently, the flexural modulus of the laminated composite specimens increases. This enhancement in flexural properties is also attributed to improve interfacial bonding between the fiber and polymer matrix.[58]

Moreover, the bending test shows that the material's resistance to stress increases with the number of carbon fiber layers. The percentage of improvement in carbon fiber-containing laminates increases by 28.1% and 57.8% for laminates reinforced with carbon and jute fiber layers, and those reinforced with carbon and linen fiber layers, respectively. This disparity may be attributed to the superior longitudinal and shear strengths of carbon fibers compared to other fibers.[47] In this test, laminates reinforced with natural, carbon, and glass fibers demonstrate the best overall performance. In addition, hybrid laminates composed of glass, linen, and carbon fibers exhibit

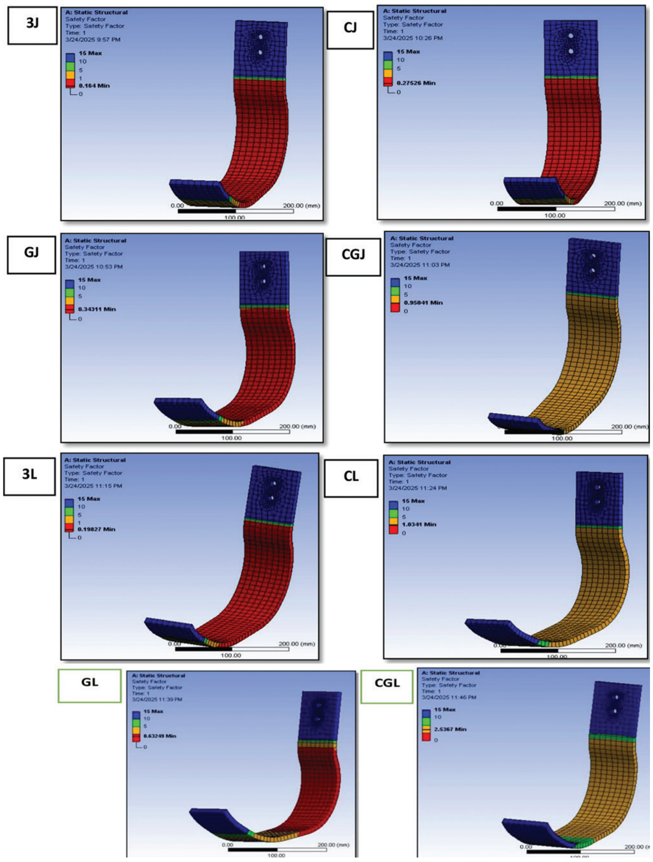

Figure 21. Contour plot showing the general layout of safe and high-risk zones across the simulated composite foot structure
Abbreviations: C: Carbon; G: Glass; J: Jute; L: Linen.

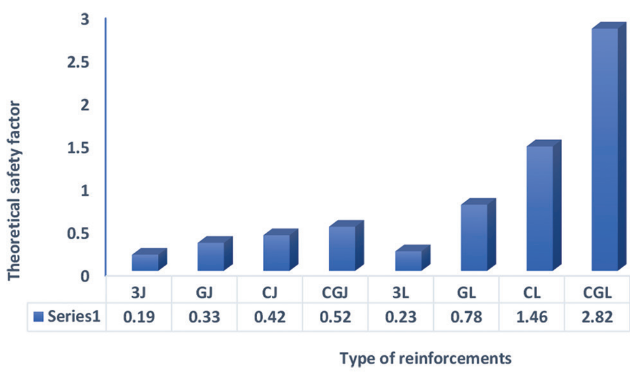

Figure 22. Theoretical safety factor distribution for prosthetic foot laminates
Abbreviations: C: Carbon; G: Glass; J: Jute; L: Linen.

the highest flexural modulus value. By introducing artificial fiber layers while maintaining constant natural and Perlon fiber layers, the flexural modulus increases from 4.5 GPa in laminates reinforced with three layers of jute and one layer each of carbon and glass fibers to 7.7 GPa in those reinforced with three layers of linen and one layer each of carbon and glass fibers. This improvement is attributed to the artificial fiber layers slipping more easily than natural fiber layers when the composite is subjected to load. Furthermore, compared to weaker natural fibers, glass fiber laminates demonstrate superior interfacial bonding and increased strength with each additional layer that crosses the interface.[59]

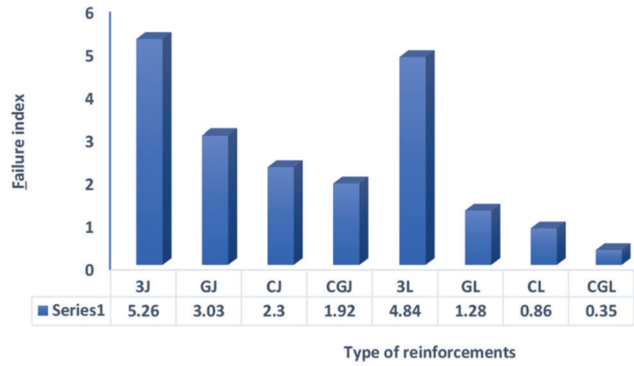

Figure 23. Failure index of prosthetic foot laminates
Abbreviations: C: Carbon; G: Glass; J: Jute; L: Linen.

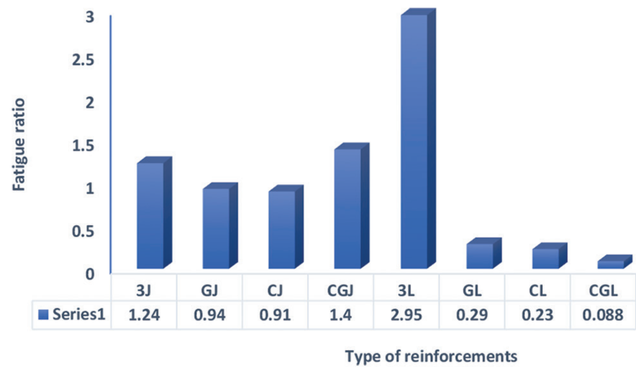

Figure 24. Fatigue ratio of prosthetic feet laminates
Abbreviations: C: Carbon; G: Glass; J: Jute; L: Linen.

As shown in **Figure 10**, the results are generally similar, with only modest variations between groups. The hardness of a composite significantly increases with the number of layers in the material. The relationship between hardness and the type and quantity of reinforcements – such as carbon, glass, linen, jute, and Perlon fibers – remains consistent across all laminated composites. The composite's hardness values are 40 Shore-D for laminates reinforced with three jute fiber layers and 48 Shore-D for those with three linen fiber layers. Increasing the number of layers enhances the composite's hardness, as it is influenced by the proportional volumes of fiber and matrix.[60] According to **Figure 10**, in laminates combining natural fibers with glass fibers, the addition of glass layers improves hardness values while the layers of jute, linen, and Perlon fibers remain constant. The increased hardness observed in hybrid composites indicates a strong bond between the reinforcing fibers and the matrix. When stiff and hard reinforcement fibers are used, the composite's stiffness and hardness improve correspondingly. The hardness reaches 60 Shore-D for laminates reinforced with glass and jute fibers and 79 Shore-D for those reinforced with glass and linen fibers.[61]

The composite's hardness increases from 76 Shore-D in laminates reinforced with jute and carbon fibers to 84 Shore-D in those reinforced with linen and carbon fibers when carbon fiber is combined with fixed jute, linen, and Perlon fiber layers. This improvement is attributed to the superior mechanical properties of carbon fiber compared to polymers. The addition of carbon fiber enhances the hardness relative to laminates reinforced solely with linen or jute fibers, as carbon fibers are stronger and more structurally complex. Hardness increases by 28% and 47.3% for laminates reinforced with carbon and linen fibers and those reinforced with carbon and jute fibers, respectively.[62] Laminates reinforced with carbon and glass fibers exhibit the highest hardness values, as these fibers are more resilient to external stresses than the polyester matrix. This may be due to the influence of fiber volume ratio and elastic modulus on hardness. Notably, hybrid laminates composed of glass, carbon, and linen fibers achieve the highest hardness value of 86 Shore-D. According to the Shore-D hardness scale, this suggests that the material is considered hard. However, to prevent cracking upon ground contact, a rubber sleeve is recommended for the prosthetic foot.[63]

In this study, a fatigue test was conducted on all lamination groups to evaluate the time required for the samples to fail. **Figures 11** and **12** illustrate the fatigue S–N curves derived from the experimental results. The data show that as fatigue failure stress decreases, the number of fatigue failure cycles increases, indicating that hybrid materials enhance fatigue life and strength. These curves are obtained using a logarithmic approach to fit the fatigue test data.[64] The stress level under which a material can sustain infinite loading cycles without failure is referred to as the fatigue limit or endurance limit. The stress level at which specimens do not fail after a pre-defined number of cycles was identified through testing.[65]

Improved fatigue endurance results from the artificial fiber reinforcements' different elastic modulus compared to the natural reinforcements, as shown in **Figure 13**. This improvement may be attributed to the strength of the fiber–matrix bond and the enhancement process, which facilitates smooth contact between the matrix and the reinforcements.[66] The incorporation of glass and carbon fibers improves the fatigue performance of natural fiber composites. However, the presence of carbon fiber in the laminates alters the fatigue durability, as carbon fibers possess a higher modulus of elasticity and greater resistance to crack propagation than the matrix. As a result, natural hybrid specimens withstand higher cyclic loads. The fatigue strength of a material is influenced by its stiffness, and materials with a higher modulus of elasticity generally exhibit higher fatigue strengths. Since the fatigue limit is often proportional to the UTS, materials with greater tensile strength tend to have higher fatigue limits. Among the tested laminates, those reinforced with carbon, glass, and jute fibers demonstrate the highest fatigue life. These results indicate that the fatigue ratio of the proposed hybrid model is lower than that of the other laminates.[67]

A novel socket was fabricated using laminates reinforced with carbon, glass, and linen fibers and was attached to a J-shaped prosthetic foot, as this lamination group demonstrates superior mechanical and compatibility performance compared to the other groups, with both theoretical and numerical results supporting the experimental findings. The pressure at the interface between the patient's stumps and the socket was then measured using the F-Socket device. As shown in **Table 4,** the highest interface pressure is 280 kPa at the lateral part, followed by 240 kPa at the posterior part. Pressure on the lower leg – particularly medial and anterior tibial areas – decreases during movement as the posterior and lateral muscles become more engaged. These results are consistent with the findings of Sarah *et al.*,[68] who utilized widely available prosthetic feet.

The ground reaction forces applied to the base of the prosthetic foot at mid-stance, heel contact, and toe-off during the gait cycle were calculated using a force plate. By analyzing the peak forces and moments at heel contact and toe-off, it is possible to assess the load on the implant's abutment and evaluate its functionality and stability throughout the gait cycle. **Figure 14** illustrates the dynamic stress experienced by the prosthetic foot during different phases of the gait cycle, with a maximum force of 610 N observed.[69] Important insights into implant loading patterns are obtained by analyzing ground reaction forces and moments on the implant's abutment using force plate measurements recorded throughout the individual's gait cycle. The amputee takes a 20-min rest after walking for 8 min.

According to **Table 5**, the average walking speed is 0.8 m/s, which aligns with previous studies. For instance, Tommy *et al.*[70] report that the average walking speed for men aged 30 – 39 ranges from 0.48 to 1.28 m/s, and the speed observed in this study falls within that range. A typical walking pace is between 70 and 90 steps/min, and this participant walks comfortably within that range. In addition, 95 steps/min is considered a moderate pace, and 120 steps/min is a fast pace.

Verne *et al.*[71] state that the range of steps per minute is 70 – 130. In this study, the mean step rate is 88 steps/min, falling within the typical range. These findings suggest that amputees can walk normally while wearing a prosthetic foot made from composites reinforced with carbon, glass, and linen fibers. Physiological criteria, such as pulse rate, serve as indicators of fatigue in ergonomic studies. During relaxed walking, pulse rates remain low. After walking activities, the participant's comfort level is assessed based on pulse rates in the low (75 – 100 beats/min) and moderate (100 – 125 beats/min) ranges.[72]

Figure 15 shows an absorption peak at 2856.3 – 2986 cm^{-1} corresponding to the stretching of C–H bonds. The ester group and polyester formation are confirmed by the peak at 1719.57 cm^{-1}, which is attributed to C=O stretching, while the peaks at 1600 cm^{-1} and 1579 cm^{-1} correspond to C=C bond twisting and the aromatic ring. The peak at 1116 – 1254 cm^{-1}, associated with C–O bond bending, further confirms the presence of the ester group.[73] To detail the polyester composite bands before and after adding natural fibers at varying layer numbers, while keeping the number of Perlon layers constant, FTIR analysis indicates no interfacial breakdown between the polyester matrix and natural fibers. This suggests that the matrix securely holds the fibers and that no cross-linking occurs within the samples.[74] Absorption peaks for C–O and C=O appear at 1433 cm^{-1} and 1721 cm^{-1}, respectively (**Figure 15**). The degree of peak shifting correlates with the type of reinforcement, reflecting enhanced molecular interactions between the resin and jute fibers.[40]

Figure 16 displays the FTIR spectra of specimens reinforced with linen fibers. The C=O and C–O bands exhibit absorption peaks at 1723 cm^{-1} and 1448 cm^{-1}, respectively. The presence of these peaks is attributed to the addition of linen fibers to the polyester resin, which enhances molecular interactions between the polymer matrix and the fibers.[71] **Figure 16** shows that the peak amplitude increases linearly with the number of reinforcement layers, reflecting the growing molecular bonding between the resin and glass fibers.

Figure 16 displays the FTIR spectra after adding hybrid laminates composed of glass and linen fibers, demonstrating the intensity of the C=O peak at 1716 cm^{-1}. This indicates enhanced molecular interactions between fibers and resin, resulting in improved miscibility.[72] **Figure 16** shows the C=O band at 1720cm^{-1} following the addition of hybrid laminates reinforced with jute and carbon fibers. After incorporating hybrid laminates of linen and carbon fibers, the C=O intensity shifts slightly to 1722 cm^{-1} (**Figure 16**), reflecting molecular bond formation between the polyester matrix and reinforcement fibers. The absence of new peaks and the similarity of peak intensities to those of the polyester matrix composites indicate improved miscibility in the laminated specimens.[75]

Polyester composites reinforced with carbon fiber did not exhibit matrix failure except at the fiber sites, as shown in **Figure 16,** indicating strong adhesion between the matrix and fibers.[74] None of these samples exhibit distinctive peaks when natural reinforcements are combined with synthetic fibers, such as carbon and glass, and no significant peak shifts are observed. This suggests that the bonds between composite components are physical in nature, reflecting improved miscibility within the lamination groups. Furthermore, the absence of residual monomers or unwanted byproducts reduces the risk of toxicity, allergic reactions, or discomfort when in contact with human tissue.[72]

6.2. Numerical analysis results

Equivalent von Mises stresses and strain, safety factor, overall deformation, and strain energy were all analyzed to evaluate the functional response of an athlete's J-shaped prosthetic foot under running forces. The effects of different boundary conditions on various lamination models were assessed to determine the optimal configuration.

Figure 17 illustrates that equivalent stress in nearly all laminates decreases as the number of fiber layers increases, due to the bonding and reinforcing effects between the matrix and fibers.[62] Composites reinforced with jute fibers demonstrate the highest equivalent stress compared to laminates reinforced with linen fibers, which is attributed to the superior mechanical properties of linen fibers over jute fibers.[49] Overall, laminates reinforced with glass fibers exhibit significantly lower stress than those reinforced solely with natural fibers.[55] Interestingly, hybrid laminates composed of carbon and natural fibers show similar results. Due to linen fiber's stronger mechanical properties, laminates reinforced with linen and carbon fibers demonstrate better performance compared to those reinforced with jute and carbon fibers.[70]

Compared to laminates composed of natural fibers, hybrid laminates reinforced with carbon and glass fibers exhibit the lowest von Mises stress – 148.3 MPa for composites reinforced with carbon, glass, and linen fibers, and 149.8 MPa for those with carbon, glass, and jute fibers. This variation arises because equivalent stress depends on the material type, the user's body size, and the applied force. The inconsistencies in the results arise from variations in the user's body dimensions – particularly thickness – which change with the number of layers and are inversely related to equivalent stress, given a constant applied force. Laminates reinforced with glass fibers perform worse than those with carbon fibers, primarily due to differences in fiber thickness. Consequently, laminates with linen fibers yield better results than those with jute fibers. Numerical analysis examines the stresses generated within different components of the foot caused by pressure buildup between the foot, muscles, and body weight during movement.[22]

Figure 18A shows that strain decreases as the number of reinforcement layers increases, although the reduction is not significant. In hybrid laminates reinforced with glass fibers, strain values are lower compared to those reinforced solely with natural fibers. Hybrid laminates reinforced with glass and linen fibers exhibit the lowest strain value at 0.02, while those with glass and jute fibers exhibit a strain of 0.06. The addition of carbon fiber further reduces strain. For example, strain decreases from 0.063 in laminates reinforced with carbon and jute fibers to 0.02 in those with carbon and linen fibers.[71]

In addition, **Figure 18A** illustrates similar strain behavior in laminates combining natural fibers with glass and carbon fibers in the prosthetic foot. The results confirm that adding artificial fiber layers reduces overall strain. Moreover, the combination of carbon and glass fibers leads to lower strain than using either artificial fiber alone with an equivalent number of layers. Specifically, laminates reinforced with carbon, glass, and linen fibers show an overall strain of 0.016, compared to 0.0391 for those with carbon, glass, and jute fibers.[23]

Figure 19A demonstrates that laminates reinforced with jute fibers exhibit the highest deformation compared to those reinforced with linen fibers, which is attributed to the lower mechanical performance of jute fibers. In contrast, hybrid laminates reinforced with carbon, glass, and linen fibers exhibit the lowest deformation value at 248.2 mm. In comparison, laminates with three layers of jute fibers show the highest at 1740 mm. These findings are based on a comparison between the volume fraction of the laminates and their total deformation across all specimens.

Deformation increases when only natural fiber reinforcements are used, due to the limited mechanical properties of natural fibers.[24] Under consistent boundary conditions, hybrid laminates reinforced with carbon, glass, and linen fibers demonstrate better performance compared to other laminated groups. The addition of carbon fiber significantly reduces deformation compared to laminates with only glass fibers, which possess lower stiffness and a lower elastic modulus.[26] These findings highlight that both material type and fiber volume percentage influence deformation behavior. Carbon fibers enhance performance and reduce deformation due to their high stiffness and Young's modulus, which are inversely linked to deformation and improve the material's resistance to external forces. As the fiber volume percentage increases, the composite's Young's modulus also increases, allowing it to better withstand external loads and minimize distortion.[72]

In **Figure 20A**, laminates reinforced with three linen fibers and those reinforced with three jute fibers exhibit the lowest strain energy among all laminated groups, compared to their counterparts reinforced with additional synthetic fibers. This is attributed to the mechanical strengths of jute and linen fibers, with linen fibers offering superior mechanical performance.[73] The addition of carbon fiber to hybrid specimens further reduces strain energy compared to laminates with a similar number of layers or those composed solely of natural fibers. For example, strain energy decreases from 1,827.4 mJ in laminates reinforced with carbon and linen fibers to 734.3 mJ in those reinforced with carbon and jute fibers. In contrast, strain energy increases in laminates reinforced with glass fibers. Specifically, laminates containing nine glass and linen fiber layers exhibit a strain energy of 3,375.1 mJ, while those with glass and jute fibers exhibit a strain energy of 3,143.6 mJ.[74]

Laminates containing both glass and synthetic fibers exhibit lower strain energy than those composed solely of natural fibers or those with an identical number of layers. For instance, the strain energy of laminates reinforced with carbon, glass, and linen fibers is 480.11 mJ. This variation in strain energy is closely related to deformation behavior and increases with the number of reinforcing fiber layers.[50]

In this study, the ANSYS Workbench software was used to determine the safety factor for the sports prosthetic foot. The von Mises stress, which influences the safety factor, varies depending on material properties and boundary conditions.[49] The distortion energy failure theorem was employed to calculate the safety factor of each composite. All materials achieve an optimum safety factor value of 15, as shown in **Figure 21**, ensuring that failure is unlikely to occur before the design life is reached. This outcome reflects the greater mechanical strength required of the fibers relative to the matrix.[48,49]

6.3. Theoretical analysis

According to **Figure 22,** laminates made of natural fibers and hybrid laminates reinforced with both artificial and natural fibers exhibit low safety factors below 1, making most of them unreliable at this number of layers. However, the addition of glass fibers does not significantly increase the safety factor. For instance, laminates reinforced with carbon and linen fibers, and those reinforced with carbon, glass, and linen fibers, exhibit safety factors above 1. The combination of linen and carbon fibers yields the best results among all lamination groups due to the superior mechanical properties of carbon fiber. Laminates reinforced with carbon, glass, and linen fibers exhibit the highest theoretical safety factor of 2.82, while those reinforced with three layers of jute fibers exhibit the lowest safety factor of 0.19. The safety factor varies according to both the number of layers and the type of material used, as each material possesses unique mechanical properties.[26]

Based on **Figure 23,** laminates reinforced with three jute fiber layers exhibit a high failure index of 5.26. In addition, laminates incorporating natural fibers exhibit higher failure indices compared to those reinforced with glass and carbon fibers. This is due to the differing mechanical properties and bonding characteristics of natural, carbon, and glass fibers. Overall, laminates composed of carbon, glass, and linen fibers exhibit the lowest failure index of 0.35 among all groups.[49,55]

According to **Figure 24,** laminates reinforced with jute fibers exhibit the highest fatigue ratio of 1.24. The fatigue ratio is higher in hybrid laminates containing three layers of jute fibers than in the other groups, as natural jute fiber possesses the lowest mechanical properties and forms weak contact bonding at the fiber–matrix interface. In contrast, laminates reinforced with carbon, glass, and linen fibers exhibit the lowest fatigue ratio of 0.088 due to their superior mechanical properties. These findings align with the known tensile strength and fatigue limit of the materials used.[76,77]

7. Study limitations and future directions

Several limitations remain in this study, including limited time and information accessibility. It is crucial to conduct finite element analysis on a wider range of models that consider differences in gender, levels of biological maturity, and types of amputation. In addition, further investigation into the mechanical properties of various naturally augmented composites is needed.

Second, biodegradability concerns. The timeframe for the biodegradability of natural fiber-reinforced composites may limit their long-term use. A new testing approach is recommended to better evaluate and address this issue.

Third, the limited scope of pressure measurements. In this study, the pressure measurements were conducted only during controlled laboratory walking sessions, which may not fully represent foot pressures encountered during daily activities. Moreover, the absence of user feedback remains a notable limitation, as subjective evaluations are essential to better understand the comfort and functional performance of the prosthetic foot.

8. Conclusions

With ongoing technological advancements, the application and benefits of prosthetic feet are expected to expand further, enhancing both user comfort and quality of life. Many lower limb amputee athletes can now participate in endurance sports, such as running, thanks to the development of advanced sports prosthetic devices. This study aimed to design and develop an innovative, cost-effective, lightweight, comfortable, adaptable, and durable prosthetic foot.

Several key findings were observed. First, differences between finite element analysis and experimental results were noted, largely due to variations in calculation techniques and boundary conditions. The finite element model revealed that the center section experiences the highest safety factor, strain energy, von Mises stress, and strain, while the bottom section exhibits the most significant deformation.

Hybrid laminates combining natural and synthetic fibers demonstrated superior tensile, flexural, fatigue, and hardness properties among all laminated groups. These superior mechanical properties are attributed to the combined effects of fiber type and the number of layers, both of which significantly influence the physical and mechanical behavior of the composite material.

Furthermore, increasing the fiber volume fraction led to improved mechanical properties, as both modulus and strength were positively correlated with fiber content. FTIR analysis revealed that no new peaks appeared following the addition of fiber reinforcement, and no new materials were formed when glass and carbon fibers were introduced. This indicates that the interaction between the resin and the reinforcement is based on physical bonding rather than chemical modification. The interface data suggest that the designed prosthetic foot can enhance biomechanical performance, improve user comfort, and better replicate natural foot motion.

Overall, the prototype prosthetic foot constructed from hybrid composites of natural and artificial fibers offers a safe and comfortable solution, with the potential for greater use of recyclable and environmentally friendly materials.

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Author contributions
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Ethics approval and consent to participate
Informed consent was obtained before participation, and the research was approved by the Ethics Committee of the College of Engineering, Nahrain University [form 202].
Consent for publication
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